STRUCTURAL ANALYSIS, EVALUATION AND RECOMMENDATIONS FOR CONSERVATION OF THE LAHORE MUSEUM

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ABSTRACT

STRUCTURAL ANALYSIS, EVALUATION AND RECOMMENDATIONS FOR CONSERVATION OF THE LAHORE MUSEUM

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This thesis aims to structurally analyze and evaluate Lahore Museum, Lahore, Pakistan to propose a structural conservation process and formulate recommendations for its conservation.

The building completed in 1893 was designed by John Lockwood Kipling and Bhai Ram Singh while Sir Ganga Ram was the engineer incharge. The building besides brick and timber uses metal for the construction of its structural members. The predominant structural system in the building is brick masonry load bearing system while a few galleries employ a dual system - bearing wall and frame. It integrates an array of roofing systems; ranging from brick masonry domes, to saw-tooth steel trussed roofing, flat wooden beam-batten roofs supported by I-Beams and RC slabs. The building from its inception has been subjected to constant repairs, additions and alterations without considering the building holistically. These interventions have been unsympathetic and the building is plagued with a multitude of problems.

For the purpose of this thesis two set of studies were conducted. Qualitative studies included historical survey, documentation of the building as well as preparation of drawings to determine current condition and problems. While, quantitative studies were carried out through analytical modelling of four reconstituted geometries of the building to study the structural behavior of the building and to evaluate its safety performance. Reconciliation of these studies showed that the building is globally structurally stable and its seismic performance is satisfactory. Studies also showed that anthropogenic actions are the main cause of localized structural and material damages which afflict the building. These findings have been used to formulate both the structural conservation process and the recommendations.

Keywords: Lahore Museum, Qualitative Assessment, Analytical Modelling, Structural Analyses, Recommendations, Structural Conservation Process

ÖZ

LAHOR MÜZESİNİN KORUNMASI KAPSAMINDA STRÜKTÜREL ANALİZ, DEĞERLENDİRME VE ÖNERİLER

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Bu tezin amacı Pakistan, Lahor'da bulunan Lahor Müzesi'ni yapısal açıdan analiz ve değerlendirmesini yaparak; yapının korunması için gerekli strüktürel koruma süreci ve öneriler geliştirmektir.

John Lockwood Kipling ve Bhai Ram Singh tarafından tasarlanan Lahor Müzesi'ni, 1893'te mühendis Sir Ganga Ram'ın gözetiminde tamamlanmıştır. Yapının taşıyıcı elemanlarında metalle birlikte, tuğla ve ahşap kullanılmıştır. Birkaç galeride ikili sistem (taşıyıcı duvar ve karkas) kullanılsa da yapı genelinde tuğla yığma strüktürel sistem hâkimdir. Yapıda tuğla yığma kubbeler, testere dişi çelik makas çatılar ve I kirişler ve betonarme döşemeler tarafından desteklenmiş düz ahşap kiriş çıtalı çatılar gibi farklı üstyapı sistemleri bir arada kullanılmıştır. Yapı başlangıcından bu yana bütünlük gözetilmeden yapılan tamirler ve eklemelerle, değişikliklere uğramıştır. Bu müdahaleler yapıya uyum sağlayamayıp, birtakım sorunlara yol açmıştır.

Bu tezin amacına uygun olarak çalışmalar iki grupta yürütülmüştür. Niteliksel çalışmalar tarihi araştırma, yapının belgelenmesi ile güncel durumun ve problemlerin saptanmasına yönelik çizimlerin hazırlanmasını içerir. Niceliksel çalışmalar ise yapının strüktürel davranışını anlamak ve güvenlik performansını değerlendirmek için yapılan müzenin dört ayrı restitüsyon dönemine özgü geometrik düzeninin analitik modellerine dayanır. Bu çalışmalarla yapının genel strüktürünün sağlam ve sismik performansının yeterli olduğu saptanmıştır. Çalışmalar ayrıca noktasal strüktürel sorunlarla, malzeme bozulmalarının insan kaynaklı olduğunu göstermiştir. Bulgular strüktürel koruma süreci tasarımı ve önerilerin geliştirilmesi için kullanılmıştır.

Anahtar Kelimeler: Lahor Müzesi, Niteliksel Değerlendirme, Analitik Modelleme, Strüktürel Analiz, Öneriler, Strüktürel Koruma Süreci.

For my parents

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
AISC	American Institute of Steel Construction
ASTM	American Society for Testing and Materials
BCP-2007	Building Code of Pakistan-Seismic Provisions 2007
CI	Cast Iron
C_a	Seismic Coefficient - Acceleration
C_v	Seismic Coefficient - Velocity
DOF	Degrees of Freedom
DSM	Dense Surface Models
EQX	Earthquake Load in X-Direction
EQY	Earthquake Load in Y-Direction
FEM	Finite Element Method
f'_m	Ultimate Compressive Strength
g / PGA	Peak Ground Acceleration
ICOMOS	International Scientific Committee of the International Council on Monuments and Sites
ISCARSAH	International Scientific Committee for Analysis and Restoration of Structure of Architectural Heritage
MoE	Modulus of Elasticity
MRP	Mass Participation Ratio
M_w	Moment Magnitude
NCA	National College of Arts
NDT	Non-Destructive Tests
NESPAK	National Engineering Services Pakistan
NSL	Natural Surface Level
PWD	Public Works Department
QIRT	Quantitative Infrared Thermography
RC	Reinforced Concrete
S11	In plane Normal Stresses for the Horizontal Direction

S22	In plane Normal Stresses for the Vertical Direction
S_D	Stiff Soil Profile
SDL	Super Imposed Dead Loads
t_f	Flange Thickness
t_w	Web Thickness
UBC	Uniform Building Code
UPV	Ultra Sonic Pulse Velocity Test

CHAPTER 1

INTRODUCTION

The focus of this thesis is the Lahore Museum (Figure 1.1), situated on the Mall Road in the city of Lahore, Pakistan. It is the oldest and the largest museum in Pakistan and is one of the most historically significant building of the Colonial Era in Lahore. The building was studied with an aim to propose a structural conservation process and to formulate recommendations through structural analyses and evaluation of the Museum building.

Figure 1.1: Lahore Museum (2015)
Source: KR. Waleed

This chapter begins by defining the aim and scope of this thesis. It is followed by problem definition and a discussion on the rationale for selecting Lahore Museum as the case study and how the thesis aims to answer the research questions. In the third section of this chapter the three pronged methodology – historical research, field surveys and documentation works, and structural investigation studies - adopted for carrying out research for this study is discussed at length. This section begins with a brief discussion about the sources used in this study to carry out historical research and how they contribute towards developing an understanding of the Museum building. It then explains the methods used for the documentation of the building, the processes used for generating various sets of drawings, and the drawing and space coding system developed for this thesis. Also in this section a brief overview of the approach used to carry out structural investigation studies is presented. At the end of this section the approach used to define the structural conservation process is briefly described. The chapter concludes with thesis chapterization breakdown and a brief discussion regarding the content of each chapter.

1.1. Aim and Scope of the Thesis

The thesis aims to propose a structural conservation process and formulate recommendations through structural analyses and evaluation of the Museum building, taking into account **qualitative** and **quantitative** approaches. It uses the conservation principles of "respect for cultural value of the building", "minimum intervention" and "reversibility", as its guides throughout the course of this study.

The thesis investigates history of the museum, with prime focus on the additions and alterations made to the building; which can cause structural problems. As part of the study, a building survey was carried out with help of a laser scanner which was then used for the production of drawings. Included in the scope of this thesis was creating a basic set of measured drawings along with sets of drawings with information overlays regarding structural features and their decay besides construction materials, etc. These drawings form the preliminaries, which provide an understanding of the building's history, spatial configuration schemes, structural and roofing systems, building materials, structural and material problems, for the qualitative assessment of the building. As part of the scope of the thesis, the quantitative assessment was carried out through the analysis and evaluation of results gained through analytical modelling of four reconstituted geometries of the building. The analyses were carried out using linear elastic analysis technique. Non-linear analysis is not included in the scope of the thesis. Analyses have been independently carried out on the reconstituted geometries of the building, in order to understand the influence of architectural alterations and their impact on building deformations. A true sequential construction analysis is not included in the scope of this thesis.

1.2. Definition of the Problem and Selection of the Case

The philosophy of preservation engineering, advocated by ISCARSAH Principles[1] (2003) and expounded by Kelley (2005), requires organization of the studies and analysis in steps similar to the medical analogy of **Anamnesis**, **Diagnosis**, **Therapy** and **Controls**; applied in a cyclic manner.

The purposive gathering of data regarding architectural interventions, alterations, past damage etc. during the **Anamnesis Stage**; when processed in conjunction with visual observations, structural analyses and laboratory tests leads to an effective **Diagnosis**. The identification of the sources and types of damages and assessment of the safety levels at this stage, through the reconciliation of the **qualitative** and **quantitative** approaches; forms the basis for determining the nature and level of intervention i.e. **Therapy**. If there are unresolved concerns at the diagnosis stage, further evaluation and long term monitoring should be recommended before prescribing treatment. As the **"minimum intervention"** principle can only be applied successfully at the therapy stage if both the earlier stages have been successfully resolved. Finally, **Controls** are set up to verify the diagnosis and monitor the long-term effects of the therapy (Kelley & Look, 2005, pp. 9-10).

In the last two decades the number of scientific approaches apropos computer-aided modelling and laboratory testing, aiding structural identification and analysis of the historical masonry structures, have rapidly increased. But a large majority of studies applying these approaches do not follow the steps delineated and prescribed by ISCARSAH principles. In some instances, only a linear elastic analysis is carried out despite the availability of data, such as non-linear properties of materials acquired through laboratory or in-situ mechanical tests. This could lead to results which do not provide a realistic assessment and would render creation of a case-specific diagnosis improbable. On the other hand if a more sophisticated non-linear analytical modelling is carried out, to determine structural vulnerability, with insufficient data, such as incorrect material and mechanical characterization, similar ineffective results will be obtained. In either of the instances mentioned above, results could lead to either over

[1] ICOMOS Charter: Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage; ratified by the ICOMOS 14th General Assembly in Zimbabwe in October 2003.

strengthening of the structure causing needless loss of original fabric and hence cultural value, or insufficient intervention which can endanger safety of people as well as the heritage.

Another key consideration when structural vulnerability of a historic structure is being assessed is its historical background. As construction processes, architectural alterations and additions, long term decay and damage and natural disasters can influence structural response of the building and provide answers to the probable causes of current damages in the building. Ideally analytical model must incorporate to a certain degree; historical stages, historical actions such as earthquake and damage processes related to long term creep (Roca, Cervera, Gariup, & Pelà, 2010, p. 304).

But in practice dimension of history is generally ignored and analysis is conducted only on the current condition of the building, resulting in imprecise diagnosis and leading to inaccurate therapy recommendations, which if implemented can negatively impact the heritage structure.

In this study, a unique colonial building located in Lahore, Pakistan is being structurally investigated to assess its safety performance and to formulate a structural conservation process and provide recommendations for its conservation. An attempt is being made to apply the medical analogy endorsed in the ISCARSAH principles (2003) to reach a stage where recommendations are in keeping with the "minimum intervention" philosophy. Additionally, the historical background of the building is being taken into account, by carrying out independent analyses on four reconstituted geometries of the building, to ensure better interpretation of the analyses results.

Lahore Museum, built in 1893 and located in the heart of the cultural and educational precinct of Lahore is selected as a case study for it is considered unique in terms of its Historic, Architectural and Aesthetic Values (Sami, 2017). Lahore Museum, established as part of the imperial network of museums, is the largest, oldest and most important museum in Pakistan. The Museum building besides being a physical presence in the city, "is an essential part of the lore and experience of Lahore" (Sami, 2017, p. 320).

The building from its inception has continued to function as a Museum and has been subjected to anthropogenic actions such as additions, alterations and repairs without any comprehensive plan. Whenever these interventions have been carried out they have only considered the part, while ignoring the whole; resulting in damage to the building. For the continued use and existence of this heritage, its structural safety is paramount. In the absence of any academic or professional studies carried out to assess structural vulnerability of the building; it was considered an appropriate case for structural modelling, analysis, evaluation and recommendations besides the preparation of a structural conservation process.

1.3. Methodology

The methodology adopted for this study was three pronged. The *Historical Research* was carried out to understand conception and significance of the Museum building, its construction techniques, additions and alterations as well as events that might have brought about structural damage. The *Field Surveys and Documentation Works* were carried out to understand the current condition of the building vis-à-vis its spatial configuration, structural systems, construction techniques, decay and damage pattern etc. The *Structural Investigations* were carried out to assess the building for its structural vulnerability.

Historical Research & Sources for the Lahore Museum Building

To reconstruct history of Lahore Museum building a variety of sources, each providing fragmentary information, have been used. Official governmental publications from the late 19th and early 20th Century such as the *Imperial Gazetteers of India* and periodically updated *Gazetteers of the Lahore District,* provide generalized accounts of the Lahore Museum. These Gazetteers published by the Government of India provide general statistics, maps along with summarized information on places and buildings. In case of the descriptions of Lahore Museum found in these documents slight inaccuracy is observed in the dimension of spaces, as they have been rounded off. The dimensions, published in various sources, have been reproduced without modifications and are shown in Table 5.

Annual Reports of the Museum and archival documents were consulted, between 8th of September and 5th of October 2015, to understand the detailed history of modifications that the museum building has gone through. The Annual Reports were published from 1889 to 1907 by the museum's parent authority i.e. the *Revenue and Agriculture Department* and then from 1908 to 1913, by the *Lahore Museum* itself. The annual reports continued to be printed by the museum authority under the new nomenclature of *Central Museum, Lahore* from 1914 to 1944. The findings are presented in tabular form in APPENDIX A of this thesis.

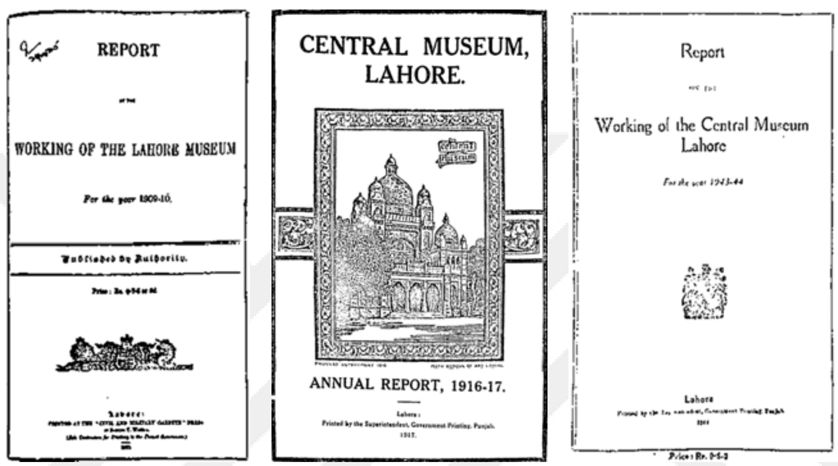


Figure 1.2: Annual Reports of the Lahore Museum (1910; 1917; 1944)
Source: Lahore Museum Library

To reconstruct history of the building interventions after the 1967 remodeling of the Museum, various sources were relied upon. The verbal information shared by Dr. Saifur Rahman Dar, Director Lahore Museum 1974 to 1998, in an interview jointly conducted by Author and Usman Sami on the 24th of February 2016. This information was corroborated through the Annual Reports published after a long hiatus by *Lahore Museum* authority between 1968 and 1972. As well as the archival documents, presented to the Director of Lahore Museum by the Public Works Department (PWD), from the museum's Official Records (Figure 1.3). These documents are primarily detailed cost estimates accompanied by partial sketch plans of existing condition at the time the works were carried out (Figure 2.80).

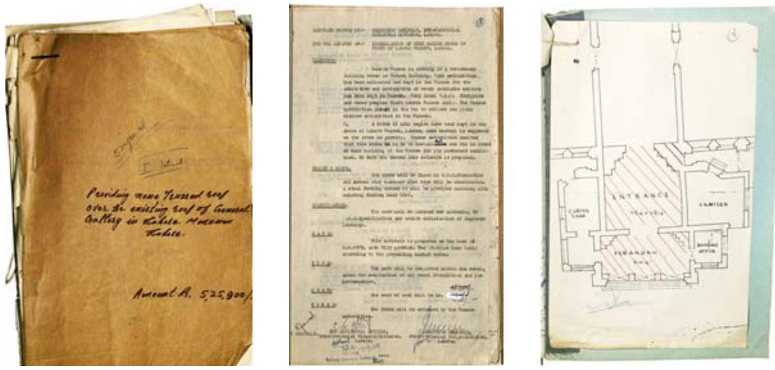


Figure 1.3: Archival Documents - Museum's Official Records (1980; 1991; 1985)
Source: Lahore Museum

The *PWD Specifications: Buildings and Roads* (1936) and *Some Practical Points in the Design and Construction of Military Buildings in India* (1910), accessed in December 2015, have been used to understand masonry details and construction standards used during the Colonial Era. Though the PWD specifications are from a later date than the initial construction of museum building, this is the earliest copy of specifications found during the course of this research.

Field Surveys and Documentation Works

The Museum building was visually inspected during three field surveys. The first field suvery, carried out between 8th of September and 5th of October 2015, coincided with the documentation of the building. The Museum building was documented using two modes of indirect measurement; laser scanning and photographic survey. The visual inspection was carried out to form an initial understanding of the building in terms of its structural systems, construction techniques and materials. The traces of additions and structural alterations as well as evident structural problems were also investigated. The second field survey was carried out, on the 24th of February 2016, to visually inspect if the building had suffered any damages as a result of the earthquakes that jolted Pakistan on 26th of October 2015 and 25th of December 2015 and had measured moment magnitude 7.5 (M_w) and 6.3 (M_w) respectively. During this survey a detailed inspection of the structural systems and elements was also carried out. A quick third and last field survey was carried out, on the 26th of May 2017, to reassess the probable causes of damages especially the most critical damages observed on the northern wall of Pre and Proto Historic gallery.

Laser Scanning

Laser Scanning was carried out using Leica Scan Station P20 laser scanner, with high redundancy to generate point-clouds, at medium resolution of 2 mm^2. A total of 262 scans were carried out to cover both exterior and interior of the building. Monochromatic texturing option available in Leica Scan Station P20 was used to create texture maps (Figure 1.4).

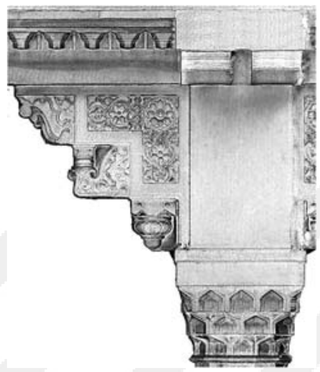


Figure 1.4: Laser Scan - Entrance Portico - Marble bracket over column (2015)
Monochromatic texturing using luminance values picked up by the laser.

Next, two point cloud processing software were used to process the laser scans. The laser scans were first loaded in Cyclone 9 software and then into Faro Scene 5.5[3] software, which offers smoother and sharper outputs and renders from the point cloud data. It took ten months to process and extract orthographic photos and section slices from the laser scans[4].

[2] Laser Scanning work was carried out by the Author along with Usman Sami, LUMS field team: Atiq Hashmi and Wajiha Arshad and students from COMSATS, Lahore: Ushna Imran and Shavaiz ul mulk

[3] Faro Scene does not accept the raw laser scan data from Leica laser scanners. Hence the scans had to be moved between software using .e57 file format.

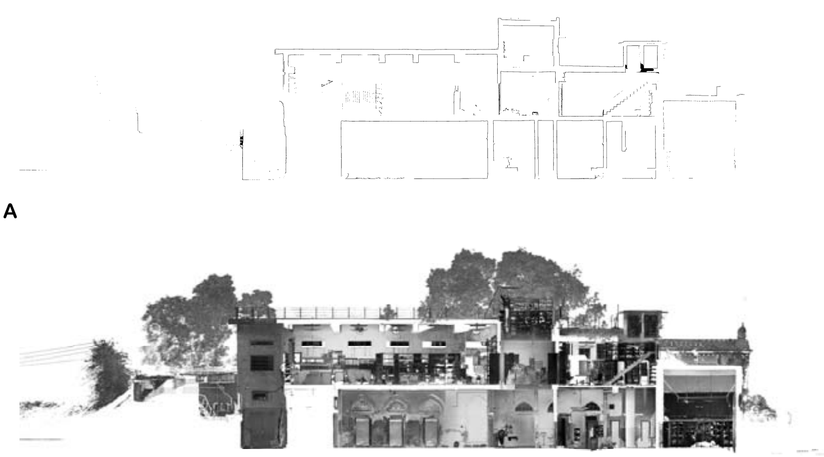
[4] Laser Scans were processed by Usman Sami, who was assisted by the Author.

Digital Photogrammetry

As it was not possible to carry out laser scanning on parts of the museum's northern and western elevations, these inaccessible areas were measured using orthographic photographs generated by a digital photogrammetry software[5]. Dense surface models (DSM) were generated for these areas using multiple high resolution photographs. The photographs needed for this process were taken at the same time as the laser scanning survey.

Production of Drawings from Laser Scans and Photogrammetric Data

Section slices of plans and sectional elevations used to generate drawings were exported from Faro Scene at 400 pixels per meter. The resulting drawings therefore have an error margin of only 2.5mm. Section slices, few millimeter in thickness, were used to produce sectional lines for plans and sections (Figure 1.5-A). Subsequently, these lines were traced as section lines in AutoCAD drawings, with as much precision as possible. In case of each section and elevation produced for the purpose of this thesis, an ortho-photo was generated using a section plane (Figure 1.5-B). The objects and surfaces thus visible were drawn with reduced line thickness to represent the objects in the background (Figure 1.6).



A

B

Figure 1.5: Scaled orthographic photo produced using Faro Scene (2016)
A: Section Slice, B: Section Background
Both images were traced over and combined to prepare the measured drawings.

[5] Digital Photogrammetry was carried out by Usman Sami who was assisted by the Author.

To add depth to the information, translucent overlays of laser scan have been provided with each measured section and elevation drawing (APPENDIX B).

Figure 1.6: Sample drawing prepared from laser scan (2016)
Ortho-photo from laser scan used as background image (left),
Sectional Drawing produced by tracing over the architectural details in ortho-photo (right)

All measured drawings have been drawn at a scale of 1:50, with the exception of the north elevation which is drawn at 1:100. The drawings have been printed at a much reduced scale of 1:500 (APPENDIX B). Dimensions are not included as they were unreadable at this reduced a scale. A System Section, drawn at 1:20 and printed at 1:100 is also included in this thesis (Figure 2.37).

Separate set of drawings with various overlays of information above the measured drawings have been produced. The drawing sets presented in this thesis are;

a. Measured Drawings
b. Laser Scans
c. Building Functions & Circulation
d. Building Parts
e. Building Phases
f. Construction Stages
g. Building Materials
h. Structural & Roofing Systems
i. Structural & Material Problems

Measured Drawings and Laser Scans drawing sets are presented in APPENDIX B of this thesis. Additionally, a digital copy of all the drawings has been provided with this thesis on a CD (APPENDIX E).

Drawing Coding System

A unified system of coding for spaces and drawings was developed and is used throughout the thesis. Plans have been produced by horizontally slicing the building at four level and the floor level of Entrance Portico was taken as the plinth level. Plans labeled Ground Floor (GF), 1st Floor (1F), 2nd Floor (2F) and 3rd Floor (3F) have been cut through horizontal section planes at 2.5m, 6.45m, 8.9m and 13.4m above the plinth level respectively. Application of this coding system is explained through Table 1 and Figure 1.7.

Table 1: *Drawing Coding Chart*

Category	**Item**	**Code**
Drawing Set	Measured Drawing	MD
	Satellite Image	SI
	Laser Scan	LS
	Building Parts	BP
	Building Functions & Circulation	BF
	Structural & Roofing Systems	SS
	Building Materials	MT
	Building Phases	PH
	Structural & Material Problems	CN
	Construction Stages	CS
Drawing Group	Plans	PL
	Section	SE
	Elevation	EL
Drawing Type	Location Plan	LP
	Ground Floor	GF
	Basement	BA
	First Floor	1F
	Second Floor	2F
	Third Floor	3F
	Roof Plan	RF
Orientation	North	N
	East	E
	South	S

Drawing Set – Drawing Type – Drawing Group – Orientation / Section Number

Figure 1.7: Drawing Coding System

In order to differentiate between space codes and drawing codes, dissimilar labels have been used to define floors etc. As an example for *Ground Floor* while Space Codes use the label **Gnd**, Drawing Codes use **GF.**

Coding of Building Volumes and Building Parts

Lahore Museum building facing north is almost symmetrical and presents itself as a large singular volume. Thus for ease of referencing the building has been split into smaller volumes, each volume is called a **Block**. On the northern façade each **Block** has been given an alphabetic label A-H (from left to right) while other distinctive labels have been assigned to the blocks towards south of the building.

Blocks have been grouped together based on a planimetric logic and are called **Part** of the building. The building parts labeled *Central, Northern, Eastern, Southern and Western* are composed of spaces that are either linked on the basis of circulation and can be accessed from each other or their access/ circulation has been intentionally disconnected from the rest.

Space Coding System

Space coding system can be used to define the space, bounding surface (ceiling etc.) and/or the architectural elements (door, windows etc.). Spaces can be coded by using the system shown in Table 2 and Figure 1.8. This space coding system works for most spaces without requiring additional details as most of them are rectangular and their walls face north, south, east and west.

The numbering of spaces, with reference to Figure 2.9 and Figure 2.12, have been referred to with original labels as seen on period drawings, but some spaces in these drawings do not have corresponding labels. Therefore, for cross-referencing original labels are accompanied by the space coding system designed for this thesis.

Table 2: *Space Coding*

Category	Item	Code
Floors	Ground Floor	Gnd
	Basement	Bas
	First Floor	Fst
	Second Floor	Snd
	Third Floor	Thd
Part	North	N
	East	E
	South	S
	West	W
	Central	C
	Auxiliary	A
	Servant Quarters / Mosque	S
Bounding Surface	Floor	F
	Ceiling	C
	Wall	W
Wall Orientation	North	N
	East	E
	South	S
	West	W
Architectural Elements	Door	D
	Window	W
	Ventilator	V

Figure 1.8: Space Coding System

Approach to Structural Investigations

A brief overview of the approach taken to structurally investigate the Museum building is being presented here while details are furnished in Section 3.2 of this thesis.

To carry out structural investigations of Lahore Museum, input was taken from both historical research and measured drawings produced as a result of the documentation work carried out on the building. First and foremost a decision was made to analyze the building by including its historical dimension by creating four analytical models each responding to a spatial configuration experienced by the building during its lifetime. By individually analyzing each stage and comparing the results it was possible to understand the influence of additions and alterations, carried out without a holistic approach, on structural behavior of the building and to determine the cause of observed deformations in individual structural elements. The measured drawings were then used to draw 3D models of the reconstituted geometries in AutoCAD. These models were then imported into SAP2000 to carry out the analyses. Large scale of the building and unavailability of detailed mechanical properties of materials dictated that FEM macro modelling with linear elastic analysis was considered best suited for analyzing the Museum building. To evaluate the building performance under seismic loading, two approaches of application of seismic loads; equivalent lateral static procedure and response spectrum analysis were conducted using Design Spectra as per UBC-97/BCP-2007 corresponding to Seismic Zone 2A in Pakistan.

Method of Preparation of the Structural Conservation Process

According to contemporary approach to conservation a thorough understanding of the architectural heritage, through its tangible and intangible aspects, is crucial for the preparation of a conservation process. This ideal can only be attained through multi-disciplinary conservation studies. Article 2 of the Venice Charter (1964) cites the importance of a multidisciplinary approach as "conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage" (ICOMOS, 1964).

A multi-disciplinary Conservation Process flowchart (Figure 1.9), defining interrelated studies and activities, was prepared by Usman Sami (2017)[6]; in light of the Burra Charter (1999) guidelines. The Conservation Process defined the tasks into groups and sub-groups; according to groups of experts responsible for accomplishing

[6] The Conservation Process was prepared by Usman Sami as part of his thesis titled "Understanding the Lahore Museum for the Definition of a Conservation Process" for a Master's degree in Conservation of Cultural Heritage, under the supervision of Prof. Dr. Neriman Şahin Güçhan, Department of Architecture, METU, Ankara, Turkey.

sequences of specialized studies. The task group concerning this thesis is **Structural Analysis (CSS)** which is a sub-group of Architectural Conservation Works.

In order to formulate a proposal for the Structural Conservation Process specific to Lahore Museum, the Conservation Process flowchart (Figure 1.9) was used as the base document. Labeling and distribution of the task groups was kept consistent with those used by Usman Sami (2017), and are presented in Table 3.

Table 3: *Conservation Process Coding Chart*

Task Group	Sub Group	Code
Architectural Conservation Works	Architecture	**CSA**
	Historical	**CSH**
	Material Analysis	**CSM**
	Structural Analysis	**CSS**
	Mechanical Systems	
	Water / Sewage	**CSW**
	Climactic Control	**CSC**
	Lighting	**CSL**
	Security Systems	**CST**
Legal, Administrative and Managerial Works	Government	**LAMG**
	Administration	**LAMA**
	Users	**LAMU**
Improvement of Building Function & Museology	Museum Collection (Objects)	**MBFC**
	Museology & Functional Aspects	**MBFM**
Preparation of Action Plan		**AP**
Preparation of Management Plan		**MP**

Note: Source Sami (2017, p. 26)

The tasks in the Structural Analysis (CSS) sub-group were redefined and flow of information needed from this task group, within the broader framework of Architectural Conservation Works, was modified as per the ISCARSAH Guidelines (2003). The process was particularized for the Lahore Museum on the basis of the safety evaluation of the building, presented in Section 4.1 of this thesis.

The detailed discussion of each requisite task in the structural conservation process and the affiliated flowchart are presented in Section 4.2 of this thesis.

1.4. Thesis Chapterization

The thesis body is divided into five chapters, with first chapter being the *Introduction*. This chapter presents the aim and scope, and methodology of the study besides the problem statement and the rationale for selecting Lahore Museum as a case study.

The second chapter titled *Lahore Museum, Lahore, Pakistan*, focuses on the qualitative aspects of the research conducted for the purpose of this thesis. It juxtaposes information from historical research and on-site surveys, to qualitatively assess the problems faced by the Museum building and their probable causes.

The chapter starts out by briefly introducing the city of Lahore through its location and traces history of the city, through the evolution of its urban layout, under Mughal, Sikh and the British regimes. This is followed by a concise description of the architecture of Lahore during the Mughal era and its appropriation by the British to legitimize their rule. The style coined “Indo-Saracenic” housed Western functions in the native Indo-Islamic façades thus recasting native architecture in a western mould. The discussion then proceeds to a short account of the genesis of Lahore Museum and the various premises it occupied during its lifetime.

Henceforth, the discussion centers on the purpose built premises of the Lahore Museum, built in 1893 and designed in the “Indo-Saracenic” tradition. It begins by chronologically charting out the spatial evolution of the Museum building and introducing three key figures that gave the building its architectural and structural form. It was their contributions that gave the building its rich native appearance and a Western technological approach to its construction. It goes on to describe in detail the indepth observations apropos the current condition of the building and structural systems and elements employed by the building. It also furnishes in detail the collection, rationalization and characterization of structural materials used in the building, from literature in the absence of any experimental data.

All this information forms the background for the main aim of this chapter that is to provide qualitative assessment of the Museum building based on historical research, visual observations and documentation carried out on the building. The chapter thus concludes with an indepth discussion about the current damages, both structural and material, to the building and assessing the probable causes of these damages.

The third chapter titled *Modelling and Strucutral Analyses of Lahore Museum*, focuses on the quantitative approach taken in this thesis for structural assessment of the Museum building. The approach takes historical background of the building into account, by developing four analytical models based on the reconstituted geometries of the building and analyzing them separately.

In the beginning of this chapter a review of the computational strategies available for modelling of historic masonry structures and possibilites and limitations of each strategy is presented. In light of this discussion the rationale for choosing FEM Macro Modelling approach for developing analytical models and then analyzing them through Linear Elastic Analysis technique is also discussed. Seismic Analysis was carried out using two approaches, equivalent lateral static procedure and the response spectrum analysis, for the current state of the building to determine seismic vulnerability of the building. Modal and Stress Analysis were carried out, on all stages of the building, to understand global structural behavior, impact of historical interventions and to assess structural vulnerability of the building. To narrow down the concerns for the structure, based on its structural behavior and performance, foremost attention was paid to its predominant load bearing system i.e. masonry walls. Locations in the building where tensile stresses exceeded the considered threshold were analyzed by sequentially considering results of each stage to determine the cause of observed damage. The masonry wall with most critical of the structural damages was studied using a part model and simulating the hypotheses apropos probable causes of the damage. A perfunctory analysis was also carried out for a localized sub-structural system i.e. the columns to assess their performance. The chapter concludes by expounding the results of these analyses and their interpretation.

The fourth chapter titled *Recommendations and Defining of a Structural Conservation Process for the Lahore Museum*, by apposing findings of all the aforementioned studies provides safety evaluation of the building which is then used to define the recommendations and to formulate a proposal for the structural conservation process specific to Lahore Museum.

The structural evaluation of the building is carried out by reconciling the assessments formed through analysis of the qualitative and quantitative approaches. The

ISCARSAH Recommendations (2003) have been used to particularize the Structural Conservation Process, within the broader framework of a multi-disciplinary Conservation Process. The chapter presents the process in form of a flow chart; with each process shown as a box that carries the title and a short description of the tasks which are numbered. The chart identifies tasks that have been completed as part of this thesis and also shows processes that need to be carried out in order to ensure a comprehensive structural conservation process. It also charts out flow of information within a multidisciplinary conservation process, from the structural perspective. Full sequential description of all tasks presents the rationale and importance for carrying out each task.

The Recommendations are formulated on the basis of safety evaluation of the building and in keeping with the principles endorsed by both Venice Charter (1964) and ISCARSAH Recommendations (2003). The Recommendations are two tiered; Immediate Actions are a set of recommendations proposing non-invasive forms of interventions, while Further Studies outlines all the recommended pre-conservation studies, required for designing a holistic structural conservation program.

The fifth and the last chapter is titled *Conclusions* and it provides summary of the findings of this thesis, limitations faced, possibilities of future studies and its wished for applications.

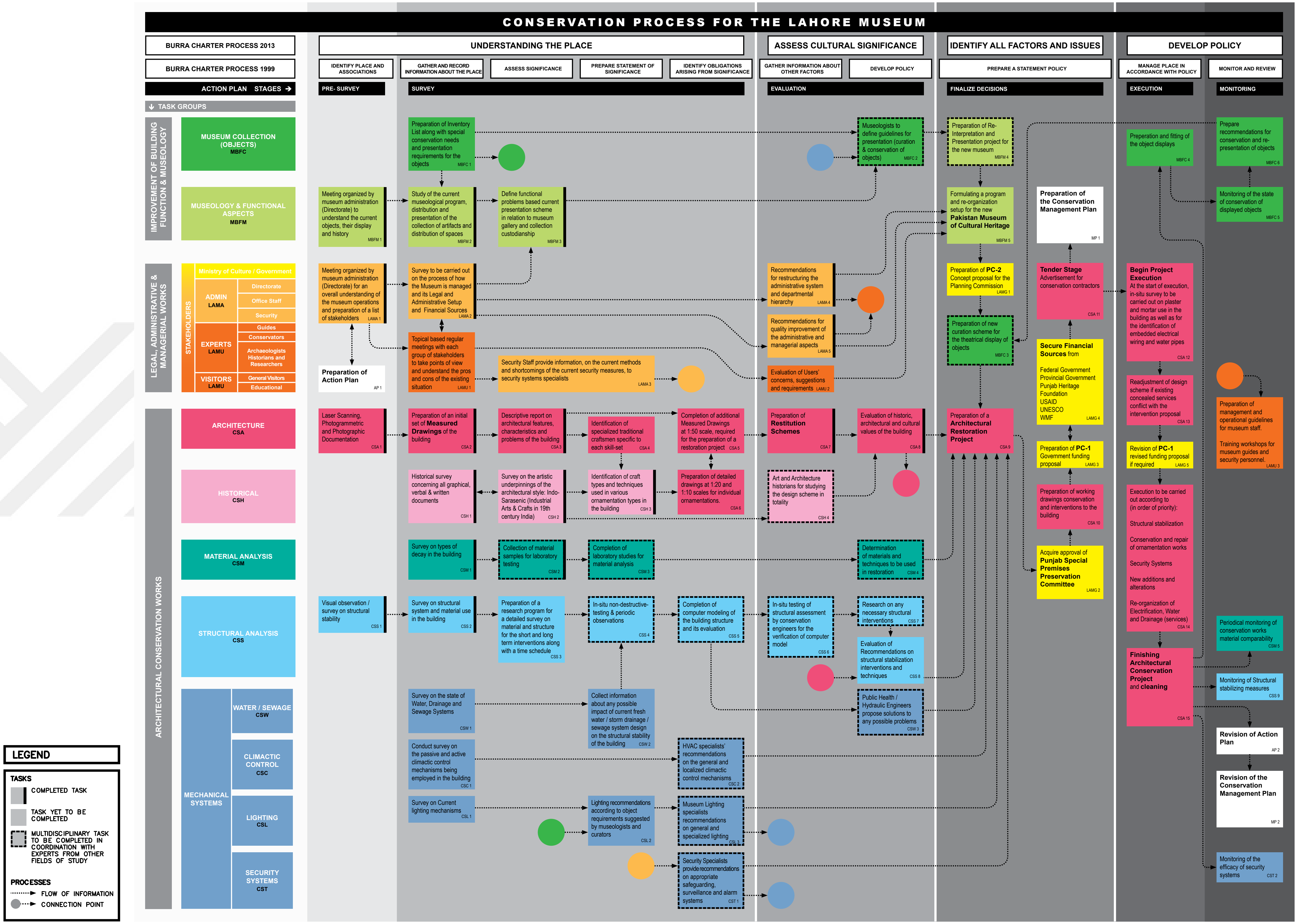


Figure 1.9: Flow Chart – Conservation Process for the Lahore Museum (2017); Source: Sami (2017 , p. 359)

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CHAPTER 2

LAHORE MUSEUM, LAHORE, PAKISTAN

The broader aim of this chapter is to assess the building through qualitative approach by juxtapositioning the information acquired through historical research, visual observations and documentation and it contains seven sections.

The first section of the chapter briefly introduces city of Lahore, by looking into its history, evolution of its urban layout and its architecture. The next section provides historical background to the Museum building. It discusses the establishment of the museum as an institution in Lahore and explains spatial evolution of the current building by timeline. It also gives information about the legal framework that offers protection to the building and its premises. The third section provides a brief description of geology and seismicity of the region followed by geo-technical conditions of the site and ends with a short note on the location and immediate setting of the Museum. The fourth section based on visual observations and documentation, provides a general description of the building. The fifth section employs historical research and visual observations to describe in detail structural systems and multiple structural elements housed in the building, from the sub structure to the super structure. The sixth section comprehensively discusses collection and rationalization of the mechanical properties of structural construction materials, from literature in the absence of any experimental data. All the above mentioned information is used to achieve main aim of this chapter i.e. the qualitative assessment of the Museum building. Hence, the last and concluding section, using the aforementioned information, defines the construction stages experienced by the building during its service life and analyzes structural interventions experienced by the building that have the potential to structurally damage the building. Besides providing qualitative assessment of the current damages, both structural and material, to the building and probable causes of these damages.

2.1. Lahore – An Overview

City of Lahore lies at 31° 34' 5" N latitude, and 74° 21' E longitude, 215 meters (706 ft.) above sea level (Latif, 1892, p. 84). It is ranked as Pakistan's second largest metropolis and is the provincial capital of Punjab. The city is situated in north-eastern part of the country (Figure 2.1), within 25 km (15.5 miles) of the international border with India (Malik, 2015, p. 4). Lahore commands a focal position in the Upper Indus Plain and lies south of River Ravi, a tributary of the Indus River. It is bounded on north and west by Sheikhupura District, on east by Wagah, and on south by Kasur District. The city covers a total land area of 1771.55 km^2 (684 sq. miles) and is still expanding.

Figure 2.1: Location of Lahore in context of Pakistan & neighboring countries.
The insert shows location of Pakistan in reference to the world.
Source: www.shutterstock.com (modified by author)

History of Lahore

Exact beginnings of the city of Lahore are untraceable but discovery of Indo-Bactrian coins in Lahore region, are suggestive of a settlement in the locality as early as 1st Century AD (Peck, 2015, p. 2). Additionally Ptolemy in *Geographia*, written around 150 AD, mentions a city by the name of *Labokla,* situated on the route east of River Indus. This place, from its name and position, might be identified as a reference to the ancient settlement of Lahore (Walker, 1894, p. 267).

Lahore according to the old accounts of neighboring states of Kashmir and Rajputana, was a Hindu principality till the Muslim invasion in 10th Century (Latif, 1892, p. 1). The Hindu rule in Lahore came to an end when Mahmood Ghaznavi in 1022 AD took Lahore without opposition (Walker, 1894, p. 269). From the Ghaznavids to the Mughals, city of Lahore has been associated with all the Muslim dynasties of Northern India.

Lahore attained wide spread prominence during the reign of Mughal Emperor Akbar (r.1556 – 1605) (Glover, 2008, p. 6). The city became the place of royal residence between 1584 and 1598 AD, and it was during this time that Akbar enclosed the city with a high brick wall having 13 gates and a circuit of nearly 5 km (3 miles) (Latif, 1892, p. 85). As people flocked to the imperial court the city grew in population, and suburbs arose outside the city walls (Peck, 2015, p. 10). In between these suburbs, tombs, mosques and pavilions were built and gardens were laid out (Walker, 1894, p. 273). Lahore, owing to the impetus provided by the Mughals to its architecture, was at the peak of its splendor during the early half of the 17th Century (Latif, 1892, p. 54).

The city, throughout the 18th Century, was subject to periodic invasions and pillage by the invaders from the West as well as the Sikh insurgents. When the Sikh Empire was established in Punjab by Ranjit Singh, in early 19th Century, Lahore had been reduced to a mere walled township (Walker, 1894, p. 283). In words of T.H. Thornton, the city population was confined within the city walls built by Akbar (Figure 2.2), "outside was ruin and devastation" (Goulding, 1924, p. 92).

Lahore came into the fold of the British Empire in 1846, after a treaty was signed between the British and the Sikhs. The British initially established themselves in an area south of the old fortified city, later known as "Civil Station", and utilized the existing Mughal tombs and mosques for administrative purposes (Qureshi, 1997, p. 71).

Lahore became capital of the British Province, after the official annexation of Punjab, in 1849. As early as 1851, a wide road – The Mall[7] was laid out to connect the Civil Station with the newly established cantonment, some 5 km (3 miles) southeast, at Mian

[7] Renamed Shahrah-e-Quaid-e-Azam, but the locals still refer to it by its original name

Mir (Goulding, 1924, p. 30) (Figure 2.3). These early architectural and infrastructural interventions before the Indian Revolt of 1857, were mere markers of the transformative wave of urbanization that took over Lahore, after 1858, when India came under the direct rule of the Crown.

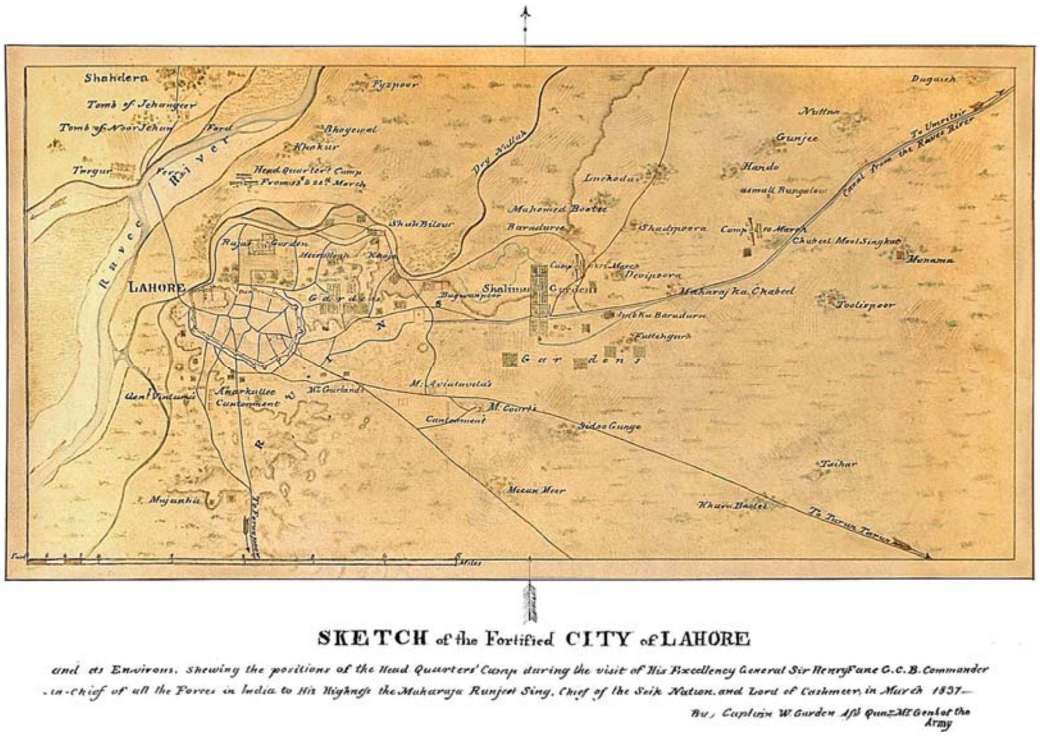

Figure 2.2: Sketch of the Fortified city of Lahore and its Environs (1837)
By Captain W. Garden Asst. Quarter Master General of the Army
Source: Punjab Archives

The new administration, implementing urbanization, held strong conviction that the material fabric of the city had power to shape the individual and collective sentiments. Colonial Lahore thus saw emergence of new building typologies like educational institutions, libraries, museums, hospitals and restaurants. By the turn of the twentieth century, Lahore's most prominent administrative buildings, commercial enterprises and places of public congregation were housed in a 1 km (0.6 mile) stretch on “The Mall”, in the “Civil Station” area (Glover, 2008, p. 19).

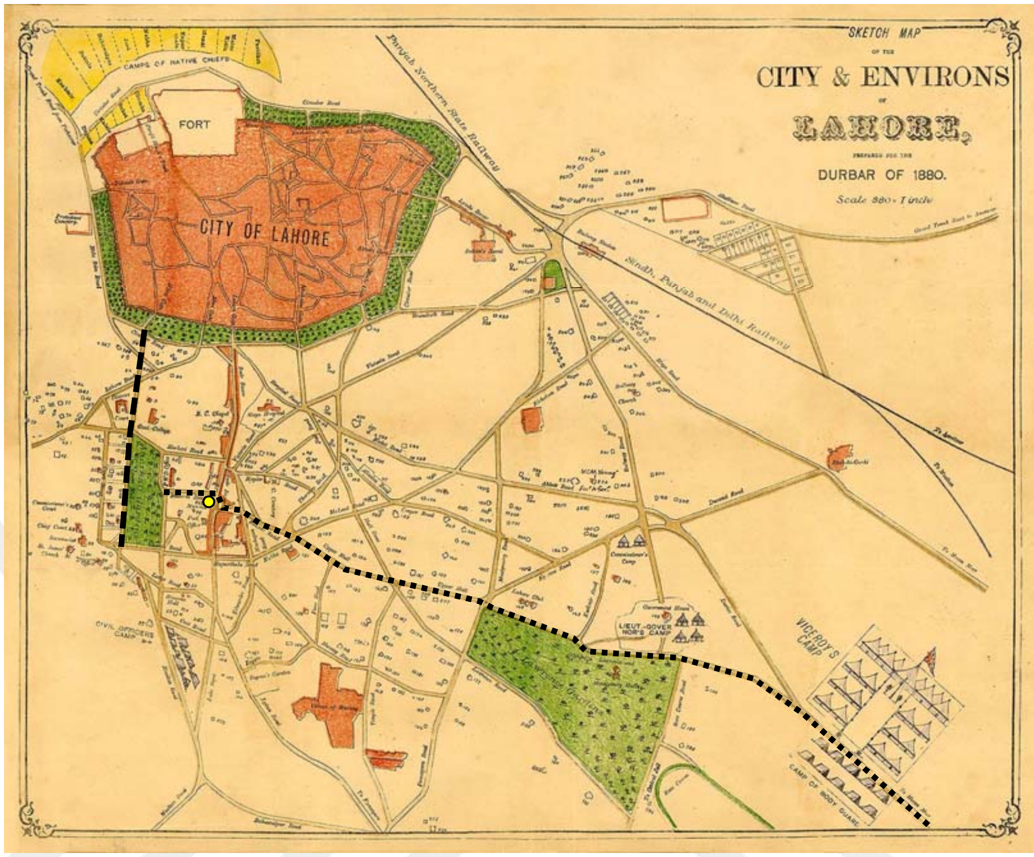

Figure 2.3: Sketch Map of the City of Lahore & & Environs (1880)
Source: Punjab Archives, Lahore – modified by Usman Sami (2017)

The Mall: ▪▪▪▪▪ , Lower Mall: ▬ ▬ ▬ ▬ , Exhibition Building: ○

Lahore witnessed major upheavals and endured everlasting changes to its socio economic and physical set up, in the aftermath of the partition of British India in 1947. In the decades since, city of Lahore has grown in size and population owing to its political and administrative role.

Architecture of Lahore

Lahore has no architectural remains from its long pre-Mughal period, and even from the Mughal era only imperial structures have survived. One of the main reasons cited for the lack of physical remains is the absence of building stone in the near vicinity of Lahore besides the destructive invasions which the city was subjected to throughout its history(Goulding, 1924, p. 83; Peck, 2015, p. 34; Walker, 1894, p. 272). Basic building materials used in Lahore were brick and timber, hence buildings either decayed quickly without maintenance (Peck, 2015, p. 34) or were demolished for the sake of building material both during the Sikh and the British period (Latif, 1892, p. 256). The monumental buildings that survive from the Mughal era in Lahore, exhibit certain characteristics such as the bulb-like domes, Ogee arches, marble lattice windows besides the extensive use of colored tiles and enameled fresco (Goulding, 1924, p. 85) (Figure 2.4).

Figure 2.4: Buildings in Lahore built in the 17th Century.
Left: Sardar Jahan Mosque (c.1880) built during the reign of Mughal Emperor Jehangir (1605 – 1627)
Right: Badshahi Mosque (c.1870) built by Mughal Emperor Aurangzeb (1658 -1707)
Source: Punjab Archives

This style coined "Indo-Saracenic" by the British was appropriated for their own buildings after India became a direct crown colony (Metcalf, 2005, p. 174). In terms of Metcalf (1989, p. 48), British to legitimize their rule needed to be seen as "heirs of the wise and tolerant Akbar." A distinctive style of architecture which was Indian in appearance but Western in function, was thus adopted and was meant to turn India's architectural heritage to the service of the Raj (Metcalf, 2005, p. 120). Therefore, many of Lahore's prominent colonial public buildings are Mughal in appearance, though they date from the late 19th or 20th Century (Peck, 2015, p. 39) (Figure 2.5).

Figure 2.5: Buildings in Lahore built during the late 19th Century.
Left: Aitcheson College building designed by Samuel Swinton Jacob, elevation and detailing by Bhai Ram Singh completed in 1890. Right: King Edward Medical College building designed by W. Purdon, Superintendent Engineer PWD completed in 1883
Source: Punjab Archives

2.2. Historical Development & Legal Protection of the Lahore Museum

The origins of a Museum in Lahore can be traced back to a March 1855 circular issued by the Financial Commissioner of Punjab, proposing the establishment of museums at district level "with a view to tracing the development of the resources of the country and improvements in agriculture, machinery and the arts" (Rehmani, 1999, p. 1).

As a consequence, Lahore's first museum named "Lahore Central Museum" was established in 1856 and housed in Wazir Khan's *Baradari*[8] (Latif, 1892, p. 188; Qureshi, 1997, p. 72; Rehmani, 1999, p. 1) (Figure 2.6).

Figure 2.6: Wazir Khan's *Baradari* (c. 1885)
Source: National College of Arts Archives

The '*Baradari*', built in the 17th Century in distinctive Mughal style, was focal point of the garden known as '*Nakhleh-e-Wazir Khan*'- The date palm garden of Wazir Khan (Latif, 1892, p. 188). By 1863, the collection had acquired an antiquarian feel and was fast outgrowing the space in the *'Baradari'* (Rehmani, 1999, p. 1).

Thus in 1864 Lahore Central Museum, coined by the people as *'Ajayabghar'* or the "house of wonders", was relocated to the Exhibition Hall[9], built earlier in the year for holding the Punjab Exhibition of Arts and Industry of 1864 (Latif, 1892, p. 353)

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[8] A pavilion building with twelve doorway openings.

[9] The Exhibition Hall served as a market after the Museum shifted to its current premises and came to be known as Tollinton Market. In 2006 it was again converted into an exhibition hall and renamed the Lahore Heritage Museum.

(Figure 2.7). After the exhibition closed, the Exhibition Hall, which had been built as a temporary structure was given a more permanent roof and floor and the Museum collection was moved in (Aijazuddin, 2003, p. 112).

Figure 2.7: The Exhibition Hall Building (c. 1864)
Source: British Library

The Museum in the 1870s under the curatorship of John Lockwood Kipling, got a new direction and an influx of ideas (Qureshi, 1997, p. 73). Kipling in his position as the curator of the Museum and Principal of Mayo School of Arts[10] encouraged the amalgamation of the two institutes (Chaudhry, 1998, p. 271). It was in 1887 that a decision was made to build the present building of the Museum as part of an institute called the Victoria Jubilee Institute (Aijazuddin, 2003, p. 108) (Figure 2.8).

The Institute was sited across the Exhibition Hall, in the grounds of the *'Baradari'* (Peck, 2015, p. 162) and included the Museum, a Lecture Hall, a Library and the Mayo School of Arts (Aijazuddin, 2003, p. 108). The venture was financed out of the funds raised throughout the Punjab Province during the commemoration of Queen Victoria's Jubilee in February 1887. On 3rd February 1890 Prince Albert Victor laid down the foundation stone for the building designed by Bhai Ram Singh, member of the first batch of students from Mayo School, under the guidance of his mentor John Lockwood Kipling. The Institute constructed by Sir Ganga Ram, then Executive Engineer of Lahore, was completed in late 1893; in time for the Punjab Exhibition of December

[10] Now National College of Arts (NCA)

1893 and was opened to the public in 1894 (Aijazuddin, 2003, p. 108; Chaudhry, 1998, p. 271; Peck, 2015, p. 160; Rehmani, 1999, p. 2).

Figure 2.8: Lahore Museum building, part of Victoria Jubilee Institute (c. 1893)
Source: Khan, H.A. (2014), p. Cover

The history of the Museum in Lahore thus encompasses more than 150 years and three remarkable buildings – The *Baradari* of Wazir Khan, The Exhibition Hall and the current Museum building – all located adjacent to one another within two blocks fronting on “The Mall” (Figure 2.14).

The Purpose Built Premises of the Lahore Museum

The 1916 *Gazetteer* describes the Museum building as a series of long galleries that resembled the letter “E”, with the Entrance Portico in the center of the back face (Punjab Government, 1916, p. 247) while the three arms constituted of two galleries and the lecture hall running in the north-south direction. At the time of its completion, the building had a total area of 2,587.35 m^2 (27,850 ft^2) (Latif, 1892, p. 273).

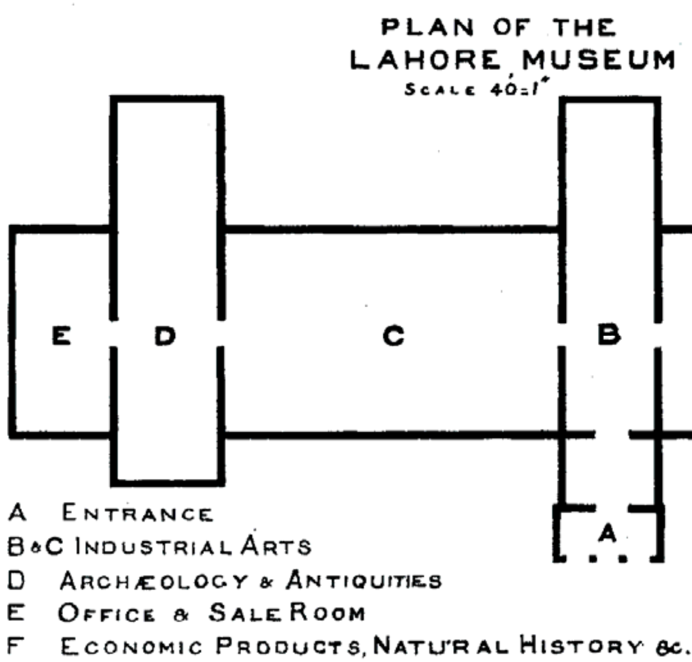

Figure 2.9: 1908 Plan of the Lahore Museum.
The plan only shows areas accessible to the general public. It does not show the Hall for the Technical Institute, Two Rooms and an Office located at the Western end of the Museum.
Source: Brown, P. (1908). A Descriptive Guide to the Department of Archeology & Antiquities

The museum was entered from the north, through the Entrance Portico (Gnd-N/01) - Space A (Figure 2.9), which lead onto the Entrance Vestibule "directly under the dome" (Gnd-N/02) (Walker, 1894, p. 301). Also accessible from the portico were two Stairwells one on either side of the entrance door to the vestibule (Department of Education, 1911, p. 166). The Entrance Vestibule opened onto the Central Gallery (Gnd-C/01) - Space B (Figure 2.9), which in turn opened out on the eastern and western side into mirrored galleries, gallery (Gnd-W/01) - Space F (Figure 2.9) on the west and gallery (Gnd-E/01) - Space C (Figure 2.9) on the east. Each gallery had two rows of Cast Iron columns supporting the Saw-Tooth trussed roofing (Department of Education, 1911, p. 166; Latif, 1892, p. 273; Walker, 1894, p. 301) which formed north facing skylights. The gallery (Gnd-E/01) on its eastern end led to gallery (Gnd-E/03) - Space D (Figure 2.9), which in turn led to gallery (Gnd-E/04) - Space E, which served as an Office, a Library and a Sales Room for "objects of Punjab [sic] art workmanship" (Latif, 1892, p. 274). The gallery (Gnd-E/04) led onto the Eastern Verandah (Gnd-

E/22) (Figure 2.10) which faced the Exhibition building previously occupied by the museum and located on the eastern end of the museum.

Figure 2.10: Museum from the East (c. 1907)
The eastern verandah clearly visible in the image has been extensively modified and closed off.
Source: Popular Science Monthly (1907), Vol. 71, p.493

Adjoining the museum on its western side was a Technical Institute, comprising of a lecture hall with an arcade running around it and three classrooms (Walker, 1894, p. 301). The access to the lecture hall (Gnd-W/10) was from a separate entrance lobby (Gnd-W/09) (Department of Education, 1911, p. 166). The Western Verandah (Gnd-W/26) (Figure 2.11) ran around the lecture hall (Gnd-W/10) and the three classroom (Gnd-W/11, Gnd-W/26 and Gnd-W/27) and faced the Mayo School of Art (Walker, 1894, p. 301).

There were no planimetric changes to the building till 1905, although repair works were frequently carried out. According to the Museum's Annual Reports recurrent repairs had to be carried out to the roofing system due to leakage of both roofs and gutters.

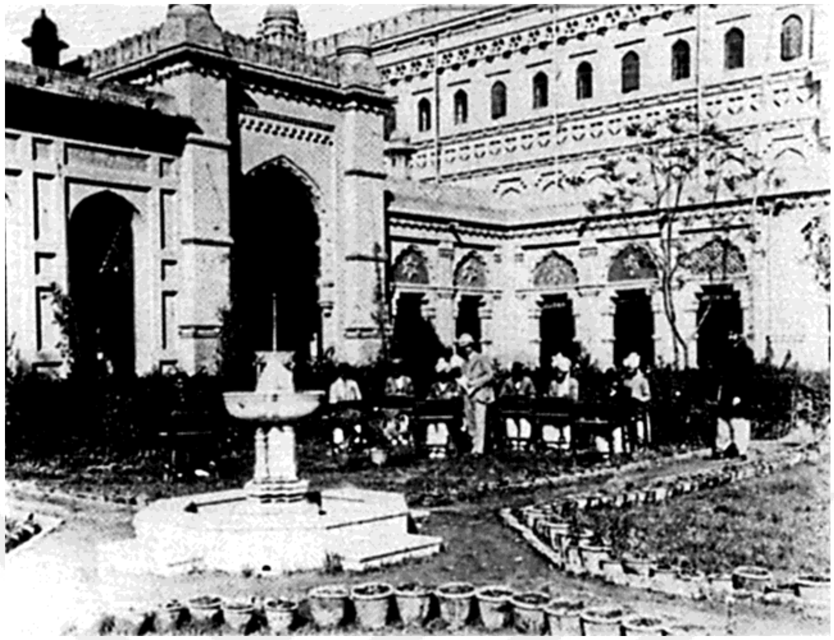

Figure 2.11: Mayo School of Art courtyard with the Museum as backdrop (c.1907)
The image shows the carriage portico shared by both the Museum and Mayo School of Arts and the covered verandah on the western side of the Museum building. The verandah is now completely encased inside parts of the Museum building constructed in the 1960's and later. The portico now exclusively part of the school serves as its main entrance.
Source: Tarapor, M. (1980), p. 67

The first addition to the building was in 1906 when two Cloakrooms (Gnd-N/04 and Gnd-N/06) were added on either side of the Entrance Portico (Gnd-N/01) and were accessible from the room (Gnd-N/03) on the east and room (Gnd-N/05) on the west (Revenue and Agricultural Department, 1906). Chronologically the next additions to the building started in 1914 and were completed in 1916. These additions included a gallery (Gnd-E/02) - Space 4 (Figure 2.12), a library (Gnd-C/04) - Space 8 (Figure 2.12), a curator's office (Gnd-E/17) and an office (Gnd-W/07) with workshop for "*mistris*"[11] (Central Museum, 1914, 1915, 1916). The building during the years 1927 to 1929 was subjected to further additions when another gallery (Gnd-W/02) - Space 5 (Figure 2.12), a coin room (Gnd-S/01) - Space 1 (Figure 2.12), a "*godown"*[12] (Gnd-E/25)and two toilets (Gnd-E/26 & Gnd-W/30) along with a verandah (Gnd-S/21) were built towards the south of the building (Central Museum, 1927, 1928, 1929).

[11] Craftsmen

[12] An alternative word used in India for warehouse

The drawing of the museum from 1929 (Figure 2.12) shows the spatial layout of the museum in that year. The Museum was to keep this spatial configuration till the post-independence renovations of 1965 (Lahore Museum, 1968).

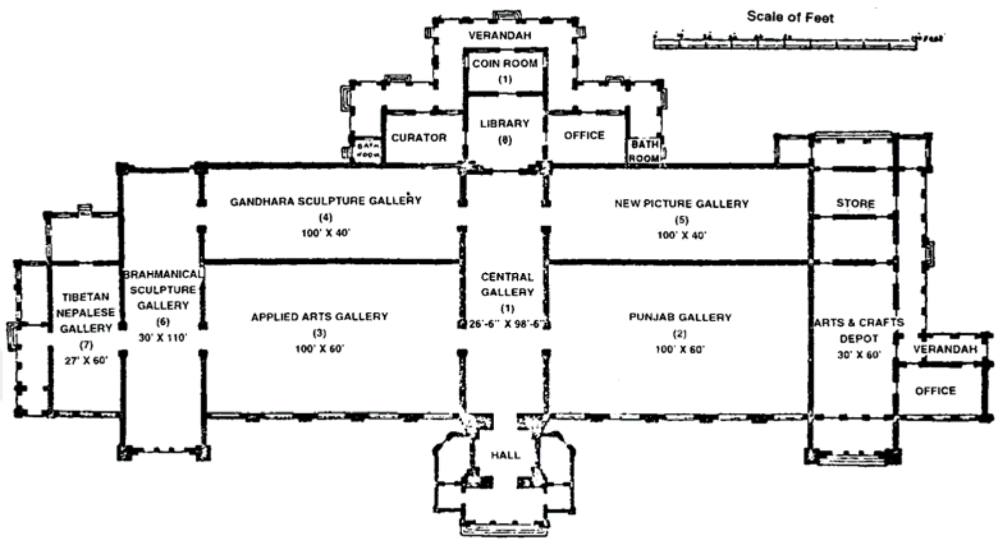

Figure 2.12: 1929 Plan of the Lahore Museum
Source: Rehmani, A. (Ed.) (1994), Lahore Museum Bulletin: Centenary Issue (1894-1994)

The building was closed off to public in 1965 for two years, to carry out repairs and also for the construction of new works (Lahore Museum, 1968, p. 2). The new additions included a laboratory (Gnd-E/14, Gnd-E/15 & Gnd-E/16), workshop (Fst-E/03), mosque (Gnd-M/01) and several servant quarters, all built at the southern end of the building (Lahore Museum, 1968, p. 1). Furthermore, in 1969 a new gallery (Gnd-W/08) was added and the empty space between the Museum and NCA[13], on the western side, was converted into stores (Gnd-W/05 & Gnd-W/25) for the reserve collection. A two storey detached structure, along the southern boundary of the Museum lot, was also constructed in the same year (Dar, 2016). Galleries (Gnd-E/18 & Gnd-E/19) along with a basement gallery (Bas-E/01) were constructed in 1972 (Lahore Museum, 1972, p. 1). In 1974 a new floor was added over the galleries (Gnd-E/18 & Gnd-E/19) to create new gallery space (Fst-E/10, Fst-E/11, Fst-E/12, Fst-E/13, Fst-E/14 & Fst-E/15). A semi-detached two storey office block connected to the main

[13] National College of Arts

building through a bridge was added to the building in 1978 (Dar, 2016). In later years till the present only a handful additions have been made to the Museum building.

Architects of the Lahore Museum

The building of Lahore Museum is a testament to the first wave of civic architecture in Colonial India built by native designers and employing vernacular design motifs. It combines the training of John Lockwood Kipling, artistry of Bhai Ram Singh and the innovativeness of its engineer - Sir Ganga Ram. The three names attached to this building hold a prominent place in the colonial history of Lahore.

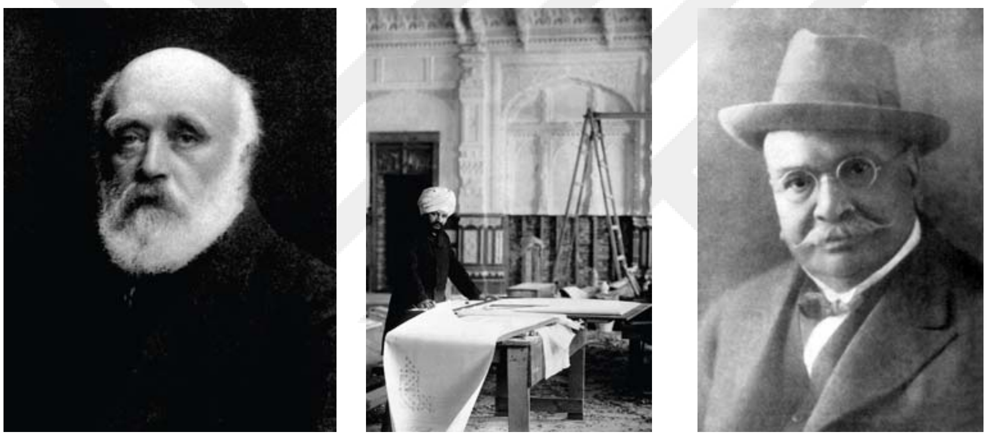

Figure 2.13: Left: John Lockwood Kipling (c. 1899); Center: Bhai Ram Singh (c. 1890) working at Osborne House; Right: Sir Ganga Ram (c. 1920)
Source: Left: The Critic: An Illustrated Monthly Review of Literature, Art and Life, Vol.35, p.585; Center: National College of Arts Archives; Right: http://lahore.city-history.com/personalities/Sir-Ganga-Ram/

John Lockwood Kipling was a designer, curator, educator and a catalyst for Arts and Crafts movement in India. Kipling began his career as an architectural sculptor at South Kensington Museum[14], before moving to India in 1865 as an educationist. He arrived in Lahore in 1875, as the Principal of the newly established Mayo School of Arts and curator of the Lahore Museum (Tarapor, 1980, p. 63). All contemporary official documents credit Kipling as being the chief designer of the new building for the school and also the Museum.

[14] Now Victoria and Albert Museum

Bhai Ram Singh, one of John Lockwood Kipling's most talented student, joined the Mayo School of Art in 1875, as a member of its first batch (Vandal & Vandal, 2006, p. 126). The systematic and rigorous training of the School gave Bhai Ram Singh an opportunity to hone his skills as a carpenter besides developing a deeper understanding of other arts and architecture.

Most of his initial work was in furniture and interiors but soon he was involved in design of buildings as well. By 1881 he worked on the design of the new building for the school and later assisted Kipling in the design of the Museum as well (Peck, 2015, p. 161). While most of his work, was in Punjab and especially Lahore, his ingenuity in design, led to two commissions for the interiors of rooms in the royal houses in England (Vandal & Vandal, 2006, p. 159).

Sir Ganga Ram[15], born in 1851, was an engineer, agriculturalist and a great philanthropist. He joined PWD, in 1873 as Assistant Engineer, upon his graduation from the Thomson Civil Engineering College at Roorki (Bhatti, 2016, p. 54).

He served as Executive Engineer of the Lahore Division for twelve years, where he oversaw the design and construction of metaled streets, paved lanes and properly laid drains besides some of the most monumental colonial buildings in Lahore (Bedi, 1940, p. 41). While all the buildings he is credited for are rich in native traditions in their appearance like the Aitchison College or the Lahore Museum but in their construction the technological approach of the West was employed by Ganga Ram (Bedi, 1940, p. 38).

Sir Ganga Ram also made inventions to improve construction, like his slide rule for calculating structural sizes or his design for an anti-thermal flat roof, that were widely used and were of far reaching importance (Bedi, 1940, p. 40; Peck, 2015, p. 147). It is both for his engineering services and his philanthropic gifts to the city of Lahore that he is rightly referred to as the "Father of Modern Lahore".

[15] Sir Ganga Ram received his knighthood in 1922 (Bedi, 1940, p. 247).

Legal Protection of the Lahore Museum

The Museum is registered under The Punjab Special Premises (Preservation) Ordinance, 1985 (APPENDIX C) along with NCA as a single property. This legislation provides protection to the building as a whole and governs the conservation works that need to be carried out. The legislation has an arbitrary system of approvals for the conservation works. A temporary committee is appointed by the Provincial Government to provide these approvals, but till date no committee has paid attention to the haphazard construction and repair works that are carried out on the Museum building.

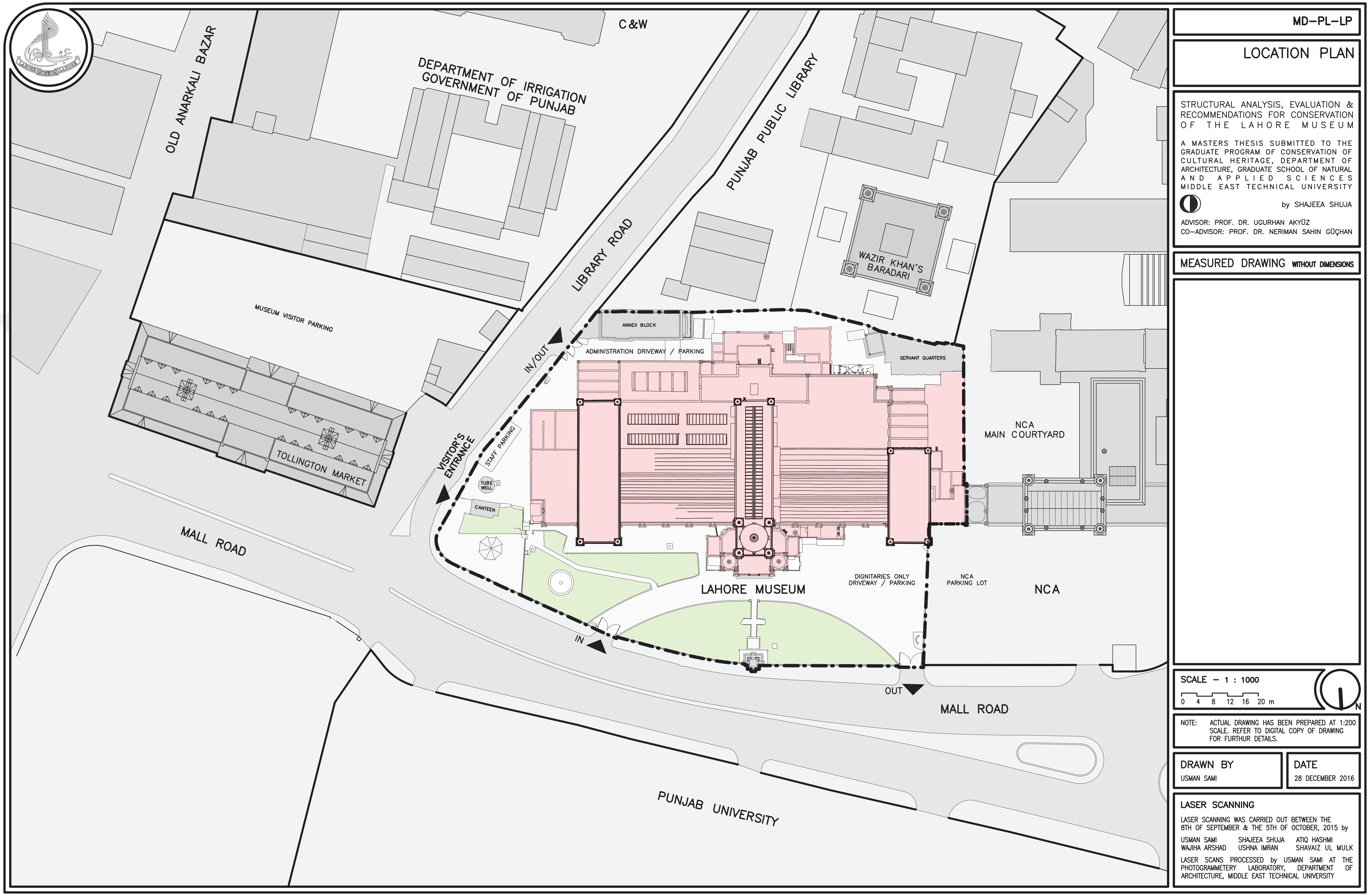

Figure 2.14: MD-PL-LP – Measured Drawing – Location Plan (2016)

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2.3. Location and Setting of the Lahore Museum

The Museum is located in the north-western part of the city of Lahore, at 31° 34' 6.35" N latitude, and 74° 18' 29.2" E longitude (centered at the main dome). The building fronting the Mall Road faces north and is set back from the road at a distance of 26.8m (87ft. 11in.).

Geological and Geotechnical Characteristics of the Site

Lahore, lies in the vast plain of alluvial material called the '*Bari Doab'* (Figure 2.15). *Doab* is a local word for interfluvial area between two rivers (Greenman, Swarzenski, & Bennett, 1967, p. 2). *'Bari Doab'* is formed by Indus River and its tributaries, and the alluvial deposits of Lahore have been deposited by the old course of one of the tributaries, the River Ravi (NESPAK, 2015b, p. 6).

Figure 2.15: Map showing Rivers and Doab's in Indus Plain.
Source: Malik, 2015, p.7

The alluvial deposits in Lahore are more than 300 m (985 feet) thick and lie over the basement rock of the Indian Shield. The alluvial layers mainly consist of sand, interpolated with clay and silt layers of varying thickness (NESPAK, 2015b, p. 6).

The city, gently sloping towards southwest at an average gradient of 1:3000, is generally flat (Greenman et al., 1967, p. 4). It can be divided into two parts; the comparatively upland area in the east, away from River Ravi and the low lying area along Ravi. The low lying areas are generally inundated by the river water during monsoon (Malik, 2015, p. 5). The project site lies in the upland area of the city.

Seismicity

Lahore is located in a low to moderate level seismic zone (NESPAK, 2015b, p. 6). The city does not have strong earthquake generating sources in close proximity but experiences moderate level of shakings from earthquake occurring in the Himalayas (Shah, Iqbal, Qaisar, & Tufail, 2008, p. 2). Main Boundary Thrust (MBT) is the known main active fault line of the Himalayas, which passes at a distance of about 180 km (112 miles) northeast of Lahore along the Himalayan front. During the past century earthquakes of magnitude greater than 8 have been recorded along this fault (NESPAK, 2015b, p. 6). Kangra earthquake of 1905, is one of the earthquakes that caused considerable damage in Lahore (Shah et al., 2008, p. 2).

Probabilistic seismic hazard assessment carried out as part of the Building Code of Pakistan-Seismic Provisions 2007 (BCP-2007), divides the country in five zones; and places Lahore City in Zone 2A, with Peak Ground Acceleration (g) of 0.15 with 10% probability of exceedance in 50 years (NESPAK, 2007, pp. 2-3) (Figure 2.16).

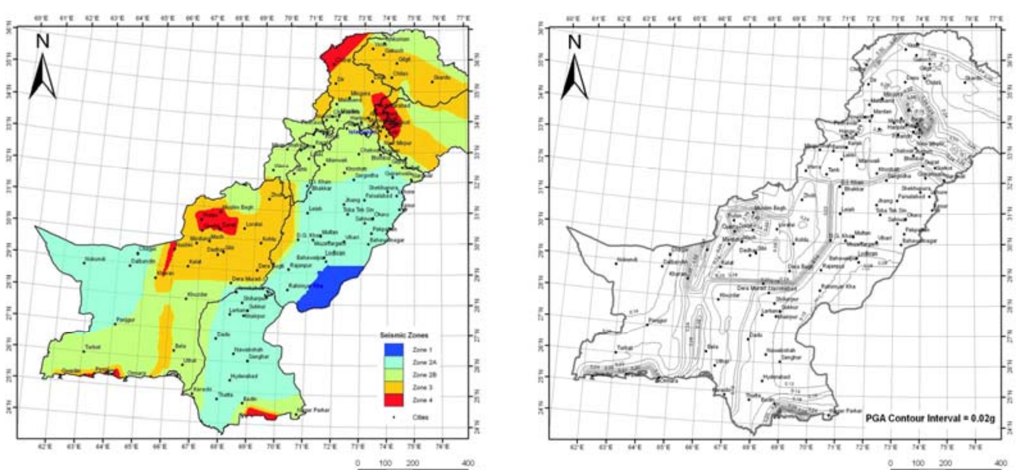

Figure 2.16: Seismic Zoning Map of Pakistan (left), Map showing Peak Ground Acceleration (g) with 10% probability of Exceedance in 50 years (right)
Source: Building Code of Pakistan – Seismic Provisions 2007

Geotechnical Conditions

The project site lies in the old catchment area of the River Ravi (Figure 2.15). Over time the river has shifted its course and currently flows approx. 4 km west of the site. No studies have been carried out to determine the subsurface conditions at site.

For the purpose of this study, the geotechnical conditions of the site have been extrapolated from the borehole data, located approx. 500 m (0.31 miles) east of the site (Figure 2.17). This borehole formed part of the larger geotechnical investigations carried out around Lahore, by NESPAK in 2015.

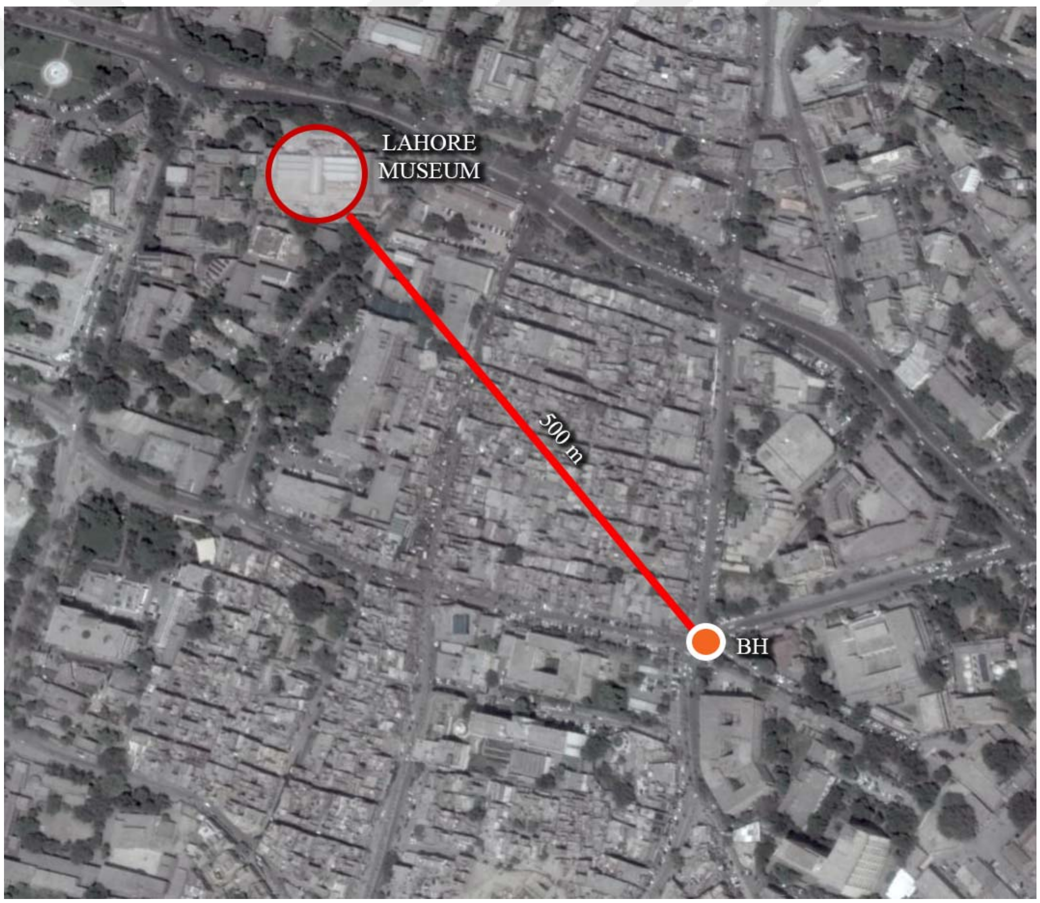

Figure 2.17: Map showing location of borehole approx.500 m east of the site.
For this study data of the borehole has been used to infer the geotechnical conditions of the site.
Source: Google Earth, 2017 (modified by author)

The borehole was bored up to a depth of 40 m (131 ft.) below Natural Surface Level (NSL). The soil strata encountered consists of a 2 m (6.6 ft.) Fill layer, followed by 3 m (9.9 ft.) of Silty Clay in firm to stiff condition. This layer is then underlain by 10 m

(32.8 ft.) of medium dense Silty Sand which in turn is followed by 9 m (29.5 ft.) of poorly graded Sand with Silt. A layer of 11 m (36.1 ft.) hard Lean Clay, is encountered at a depth of 24 m (78.7 ft.). Finally a very dense Silty Sand is present up to the maximum investigated depth. The ground water was encountered at a depth of 25 m (82 ft.) below NSL (NESPAK, 2015b, p. 18) (Figure 2.18). The clayey subsoil does not have any swelling potential (NESPAK, 2015b, p. 20).

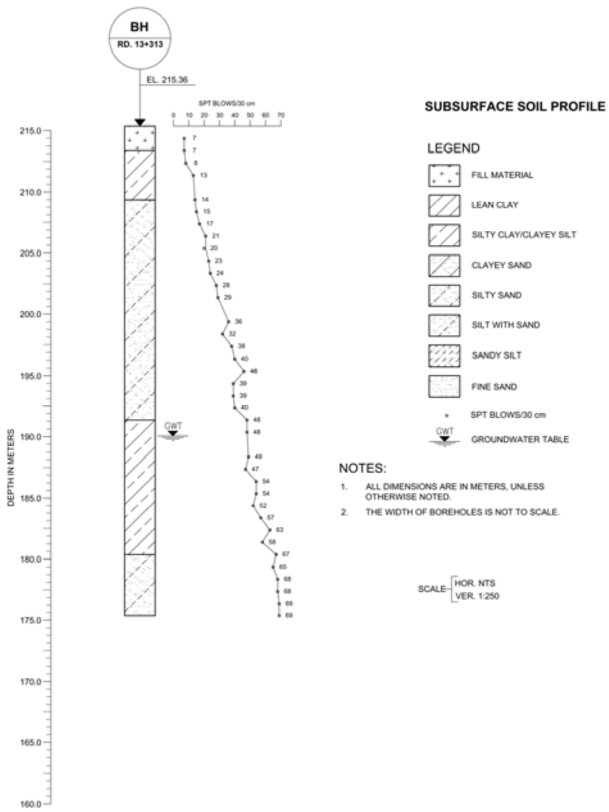

Figure 2.18: Subsurface soil profile
Source: NESPAK, 2015

The bearing capacity of the soil for under the wall strip foundation has been calculated using the Terzaghi's method. The foundation width of 0.76 m (2.5 ft.) has been used for calculations while the depth of the foundation has been assumed at 1.8 m (6 ft.). This assumption is based on the information provided in literature regarding the foundation depths of various contemporary colonial buildings in Lahore. The ultimate bearing capacity of the soil thus determined is 437.85 kPa (4.57 tons/ft^2). The allowable bearing capacity of the soil calculated by applying a factor of safety of three, comes out to be 145.95 kPa (1.52 tons/ft^2). In accordance with BCP-2007, the seismic soil profile for Lahore can be taken as S_D i.e. Stiff Soil Profile[16] (NESPAK, 2015b, p. 20).

Current Setting of the Lahore Museum

The Museum is located in the section of the city that saw the earliest developments made by the British to the city of Lahore. The area forms the cultural and educational hub that spreads east along the Mall Road (Figure 2.19 & Figure 2.20).

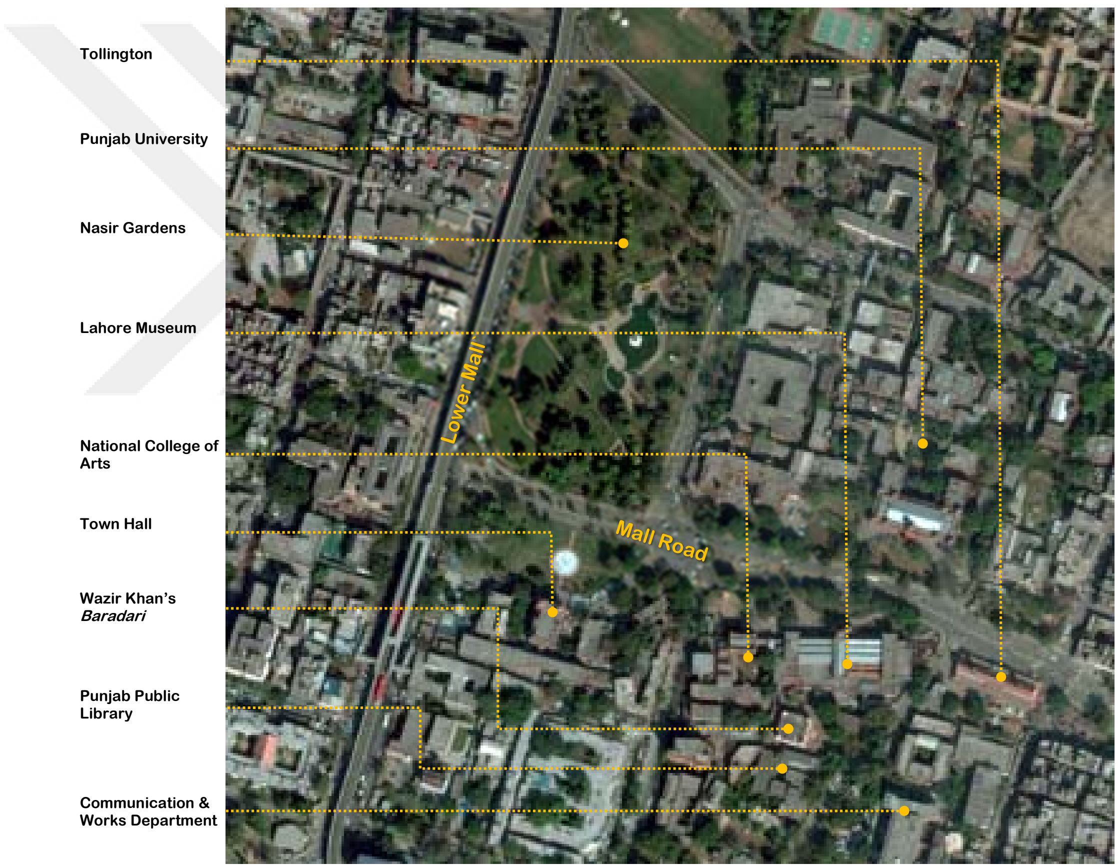

Figure 2.19: Lahore Museum Context: The Cultural and Educational Precinct.
Source: Google Earth, 2017 (modified by author)

[16] S_D i.e. Stiff Soil with 175 m/s < v_s < 350 m/s (575 ft./sec. < v_s < 1,150 ft./sec.) or with 15 < N < 50 or 50 kPa < s_u < 100 kPa (1,044 psf < s_u < 2,088 psf)

The Museum along with NCA[17] sits in a city block bounded by Mall Road on the north, Library Road on the east and Prof. Ashfaq Ali Khan Road[18] on the west.

In the city block, sited north of the Museum, across the Mall are the Punjab University buildings including College of Pharmacy, University Senate Hall, Woolner Hall and other faculties. To the east of the Museum across the Library Road is the Lahore Heritage Museum[19]. The building fronting the Mall occupies the northern end of the entire city block while its southern end is empty and currently serves as a public parking lot. To the south of the Museum lot is Wazir Khan's *Baradari* (Figure 2.19) which is now part of the Punjab Public library complex. The *Baradari* currently functions as a reading room for the Library.

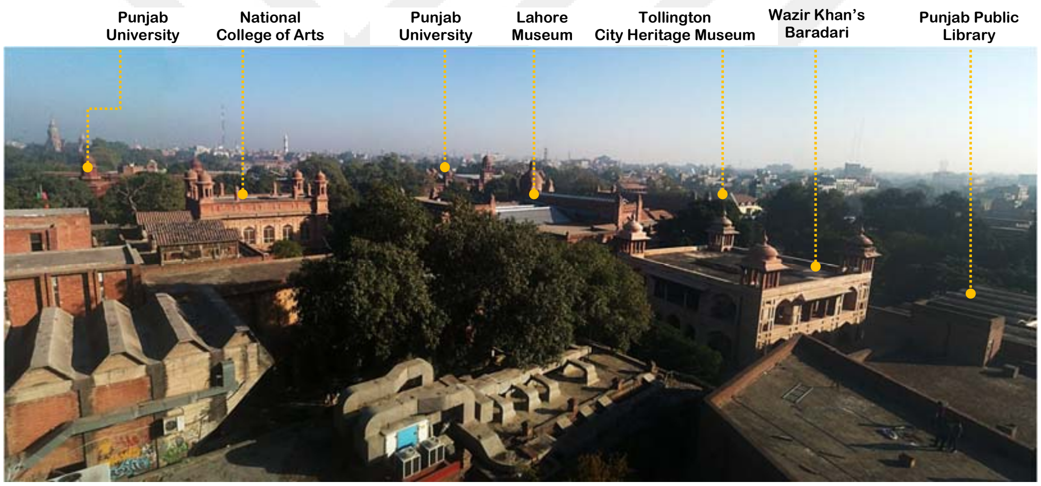

Figure 2.20: Lahore Museum and its Environs (2013)

On its western end the Museum adjoins the NCA building. The two were initially conceived as a single complex and form a cohesive whole as single composition. The Museum is built up to the boundary between the two institutions, with its western wall forming the eastern edge of the NCA premises. The boundary between the two

[17] Originally called Mayo School of Arts

[18] Formerly known as Bank Road

[19] Formerly known as Tollinton Market and home to the Museum before it moved to its current building

staggers towards the north so that the most western room of the museum lies across the fence in the adjoining NCA lot and its windows open onto the NCA parking lot.

Museum Building and the Museum Lot

The Museum building sits on an approx. 10,000 m^2 (108,000 ft^2) trapezoidal lot. The footprint of the main Museum building is 5225 m^2 (56241.5 ft^2), while additional structures namely the Servant Quarters, Annex building, Canteen and the Tube well occupy another 462.13 m^2 (4974.33 ft^2) (Figure 2.14). More than half of the lot has been built upon; out of the remaining empty space on the lot a major chunk, around 309.4 m^2 (3330.32 ft^2), is dedicated to a manicured lawn laid out between the northern façade of the Museum and the Mall Road.

The northern end of the lot is fenced with an iron grille 2.3 m (7ft. 6in.) in height and interspersed with brick masonry columns at regular intervals (Figure 2.21). There is a semi-circular driveway that passes through the lawn and is accessed from the Mall Road (Figure 2.14). This driveway now only used by dignitaries is entered and exited through two iron grille gates set into the fencing of the northern boundary. An ornamental drinking fountain is located at the northern end of the lot with the fence passing through its center.

Figure 2.21: Lahore Museum – Northern Fence & Drinking Fountain (2015)
Source: Sami, U. (2017). Understanding the Lahore Museum for the Definition of a Conservation Process. Middle East Technical University, Ankara, Turkey

The eastern end of the lot has a boundary wall 3.65 m (12 ft.) in height, built in brick masonry and topped with a barbed wire. The southern section of the Museum that houses the administrative block is accessed through a gate set into this boundary wall from the Library Road. The Museum lot on its southern end is separated from the Punjab Public Library by a boundary wall topped with a barbed wire while on its western end the Museum built to the lot boundary acts as a boundary wall.

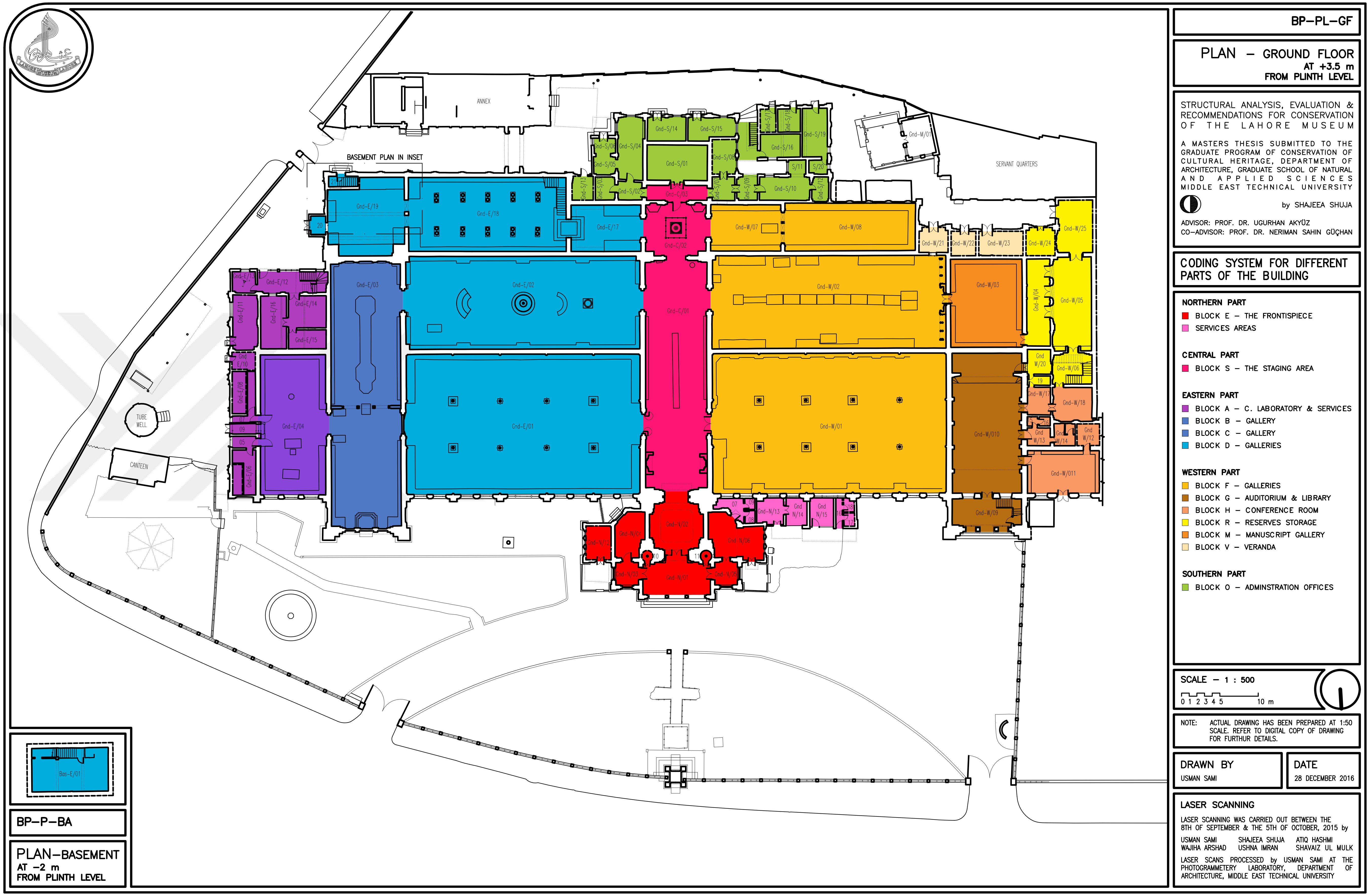

Figure 2.22: BP-PL-GF / BA – Coding System for Parts of the Building (2016)

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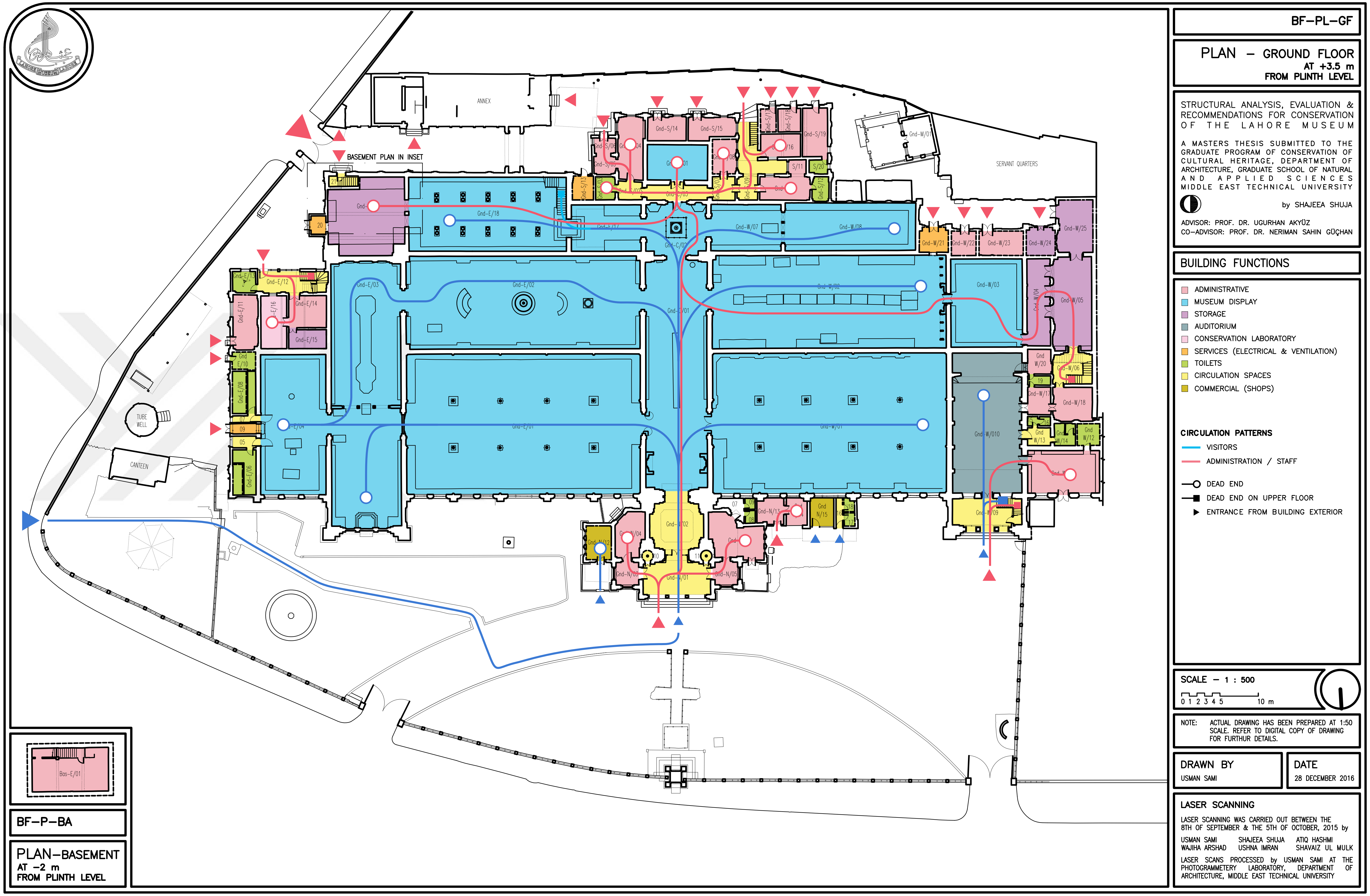

Figure 2.23: BF-PL-GF / BA – Building Functions & Circulation Patterns (2016)

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2.4. Architectural Features

The Lahore Museum building built entirely in exposed red brick and designed in the "Indo-Saracenic" style is conglomerate of volumes of various sizes resulting in a large singular volume that is subdivided internally and is accessible through multiple entrances.

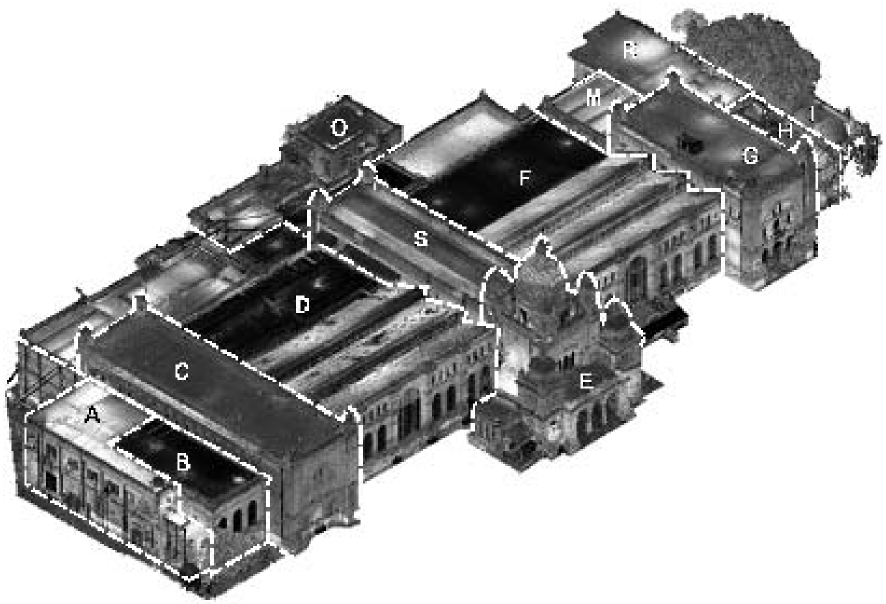

Figure 2.24: Massing of the Lahore Museum (2016)
Isometric projection of the laser scan point-cloud
A: Conservation Laboratory, B/C/D/F/M/S: Galleries, E: Frontispiece, G: Auditorium and Library, H: Conference Room, O: Administrative Offices, R: Reserves Store.
Source: Sami (2017, p. 100)

The volumes when viewed from the north are composed in a nearly symmetrical arrangement and for ease of referencing can be divided into eight blocks A-H, from east to west (Figure 2.25). The features of Northern façade are linked to the volumes of the building (Figure 2.24).

The central block in this arrangement, referred to as the "Frontispiece"[20] by Percy Brown in the 1909 Descriptive Guide is **Block E**. The block is 17.26 m (56 ft. 7 in.) in width while pinnacle of the main dome forming the apex of the Frontispiece lies at 24.7 m (81 ft.) above plinth level. On the eastern and the western side of Block E are **Block D & F** respectively, each 30 m (98 ft. 6 in.) in width and 11.7 m (38 ft. 3 in.) in height. Block D extends towards the south a total depth of 40.59 m (133 ft. 2 in.) while Block F extends a total of 38.64 m (126 ft. 9 in.) towards south.

South of **Block E** and flanked on either side by **Block D& F** is **Block S** which is 9.45 m (31 ft.) in width, 14.5 m (47 ft. 7 in.) high and extends towards the south a depth of 31.3 m (102 ft. 8 in.). South of Block S is **Block O** housing the Administrative Offices. The block is 28.5 m (93 ft. 6 in.) in width and extending towards south has a depth of 8.7 m (28 ft. 6 in.). The western part of the block rises 8.2 m (26 ft. 11 in.) above plinth level while the eastern half has a height of 5.95 m (19 ft. 6 in.) above plinth level.

To the east of Block D is **Block C** which is 11.4 m (37 ft. 5 in.) in width, 13.82 m (45 ft. 4 in.) in height and extends towards south a depth of 38 m (124 ft. 8 in.). East of Block C is **Block B** which is 9.48 m (31 ft.) in width, 9.54 m (31 ft. 3 in.) in height and extends 19.6 m (64 ft. 3 in.) towards the south. The eastern most end of the Museum is formed by **Block A** which wraps around Block B towards the south. This block has a width of 3.28 m (10 ft. 9 in.) at the northern end and 12.6 m (41 ft. 4 in.) at the southern end. It extends 30.5 m (100 ft.) towards south and rises to a height of 8.5 m (27 ft. 10 in.) above plinth level.

To the west of Block F is **Block G** which is 11.4 m (37 ft. 5 in.) in width, 13.82 m (45 ft. 4 in.) in height and extends towards south a depth of 25.2 m (82 ft. 8 in.). To the south of Block G is **Block M**. The width of this volume is the same as Block G but is 7.9 m (26 ft.) high and extends 12.2 m (40 ft.) towards south. Further south of Block M is **Block V** which houses the stores of the museum. The block is 17.7 m (58 ft.) in width, 5.2 m (17 ft.) high and extends 4.1 m (13 ft. 6 in.) towards the south.

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[20] "Frontispiece" in architecture is the composition emphasizing the principal entrance bay of the building. It is generally raised from the rest of the building and is ornamented.

The museum culminates on the western end with **Block H** which is 8.78 m (28 ft. 9 in.) wide, 6.53 m (21 ft. 5 in.) high and extends 14.4 m (47 ft. 3 in.) towards south. South of this volume is **Block R** which is similar in width but has a height of 10 m (32 ft. 10 in.) above plinth and extends to a depth of 24.83 m (81 ft. 6 in.) towards south.

Building Exterior

The 114 m (374 ft.) long *Northern Façade* primarily defines the Museum's exterior and together with NCA forms a continuous elevation along the entire length of the city block (Figure 2.25).

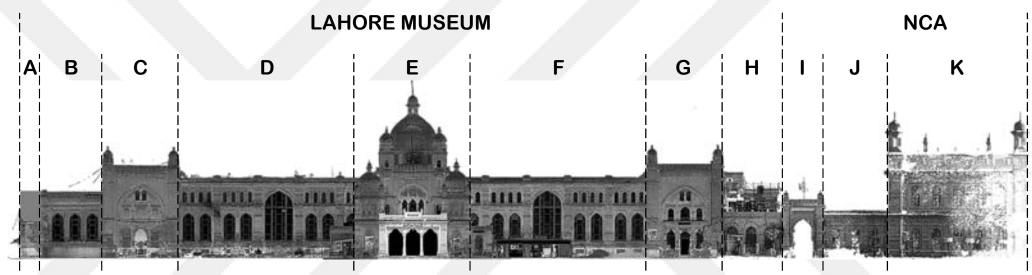

Figure 2.25: Lahore Museum – Northern Façade (2016)
Orthographic projection from laser scan and photogrammetric point-clouds.
A: Laboratory, B/C/D/F: Galleries, E: Frontispiece, G: Auditorium and Library, H: Conference Room, I: NCA – Entrance Portal, J/K: NCA
Source: Sami (2017, p. 102)

The Block C, E and G accentuate the façade through their verticality and by protruding slightly towards the north. Of the three, Block E - The Frontispiece, is the most elaborate in design and forms the center of the symmetrically laid out elevation. Block C & D on the east of Block E are mirrored by Block F & G on the west. Block H on the west though has the same width as Block B on the east but is much lower in height. Its height is more in keeping with Block J of the NCA building. Breaking the symmetry at the eastern end is a low narrow volume of Block A.

Block A which forms the eastern most end of the museum building is the smallest in width and has no openings on its northern wall. Adjoining Block A towards the west is Block B. This block has three arched windows on its northern wall which are 1.78 m (6 ft.) wide and 4.27 m (14 ft.) high separated from one another by 52 cm (21 in.) wide pilasters. The base of the arches is 2.1 m (6 ft. 11 in.) above the plinth.

To the west of Block B is Block C. This block protruding 5 m (16 ft. 6 in.) towards north, is bounded on either side by 1.6 m (5.25 ft.) wide piers which are topped by small ornamental domed canopies. A large 6.5 m (21 ft. 4 in.) wide arch, vertically divided into three sections, is placed between the piers. The lowest section is separated from the middle section via a 56 cm (1 ft. 10 in.) thick horizontal brick band while the middle and the upper section are separated through a 30 cm (1 ft.) wide horizontal brick band. The lowest section which is 4.5 m (14.75 ft.) high, is horizontally divided into three sections through 53 cm (21 in.) wide brick columns spanned by flat arches supported on brackets. The middle section is horizontally divided into three arches and is 2.13 m (7 ft.) in height. The upper section is divided into two triangular arches on top of which is a horizontal diamond shaped window. All the openings in Block C are blind and in-filled with recessed masonry walls.

Block D adjoining Block C towards the west has a horizontal composition and is divided into five equal bays through 30 cm (1 ft.) wide brick pilasters. The central bay has a single arched window 4.2 m (13.75 ft.) wide and 7.68 m (25 ft.) high. The four remaining bays are vertically divided into two parts by a 50 cm (19.5 in.) thick horizontal brick band, placed at a height of 7 m (23 ft.) above the plinth level. The lower sections of each bay have two arched windows 1.78 m wide and 4.27 m high (70 in. x 168 in.) while the upper sections have four arched ventilators 70 cm wide and 172 cm high (27 in. x 68 in.) with the base of the arch 7.82 m (25 ft. 8 in.) above the plinth level.

At the center of the composition is Block E, the Frontispiece which can be read vertically in three distinct tiers. At the ground level is the white marble colonnaded entrance portico with three openings with pilaster on the sides and two marble columns in the middle (Figure 2.26). The portico is flanked on either side by two storey high turrets. The ground level of each turret forms a room. The external walls of these rooms have arched openings that are closed off by carved sandstone *jalis*. The upper level of both the turrets are open chambers, with the northern, eastern and the western side each having three corbelled openings while the southern side has been closed off by means of recessed brick masonry. The chambers are covered by domes surrounded by ornamental domed canopies and surmounted by lanterns.

Between the turrets, on the middle tier, is a 4.49 m (14.5 ft.) wide arch which frames a smaller archway which is 3.53 m (11 ft. 7 in.) in width (Figure 2.27). This archway is vertically divided into two sections, each section is further divided horizontally into three sections. The three upper sections are each fitted with terracotta *jalis* while the three lower sections forms an arch opening. The middle arch is fitted with a door while the arches on either side have floor length windows. This arrangement is topped by dome with an external diameter of 7 m (23 ft.). The pinnacle of the dome forms the highest point of the composition at 24.7 m (81 ft.) above the plinth level and is surrounded by four small domed canopies. The canopies have balconies on three sides. The balconies are fitted with terracotta *jali* balustrades and supported on corbelled masonry brackets.

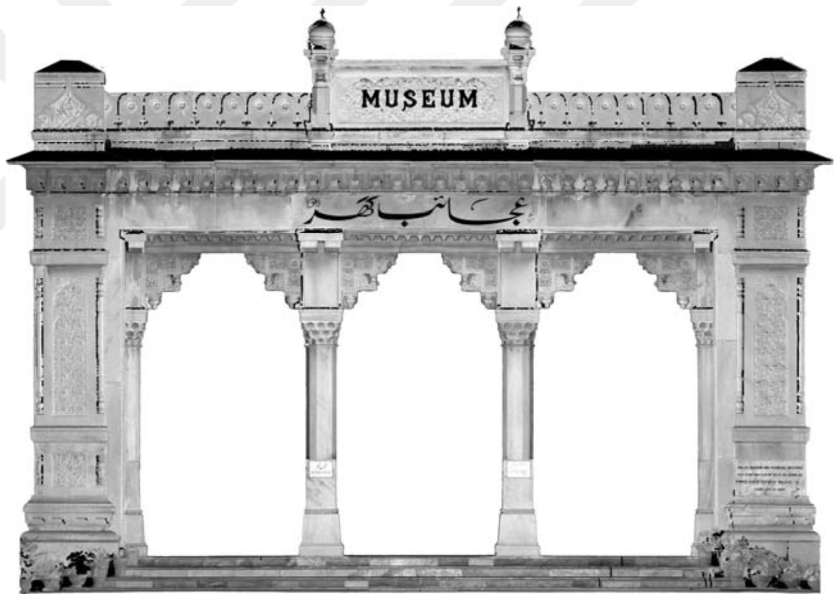

Figure 2.26: Marble Portico (2016)
Orthographic projection from the point cloud of the laser scan

Towards the west adjoining Block E is Block F. This block has identical dimensions and detailing as Block D. The only difference is the row of small rooms on the northern face of Block F, the roofs of which are at level with the base of the arch windows of the block. Block G adjoining Block F on the west is symmetrically placed with respect to Block C. Both blocks are identical in dimensions and detailing except that all the arches and bracketed openings on the northern wall of Block F are open, hence the brackets are structural in nature and made of sandstone.

Block H adjoins Block G to the west and is the western most block of the museum and although it is part of the museum premises it lies across the fence in the adjoining NCA lot. The block on its northern wall has three 2 m (6 ft. 6 in.) wide and 4.21 m (13 ft. 9 in.) high arched openings, fitted with iron grilles, and looking onto the NCA parking lot.

Figure 2.27: Turret and Central Arch (2016)
View from the roof of the portico

The *Eastern Façade* is formed through the overlapping volumes of the museum building, primarily Block A and D (Figure 2.28). The façade is a reflection of the sporadic additions and alterations that the building has seen throughout its life.

Figure 2.28: Lahore Museum – Eastern Façade (2016)
Orthographic projection from laser scan point-clouds
A: Laboratory, B/C/D: Galleries, E: Frontispiece
Source: Sami (2017, p. 108)

Towards the southern end of the elevation the eastern face of Block D is visible. This part of the elevation has two blind arches on the lower level. A small chamber fitted with a metal door is built in front of the northern arch. On the upper level there are two rectangular openings for exhaust fans.

The eastern face of Block A, forming the major part of the eastern façade, has haphazard openings punctured into it. There is no correlation between the openings on the upper and the lower level of the wall. The lower level has seven openings of various shapes and sizes. The openings from south to north are, a large window opening fitted with an iron grille, next is a glazed wooden double door followed by a small wooden door. Further along are two rectangular ventilators fitted with an iron grille, a large opening with slit window fitted with an iron grille and a large metal door with a ventilator above fitted with an iron grille. These doorways have been blocked with brick masonry. On the upper level of the wall there are six rectangular windows spaced at regular intervals.

Traces of earlier archways blocked with brick masonry, some of which have been punctured again to create new openings, can be seen spread across the façade. The chaos is added to by the exposed electric cables and randomly placed drain pipes on the façade.

The *Southern Façade* of the building is a chaotic arrangement of volumes and like the eastern façade is reflective of the need basis growth of the museum (Figure 2.29). The façade primarily formed by the Blocks V, F, O, D and A, has some of the most unsympathetic interventions made to the museum building over the course of its existence.

Figure 2.29: Lahore Museum – Southern Façade (2016)
Orthographic projection from laser scan point-clouds
A: Laboratory, C/D/F/M/S: Galleries, E: Frontispiece, G: Auditorium and Library,
R: Reserves Storage, V: Stores
Source: Sami (2017, p. 109)

Block V located at the western end of the façade has traces of five openings which have been blocked off with brick masonry walls. The openings on the eastern and western end of the block are archways while the ones in the middle have flat brickwork lintels. Four of the openings have been fitted with doors and ventilators while one only has a ventilator. Adjoining Block V on the eastern end is Block F, its wall has five blind arches on the lower level and ornamented recessed panels on the upper part.

Block O housing the administrative offices can be read in two parts, the western and the eastern part. The western part of Block O is divided into a grid of six with three bays on the ground level and three on the upper level. The bays on the ground each have a blinded archway fitted with a door with a ventilator above while those on the upper level each have a rectangular window with a ventilator above. The eastern part of Block O has traces of five earlier archways which have been in filled with brick masonry and later punctured to fit in new doors, windows and ventilators.

The southern wall of Block D has an earlier archway fitted with metal door on its western end following which there is a series of nine blinded archways of which the eastern most is punctured to add an arched door of smaller dimensions. The upper part of the wall like Block V has ornamented recessed panels.

Block A is the eastern most part of the southern façade. It has two vertical slit windows one on top of the other at its western end. Next the block has two openings on the ground level with corresponding openings on the upper level all of which have been fitted with iron grilles. At the eastern end of the block there is a ventilator on the ground level and a rectangular window on the upper level.

Spatial Layout

The Museum building in its current form is series of covered spaces which collectively form a large singular covered space. The volumetric blocks when read in plan divide the building in five distinct parts. Located towards the north is Block E, the Frontispiece while Block O, the Administrative Offices, lie towards the south. In the middle of the two is Block S. The remaining blocks lie on either east or west of Block S. As the building is oriented towards the north, parts of the museum can thus be defined using the cardinal directions. The parts are thus named *Northern*, *Southern*, *Eastern* and *Western* while the central part linking the four parts together is named *Central* (Figure 2.22).

The **Ground Floor** (Figure B.124) housing 87 out of the 132 spaces in the Lahore Museum can be accessed from three directions (Figure 2.23). From the north of the building, the Exhibition areas are accessed through Block E, space Gnd-N/01(Entrance Portico) and the Auditorium/ Library are accessed through Block G, space Gnd-W/09 (Entrance Lobby). From the eastern side spaces Gnd-E/11 (Rest Room for Staff), Gnd-E/10 (Toilet adjacent to the Rest Room) and Gnd-E/09 & 20 (Ventilation Extractors) can be accessed. While the Annex block, the Mosque, the Servant Quarters, space Gnd-S/13 (Electric Control Room) and most of the administrative areas are accessed from the south.

The **Basement** (Figure B.124) only has one room and access to the space is from the south of the building. The access from inside the building through space Gnd-E/19 has been blocked off by a masonry wall.

The **First Floor** (Figure B.125) has a total of 34 spaces out of the 132 spaces. As all the spaces on this floor are not interconnected they form six separate sections, each accessible only through its own separate staircase. The Northern Part is accessed through the stairwell rising from space Gnd-N/11. In the Eastern Part, the Conservation Workshop is accessed through the staircase rising from the space Gnd-E/12 while the Pakistan Freedom Movement Gallery is accessed through the staircase rising from the space Gnd-E/18. The Administrative section in the Southern Part is accessed through a staircase accessible from the southern alleyway. In the Western Part the Auditorium Gallery is accessed through a staircase rising from the space Gnd-W/09 while the Reserve Storage is accessed through the staircase rising from the space Gnd-W/06.

The **Second Floor** (Figure B.126) houses 5 out of the 132 spaces and they are all located in the Western Part. The access to the spaces is from the staircase rising from space Gnd-W/09.

The **Third Floor** (Figure B.128) houses 5 out of the 132 spaces of the Lahore Museum and they are all located in the Northern Part. These spaces form a symmetrical composition of four domed canopies around the main dome. The spaces can be accessed through the spiral staircase rising from space Gnd-N/11 or the temporary ladders installed at the southern end of the building.

The detailed description of each space has been provided in APPENDIX B of this thesis.

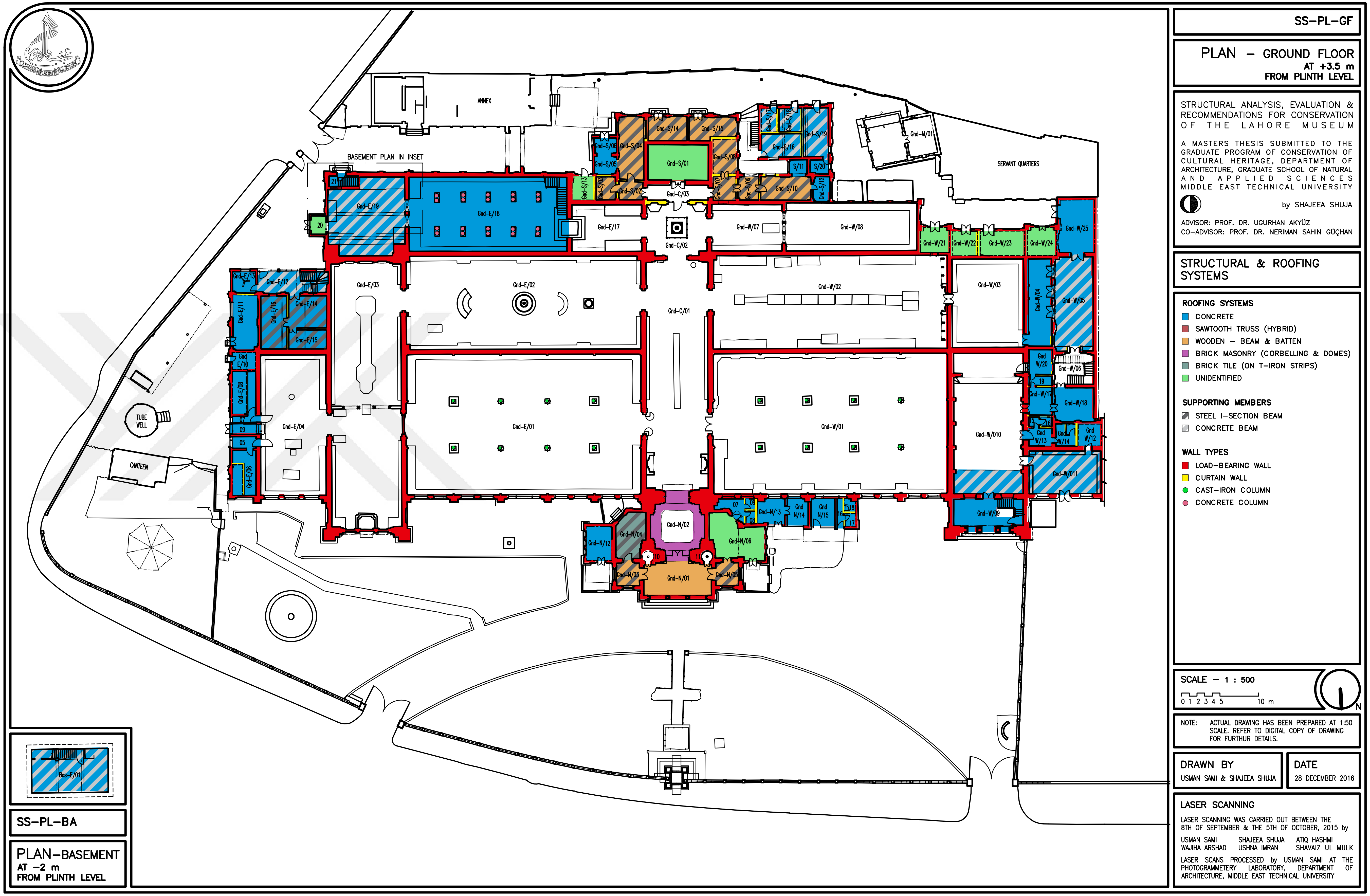

Figure 2.30: SS-PL-GF / BA – Structural & Roofing Systems – Plan – Ground Floor (2016)

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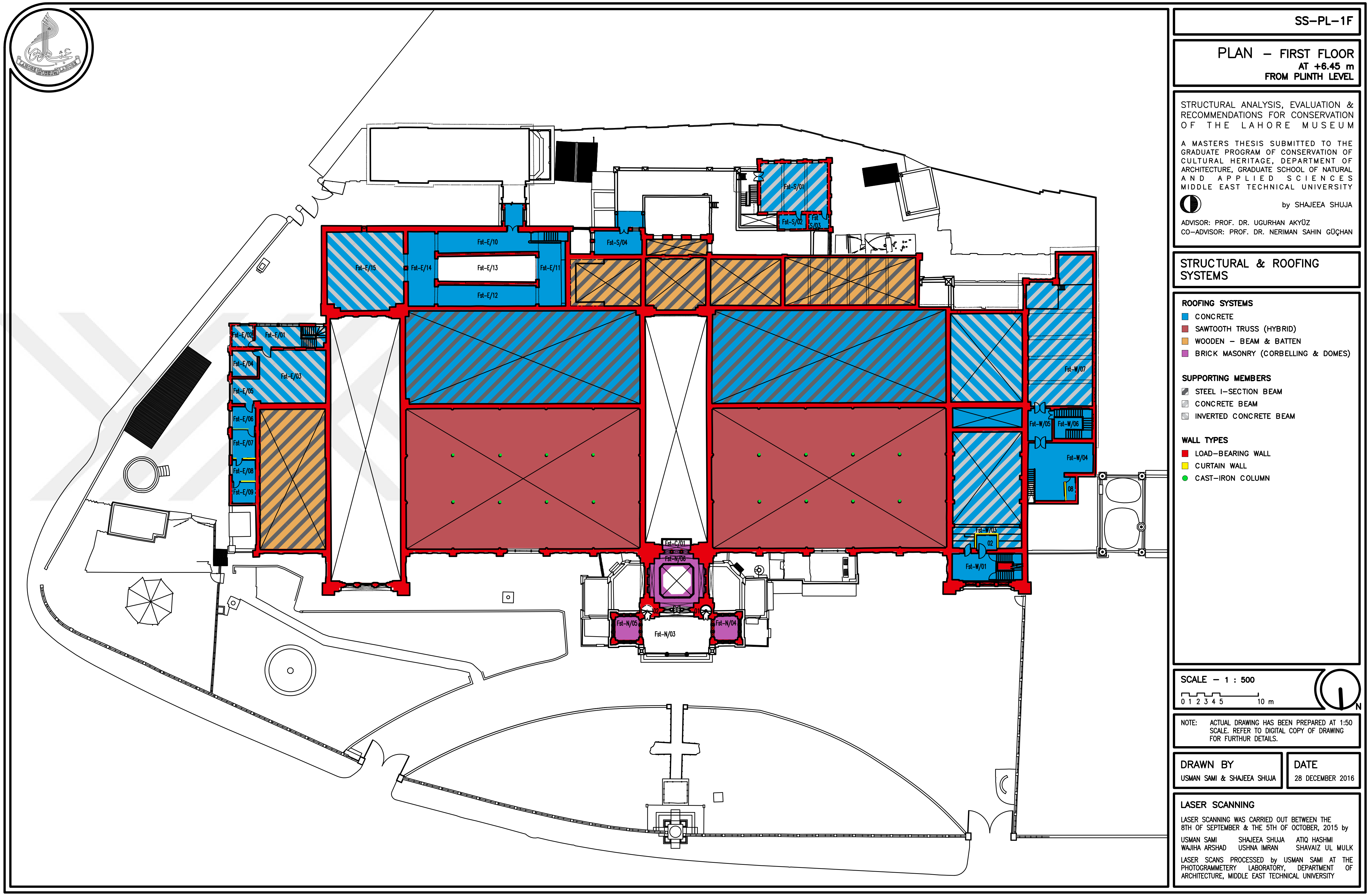

Figure 2.31: SS-PL-1F – Structural & Roofing Systems – Plan – First Floor (2016)

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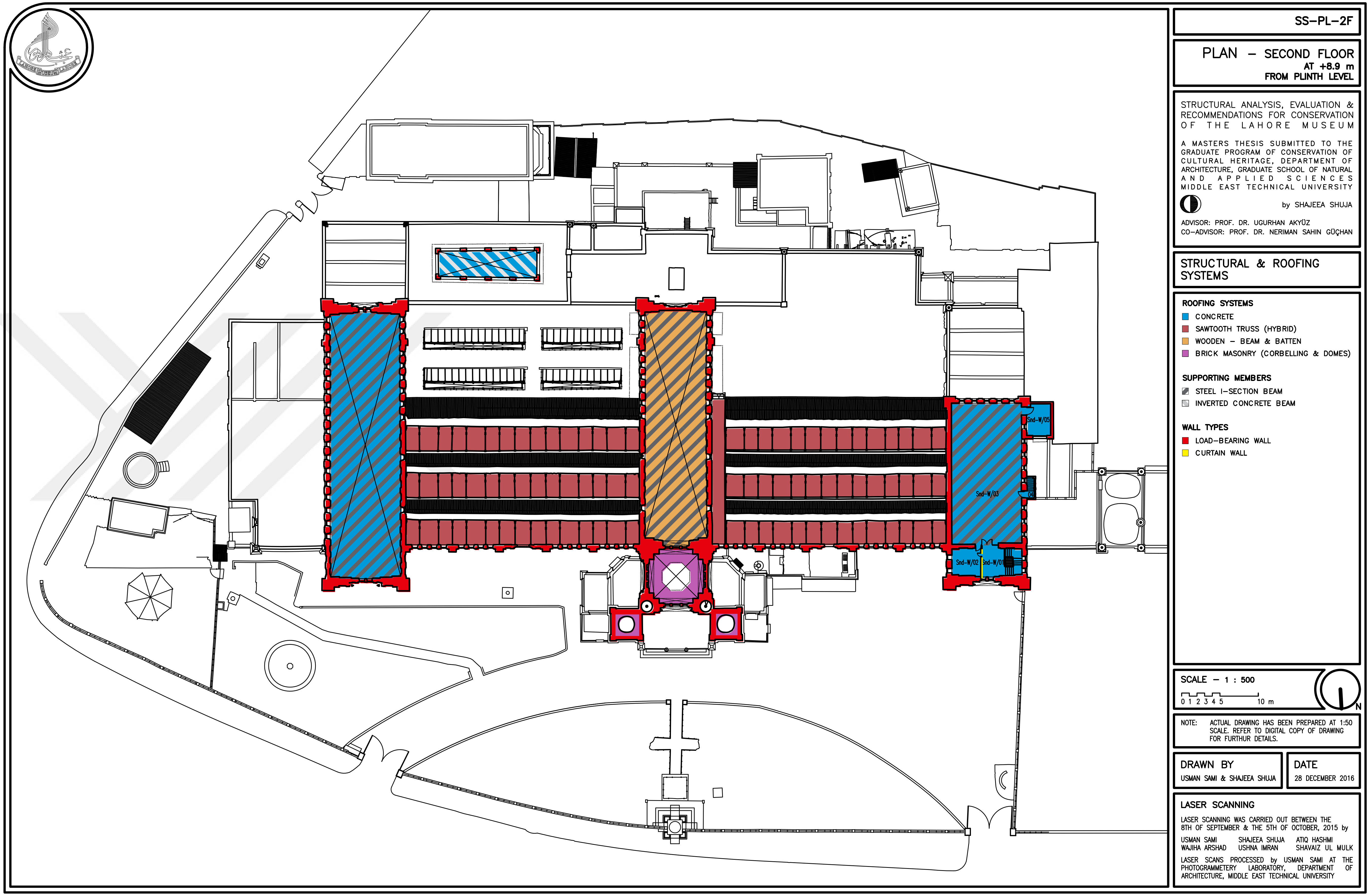

Figure 2.32: SS-PL-2F – Structural & Roofing Systems – Plan – Second Floor (2016)

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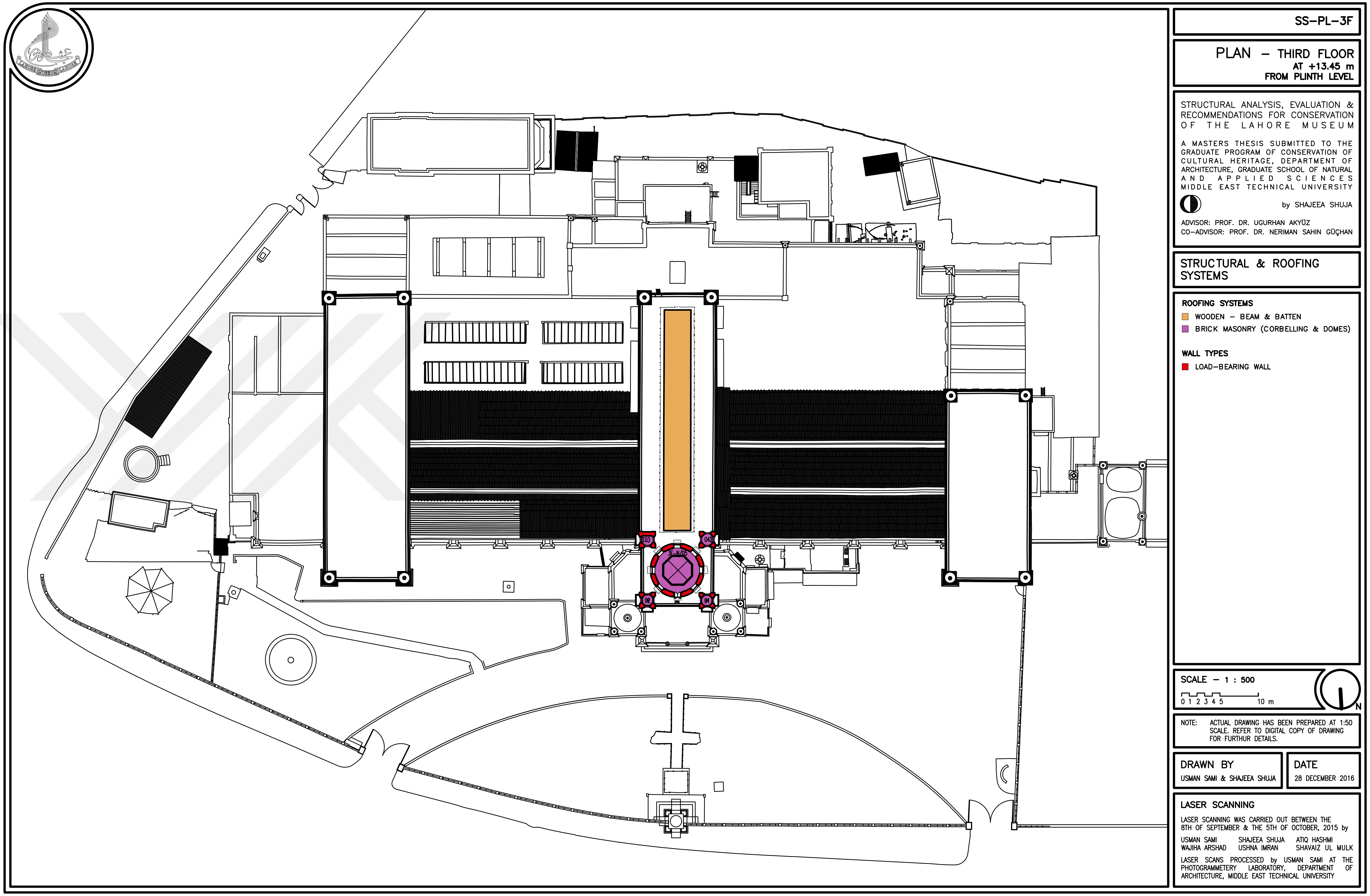

Figure 2.33: SS-PL-3F – Structural & Roofing Systems – Plan – Third Floor (2016)

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Figure 2.34: MT-EL-N/E/S – Building Materials – Elevations – North / East / South (2016)

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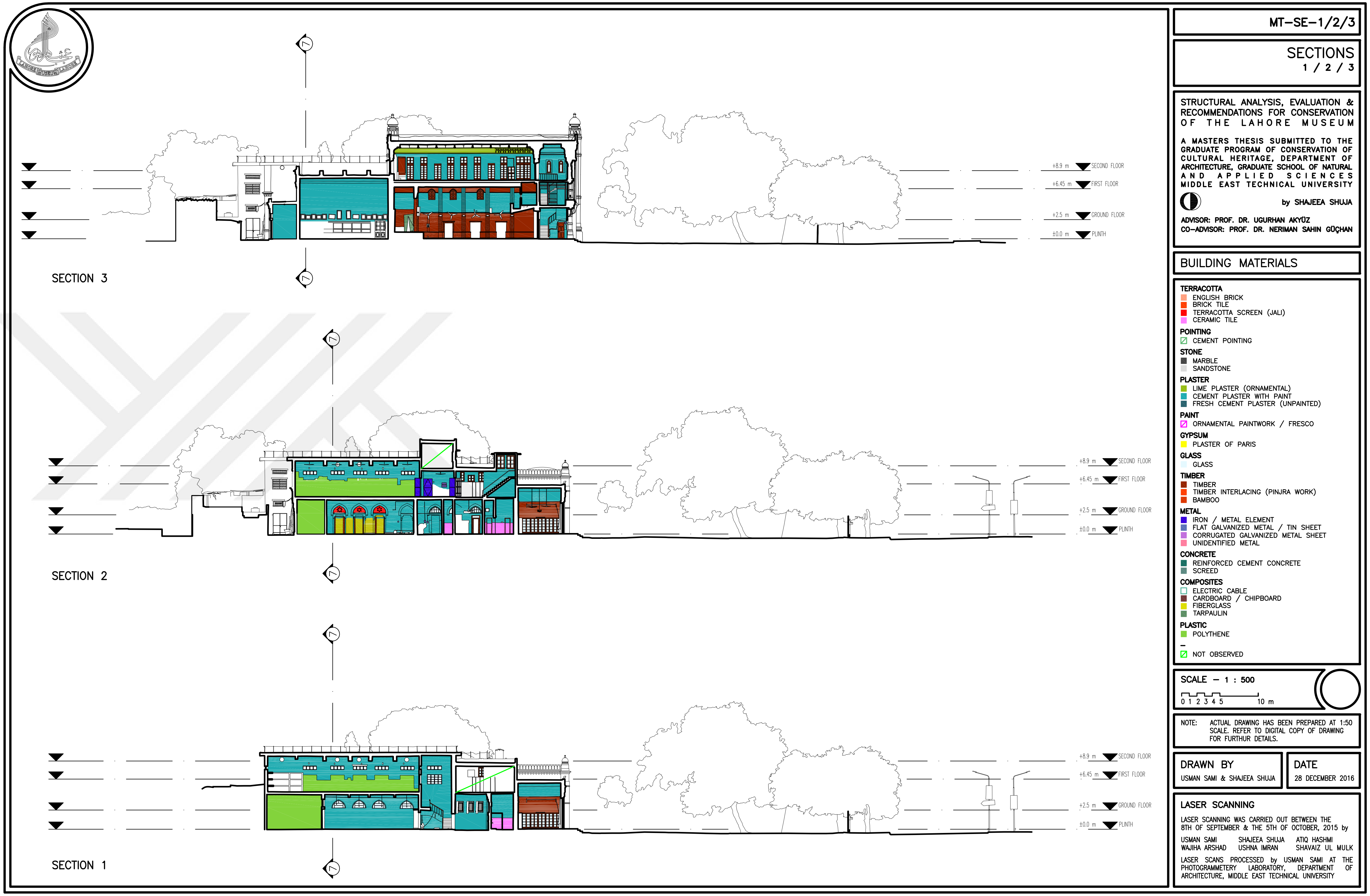

Figure 2.35: MT-SE-1/2/3 – Building Materials – Sections – 1 / 2 / 3 (2016)

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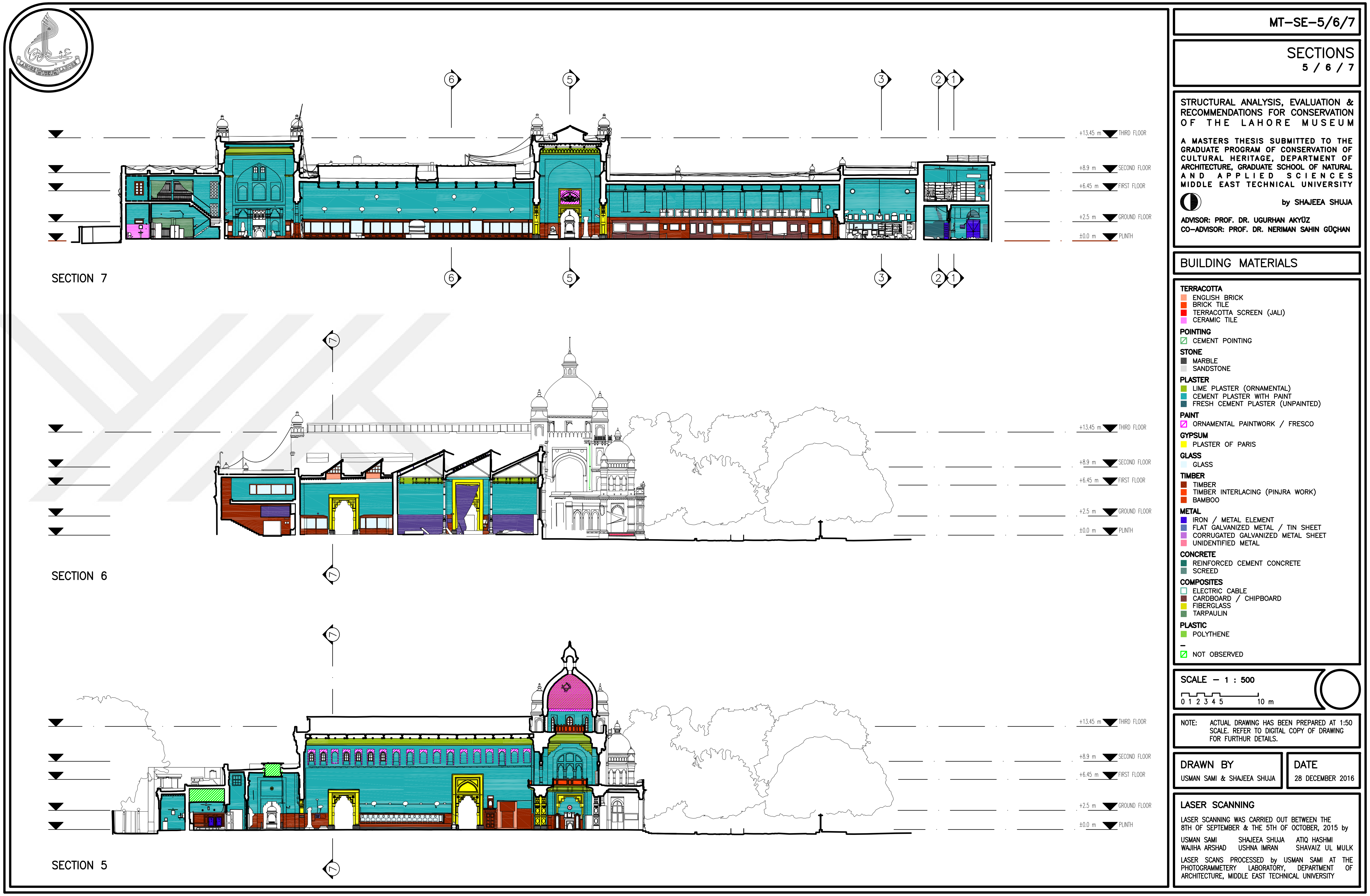

Figure 2.36: MT-SE-5/6/7 – Building Materials – Sections – 5 / 6 / 7 (2016)

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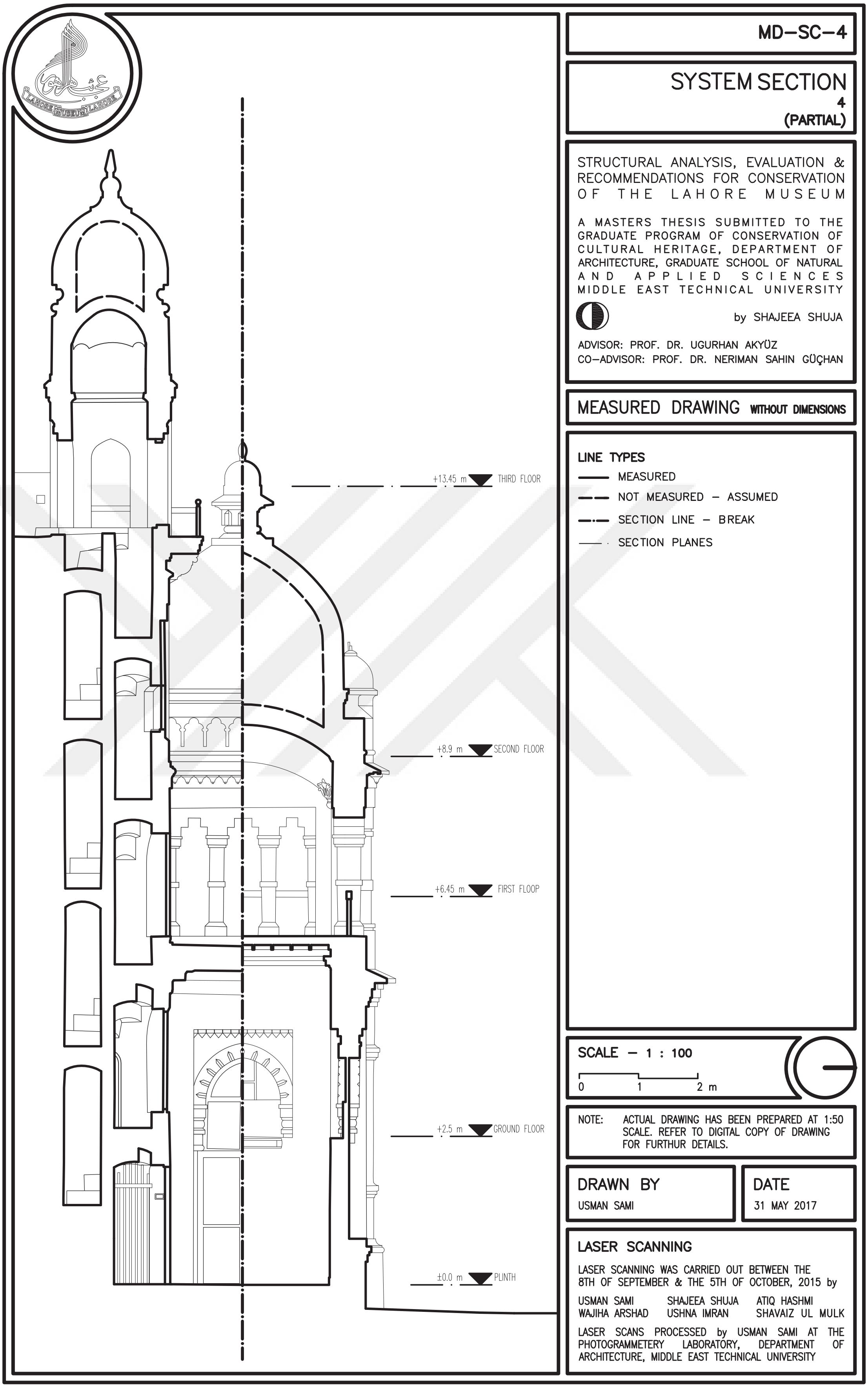

Figure 2.37: MD-SE-4 – Measured Drawing – Section – 4 (2016)

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2.5. Structural Systems and Elements

This section focuses on the structural system of the Lahore Museum building by discussing in detail the horizontal and the vertical structural elements of the building both above and below grade.

Foundations

Foundations of the Lahore Museum have not been observed by the Author. The information regarding the foundations is based on the interview with PWD engineer in charge of maintenance and upkeep of the Museum and backed by literary sources. In 2013 foundations in the north eastern wing of the Museum were dug out to waterproof them using crushed marble chips mixed in Portland cement. At the time it was observed that the foundations are stepped strip foundations placed over concrete bed, approx. 1.83 m (6 ft.) deep and nearly twice the width of the wall. It was further noticed that the depth of the foundation did not vary in the portions that had been dug out despite the difference in wall thickness and heights (Haque, 2014).

The contemporary PWD specifications and codal books support these observations and provide further details. The brickwork was stepped by providing offsets which were 63.5 mm (2.5 in.) or quarter of a brick in breadth and the height was not to be less than two courses. The width of the concrete bed was calculated by forming a 30° angle with the vertical of the last offset of the brickwork (Stokes-Roberts, 1910, p. 64) (Figure 2.38). Furthermore, according to PWD, buildings where strength and stability was required, the bed was to be made using a 203.2 mm to 457.2 mm (8 in. to 18 in.) thick lime concrete called "*Pucca*[21] Concrete". In such building the brick masonry foundations were also constructed with lime mortar (M. A. Khan, 2013, p. 191).

In the colonial era the PWD engineers designed the foundations keeping in mind the load requirements of the building and the bearing capacity of the soil. The maximum pressure on foundations in Lahore, during the colonial era, was considered as 76.61 kPa (0.8 tons/ft^2) (M. A. Khan, 2013, p. 190), which meant that the soil was considered

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[21] The word *"Pucca"* is an Indian term which stands for the permanent nature of something

to be soft soil. Although, according to BCP-2007 the seismic soil profile for Lahore is stiff soil (NESPAK, 2015b, p. 20).

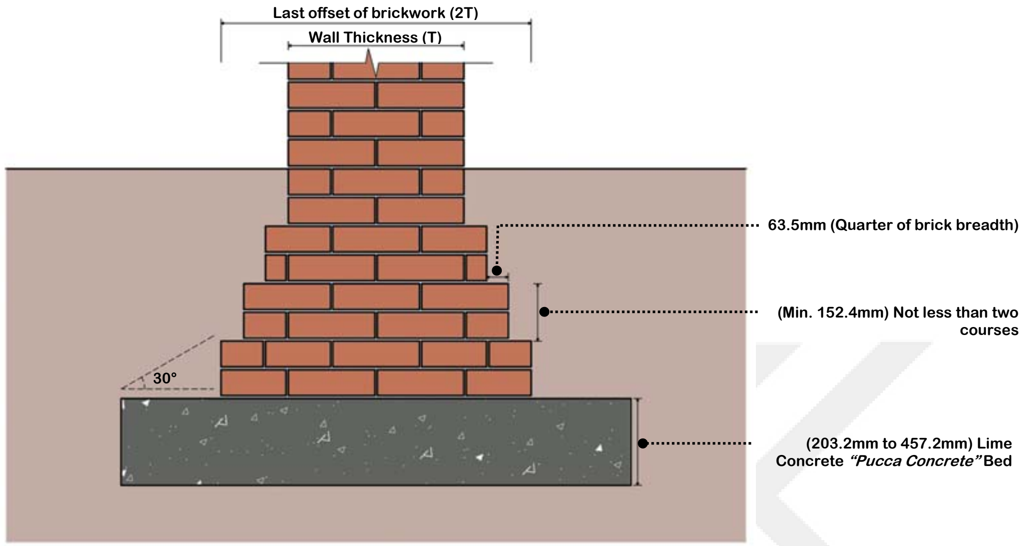

Figure 2.38: Hypothetical drawing of Lahore Museum Stepped Strip Foundation Constructed during the Colonial Era as per PWD specifications.
Drawn by the Author

According to the PWD engineer, post-partition construction of the Museum also uses stepped strip foundations only difference is they are shallower approx. 1.22 m (approx. 4 ft.) and are not placed on concrete bed. For the basement built in 1972 raft foundation was used (Haque, 2014).

Walls

The structural system of the Lahore Museum according to BCP-2007 can be classified as Bearing Wall System, where bearing walls provide support for all or most gravity loads. The masonry unit for all load bearing as well as non-load bearing walls in the building is solid brick laid in mortar (Figure 2.30, Figure 2.31, Figure 2.32, Figure 2.33 and Figure 2.34). These solid bricks called the "English Brick" are rectangular in shape with the nominal size of 228 mm x 114 mm x 76 mm (9 in. x 4.5 in. x 3in.). The bricks in the Museum building have been laid with frog upwards in English bond (Figure 2.39), which consists of alternate course of headers and stretchers. All the bed joints in the walls are parallel while the vertical joints in the alternate courses are directly over one another.

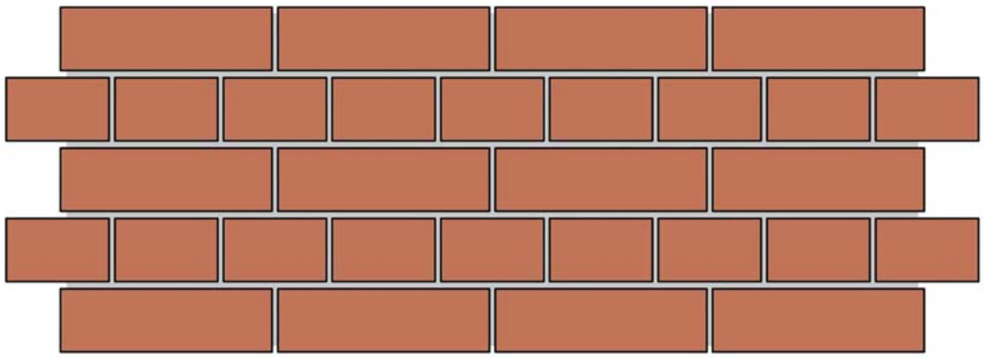

Figure 2.39: Drawing illustrating the English Bond used in Lahore Museum
Drawn by the Author

According to specifications the exact size of the brick manufactured for architectural works during the Colonial era, was 228 mm x 111 mm x 68 mm (9 in. x 4⅜ in. x $2^{11}/_{16}$ in.) (MacFarlane, 1936, p. 13). Each brick was to be set with both the bed and vertical joints filled with mortar, the bed joints were to be 8 mm ($^{5}/_{16}$ in.) thick while the head joints were to be 6 mm ($^{1}/_{4}$ in.) thick. Moreover the height of 4 courses of brickwork including 4 bed joints was not to exceed 304 mm (12 in.) (MacFarlane, 1936, p. 53) (Figure 2.40).

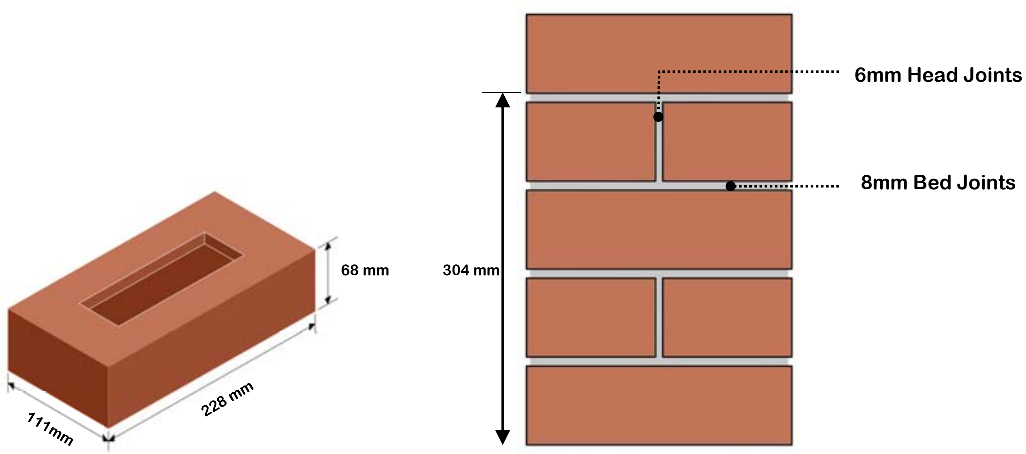

Figure 2.40: English Brick size used in the Lahore Museum during Colonial Era (left) Brickwork details employed during the Colonial Era (right).
Drawn by the Author

The heights of Lahore Museum walls are determined on the basis of the wall thickness and vice versa, as per PWD specifications. As can be seen from Table 4 the type of brickwork used, helped determine the maximum permissible height and thickness of the wall (MacFarlane, 1936, p. 68). The specification further stipulates that the minimum thickness of the external wall should be at least 1/16th the storey height for ordinary buildings and 1/14th in case of warehouses. Based on this criterion if the wall thickness is greater than those provided in Table 4, the additional thickness can be adjusted by providing engaged columns[22] that are properly distributed along the wall. Furthermore collective width of these columns should not be less than one fourth the length of the wall to cater for the vertical loads and also to provide lateral stability to the building (MacFarlane, 1936, p. 67).

Table 4: *Thickness of wall and maximum permissible height*

Material of which the wall is built	**f=safe pressure in tons/ft^2**	**Maximum permissible height (ft.)for a thickness of**				
		9 in./ 1 brick	13$^1/_2$ in./ 1$^1/_2$ bricks	18in./ 2 bricks	22$^1/_2$ in./ 2$^1/_2$ bricks	27 in./ 3 bricks
Burnt brickwork in 1:3 cement mortar	8	25	38	51	..	..
Burnt brickwork in lime mortar or lime; cement; sand mortar	4	16	24	32	40	..
Burnt brickwork in mud	2$^1/_2$	11	17	23	28	34
Sundried brick in mud	1	6	9	12	15	18

Note: The table has been duplicated from the source document without any modification.
Source: PWD Specifications 1936, Building and Roads, Vol. 1; Page No. 68

From Table 4 it can also be inferred that the Museum walls greater than 229mm (9in.) are solid bonded walls, where two or more wythe[23] are bonded to act as a structural unit.

[22] Engaged columns are directly built into a wall and are load bearing in nature. They hold the weight of the ceiling and also act as buttresses that reinforce and support the actual wall.

[23] Wythe is the portion of a wall which is one masonry unit in thickness.

Columns

In the Lahore Museum, the principle support against gravity loads is provided by load bearing masonry walls but in a few galleries a dual system, bearing wall system in conjunction with frame system, has been used (Figure 2.30).

The first instance where dual system was brought into use was in the two northern galleries - Gnd-E/01 and Gnd-W/01, constructed in 1893 (Figure 2.41). The galleries have a grid of cast-iron (CI) columns supporting the saw tooth metal truss roof in tandem with the load bearing walls. Each gallery has twenty four CI columns 7.1 m (23 ft. 4 in.) in height which are bolted to the ground and are 254 mm (10 in.) in dia. each. They divide the space in five bays and three aisles, with an approximate c/c spacing of 6 m (19 ft. 9 in.) in both direction. Within each space there are eight CI columns standing in two rows of four columns each, rest of the columns are embedded into the brick masonry reducing effective length of the unsupported walls.

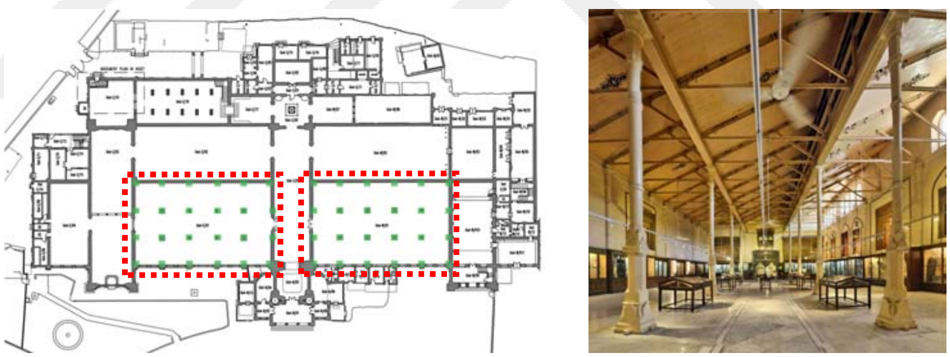

Figure 2.41: Lahore Museum key plan showing location of Cast Iron Columns
In Spaces Gnd-E/01 and Gnd-W/01 (left)
Looking West rows of CI Columns supporting truss roof in Space Gnd-W/05 (right)

Another gallery where the dual system has been used is Gnd-E/18, constructed in 1972 (Figure 2.42). There are twenty reinforced concrete (RC) columns, each with a dia. of 381 mm (15 in.) and 4 m (13 ft. 3 in.) in height. Every two columns stands on a RC base of 1295 mm x 609 mm x 609 mm (4 ft. 3 in. x 2 ft. x 2 ft.) forming two rows and dividing the space in six bays and three aisles. These columns were added after the first floor was constructed in 1974 and it was noticed that the roof was starting to sag because of the additional load and were propped from the floor of the gallery (Dar, 2016). In the absence of any footing vertical resistance provided by these columns is only equal to the bearing capacity of the floor on which they rest. Also as these columns have not been tied together they exhibit tying force only through friction, generated by the compressive forces at each end.

Figure 2.42: Lahore Museum key plan showing location of Reinforced Concrete Columns In Space Gnd-E/18 (left) Looking East rows of RC columns in space Gnd-E/18 (right)

The only other space in the building that employs the dual system is Gnd-W/10. An additional floor was added to the space that was originally 12.19 m (40 ft.) high in 1969. The additional space Snd-W/03 created above houses the Museum library. Five frames were built at regular intervals along the N-S axis of the space Gnd-W/10 using the brick masonry columns and RC beams to support the RC slab and the weight of the additional floor. The columns were tied with the wall to make both masonries monolithic, by removing alternate bricks from the existing wall to form a tongue and groove joint in the vertical direction. The columns seems to have been propped up from the floor hence they provide vertical resistance that is only equal to the bearing capacity of the floor.

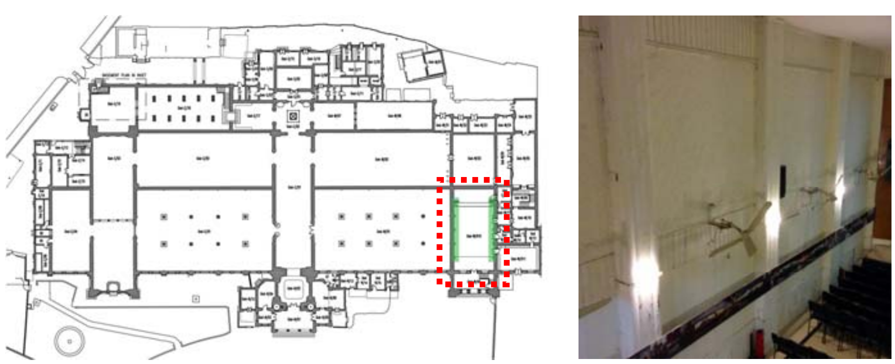

Figure 2.43: Lahore Museum key plan showing location of Brick Masonry Columns In Space Gnd-W/10 (left) Looking East Brick Columns in Space Gnd-W/10 (right)

Roofing Systems

The Museum uses a composite system for the roofs and the choice of the roof system used is almost entirely reflective of the time when it was built.

Domes

Seven spaces, Fst-N/04, Fst-N/05, Thd-N/01, Thd-N/02, Thd-N/03, Thd-N/04 and Thd-N/05, in the Museum are covered with domes made out of brick (Figure 2.44).

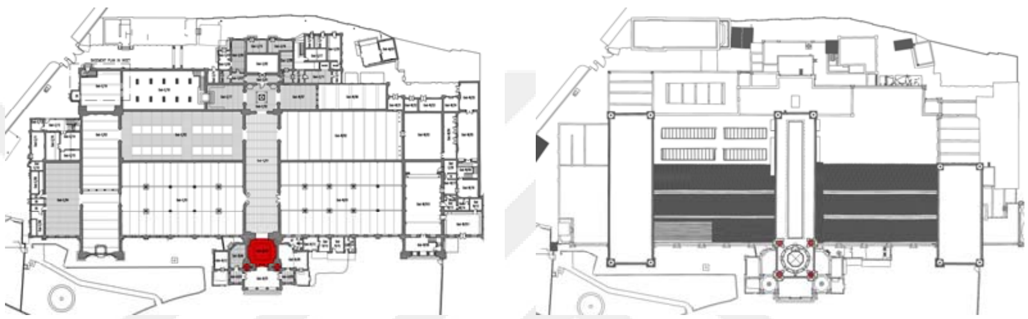

Figure 2.44: Lahore Museum key plans showing locations of domes
In spaces Gnd-N/01, Fst-N/04 and Fst-N/05 (left)
In spaces Thd-N/01-04 (right)

The domes over spaces Fst-N/04 and Fst-N/05 are most probably double-domes, constructed in brick masonry with the cavity in between[24] (Figure 2.37). The dome over the space Fst-N/04 is covered in plaster but the plaster in the space Fst-N/05 has been lost and shows that brick has been used for the construction of the dome (Figure 2.45). They use drums, 1.31 m (4 ft. 3 in.) in height, as the transition element and have a radius of 762 mm (2.5 ft.) while the soffit of the center of the lower dome is 3.5 m (11ft. 6in.) high, from the floor of the spaces. The lower dome, with its center at +9.43 m (31 ft.) above the plinth, has a single-centered segmental-profile. While the upper dome has a four-cross-centered profile and the center of the extrados is +12.5 m (41 ft.) above the plinth.

[24] It is improbable that the dome is solid as that would place unnecessary load on supporting walls and arches.

Similarly, the domes over the spaces Thd-N/01-04, seem to be double-domes constructed in brick masonry and use drum, 0.75 m (2 ft. 6in.) in height, as the transition element (Figure 2.37). They have a radius of 728 mm (2.4 ft.) and the soffit of the center of the lower dome is 3.75 m (12 ft. 3 in.) high, from the floor of the spaces. The lower dome, with its center at +15.78 m (51 ft. 9 in.) above the plinth, has a semicircular profile. The upper dome also has a semicircular profile and its center is at +17.14 m (56 ft. 3 in.) above the plinth.

Figure 2.45: Loss of plaster in space Fst-N/05
Showing use of brick in the construction of the dome

The dome over the space Thd-N/05 is a single leaf dome with a two-cross-centered profile and constructed in brick masonry. It has a 2.9 m (9.5 ft.) radius and is 4.5 m in height, while the center of the dome at +20.28 m (66 ft. 6 in.) above the plinth (Figure 2.36). The load of the dome is transferred to bearing walls through drum and pendentives, built in brick masonry. The drum is 4.13 m (13 ft. 6 in.) in height and is visually separated from the curvature of the dome through a 30 cm (1 ft.) high molding.

Saw Tooth Trusses supporting Wooden Roofs

Two spaces, Gnd-E/01 and Gnd-W/01, make use of the saw-tooth truss roofing system. Each space has fourteen trusses placed along their shorter span in the N-S axis. The trusses are made from bullhead railway steel girders, 5.4 cm (2.125 in.) wide and 13.57 m (5.343 in.) high, which have been riveted together with steel gusset plates. Each truss is designed as a series of three ridges with dual pitches either side. The shallow pitch is at an inclination of about twenty five degrees while the steep pitch forms a ninety degree angle with the bottom chord of the truss and is fitted with glazing (Figure 2.46).

Figure 2.46: Lahore Museum key plans showing locations of saw tooth roof trusses
In spaces Gnd-E/01and Gnd-W/01 (left)
Looking West at Trusses made with railway steel girders riveted together with steel gusset plates in Space Gnd-W/01 (right)

The trusses support the roof which originally consisted of wooden boards laid over the trusses followed by wooden battens 64 mm x 102 mm (2.5 in. x 4 in.) in the E-W axis. The battens in turn were overlain by brick tiles 305 mm x 305 mm x 51 mm (12 in. x 12 in. x 2 in.) over which was a 102 mm (4 in.) thick lime concrete layer. Over the concrete layer wooden battens 64 mm x 64 mm (2.5 in. x2.5 in.) were placed which were used to secure the GI corrugated sheets with bolts (Figure 2.47).

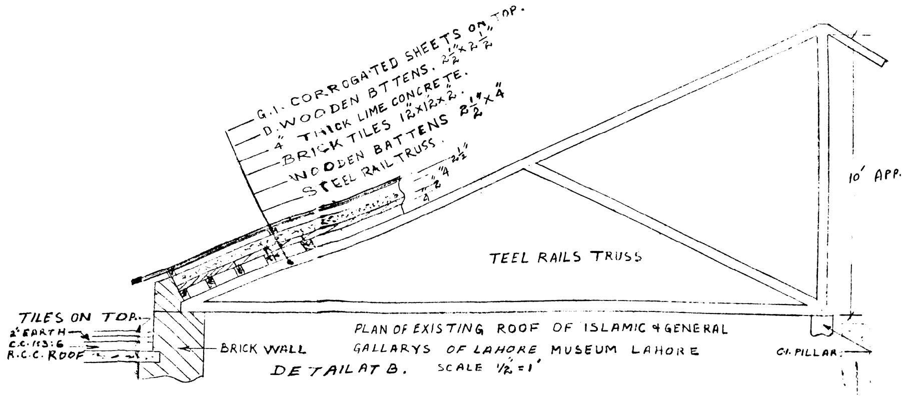

Figure 2.47: Section through the General Gallery Roof – Existing (1980)
Partial drawing extracted from: Butt, Q. U. H., Executive Engineer, 4th Provincial: Building Division, Lahore. (1980). Estimate for: Re-construction of corrugated sheet roofing & drains over existing trusses of Islamic & General gallery in Lahore Museum Lahore. To: Director Lahore Museum. Letter No. E-50-0/50-LM-5915 dated. 10.9.1980. p. 52

On the exterior the space between the two sections of a truss was used to provide a 610 mm (24 in.) wide gutter. In 1980 the roof detail of space Gnd-W/01 was modified. The wooden boards and wooden battens 64 mm x 102 mm (2.5 in. x 4 in.) from the original detail were maintained while the other layers were removed. These then were topped by GI corrugated sheets which were secured to the steel trusses through iron hoops (Figure 2.48) (Butt, 1980, p. 50).

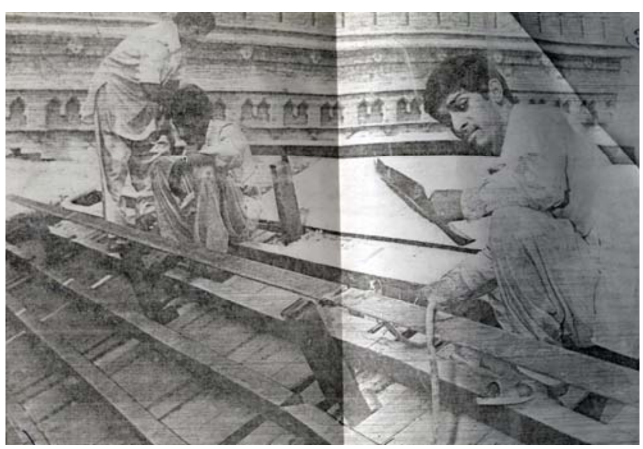

Figure 2.48: The roof of General Gallery being replaced in 1980
Source: Butt, Q. U. H., Executive Engineer, 4th Provincial: Building Division, Lahore. (1980). Estimate for: Re-construction of corrugated sheet roofing & drains over existing trusses of Islamic & General gallery in Lahore Museum Lahore. To: Director Lahore Museum.
Letter No. E-50-0/50-LM-5915 dated. 10.9.1980. p. 32

The same roof detail has been used for the roof modification of space Gnd- E/01 in 2015 (Figure 2.49). The trusses and the roofs above are supported in the middle by two compound girders running along the length of each space in the E-W axis. The compound girder consists of two steel channel sections 305 mm x 102 mm (12 in. x 4 in.) welded together both at top and bottom with 102 mm (4 in.) wide steel plates. The girders rest on the CI columns and masonry walls which help transfer the load of the truss and the roof to the ground.

Figure 2.49: Gnd-E/01 – Islamic Arts Gallery – Roof Repairs (2015)
Looking West over the roof (left)
Pile of Lime Concrete and brick tiles removed from the roof of Gnd-E/01 during repairs (right)

I-Beams supporting Wooden Flat Roofs

This roofing system has been used in spaces Gnd-N/03, Gnd-N/05, Gnd-E/04 built in 1893, Gnd-E/17, Gnd-W/07 built in 1916 and Gnd-S/02, Gnd-S/03, Gnd-S/04, Gnd-S/07, Gnd-S/08, Gnd-S/09, Gnd-S/10, Gnd-S/14, Gnd-S/15 and Gnd-C/03 built in 1929 (Figure 2.50).

In this roofing system, the steel I-Beams resting on the walls support wooden battens which in turn are overlain with wooden boarding. The I-Beam section used in space Gnd-E/04 is 304 mm (12 in.) deep with the flange size of 152 mm (6 in.) with a web thickness of 12.7 mm (0.5 in.) and flange thickness of 22.4 mm (0.883 in.), while in all the other spaces the I-Beams are 152 mm (6 in.) deep with the flange size of 76 mm (3 in.) with a web thickness of 8.6 mm (0.34 in.) and flange thickness of 12.3 mm

(0.484 in.). The wooden purlins in all the spaces are 102 mm (4 in.) deep and 51 mm (2 in.) wide.

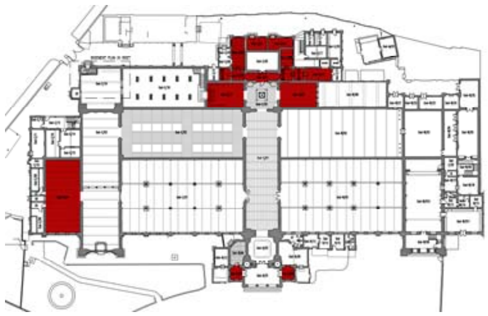

Figure 2.50: Lahore Museum key plans showing locations of I-Beam supporting Wooden Flat Roofs (left) Looking South at Wooden Flat Roof supported on I-Beams in Space Gnd-W/07 (right)

Historically these roofs were protected from the weather by providing a 102 mm (4 in.) thick layer of *"kankar lime"*[25] over the wooden boards followed by a 51 mm (2 in.) thick soil layer, a 25.4 mm (1 in.) thick mud plaster topped by roof tiles 304 mm x 152 mm x 51 mm (12 in. x 6 in. x 2 in.) (MacFarlane, 1936: 167). Overtime this roof treatment was discontinued and currently the roofs are protected with a much lighter system. A bitumen layer is applied to the wooden boards which is then covered by a plastic layer; followed by a 102 mm (4 in.) thick soil layer and is topped by brick tiles 228 mm x 114 mm x 38 mm (9 in. x 4.5 in. x 1.5 in.) in size.

I-Beams supporting Wooden Flat Roofs with Skylights

This roofing system is observed in spaces Gnd-C/01 and Gnd-E/02 built in 1893 and Gnd-C/02 built in 1916 (Figure 2.51). The roofing system is very similar to the system described above i.e. I-Beam supporting the wooden flat roof, with one difference that skylights have been provided in these rooms to bring in natural light. The I-Beam section used in space Gnd-E/02 is 508 mm (20 in.) deep with the flange size of 191 mm (7.5 in.) and with a web thickness of 15.2 mm (0.6 in.) and flange thickness of 25.7 mm (1.01 in.), while in Gnd-C/01 and Gnd-C/02 the section size is 406 mm (16

[25] *Kankar lime* is a type of lime used in India. It is made from *kankar* which literally means a pebble or a stone and is a time-tested impure limestone which produces lime of reasonable quality.

in.) deep with the flange size of 152 mm (6 in.) and with a web thickness of 14 mm (0.55 in.) and flange thickness of 21.5 mm (0.847 in.).

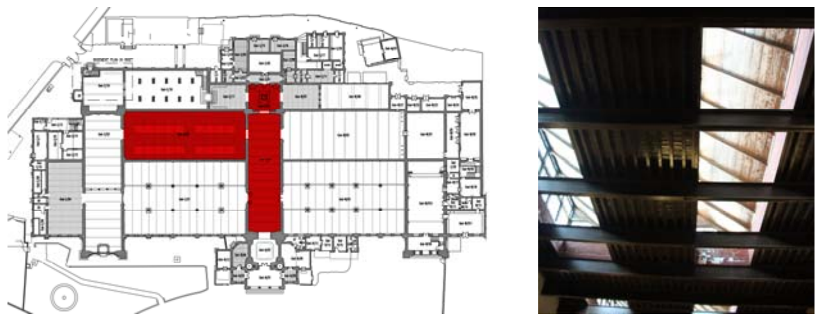

Figure 2.51: Lahore Museum key plans showing locations of I-Beam supporting Wooden Flat Roofs with skylights in spaces Gnd-E/02, Gnd-C/01 and Gnd-C/02 (left) Looking West at Wooden Flat Roof with skylight supported on I-Beams in Space Gnd-E/02 (right)

I-Beams supporting RC Slabs

This type of hybrid roofing system is only observed in Gnd-E/03 and Snd-W/01- 03 built in 1893 and Gnd-W/02 built in 1929 (Figure 2.52).

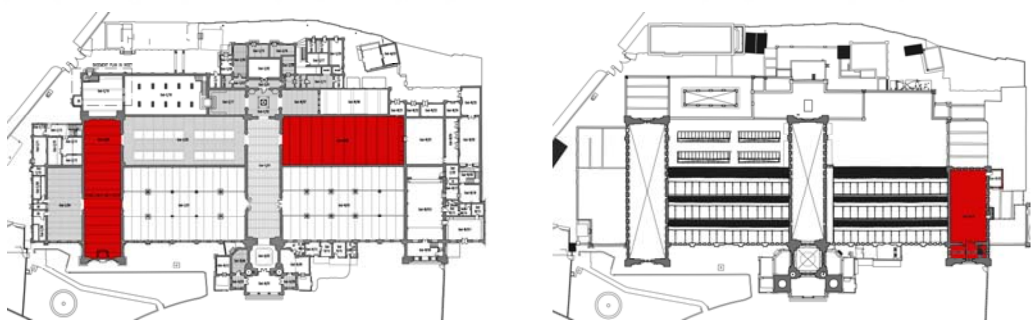

Figure 2.52: Lahore Museum key plans showing locations of I-Beams supporting RC Slabs
In spaces Gnd-E/03 and Gnd-W/02 (left)
In spaces Snd-W/01-03 (right)

The original roofing system for the spaces was I-Beams supporting wooden flat roofs. But by mid 1960s the wooden members were severely damaged either due to wood rot or termite and the roofs were near collapse. During the 1965-67 renovation the wooden roof members were removed and replaced by RC slabs (Dar, 2016). The RC slabs lying over the I-Beams in these spaces are 152 mm (6 in.) deep and as per the PWD specifications have been treated with a bitumen layer which is then covered by a plastic layer, overlain by 102 mm (4 in.) thick soil layer and topped by 228 mm x 114 mm x 38 mm (9 in. x4.5 in. x1.5 in.) sized brick tiles. The I-Beam section used in space Gnd-W/02 is 609 mm (24 in.) deep with the flange size of 191 mm (7.5 in.) and with a web thickness of 15.2 mm (0.6 in.) and flange thickness of 27.2 mm (1.07 in.), while in spaces Gnd-E/03 and Snd-W/03 the I-Beams are 406 mm (16 in.) deep with the flange size of 152 mm (6 in.) and with a web thickness of 14 mm (0.55 in.) and flange thickness of 21.5 mm (0.847 in.).

I-Beams supporting T-Iron Brick Roofs

This system is only observed in space Gnd-N/04 built in 1906, but its roof was modified in 1965. In this system the steel I-Beams have been laid in the direction of the shorter span and support T-Iron strips which are then overlain by brick tiles 228 mm x 114 mm x 38 mm (9 in. x 4.5 in. x 1.5 in.) in size. The weather protection treatment used is the same as explained above. The I-Beam section used is152 mm (6 in.) deep with the flange size of 76 mm (3 in.) with a web thickness of 8.6 mm (0.34 in.) and flange thickness of 12.3 mm (0.484 in.).

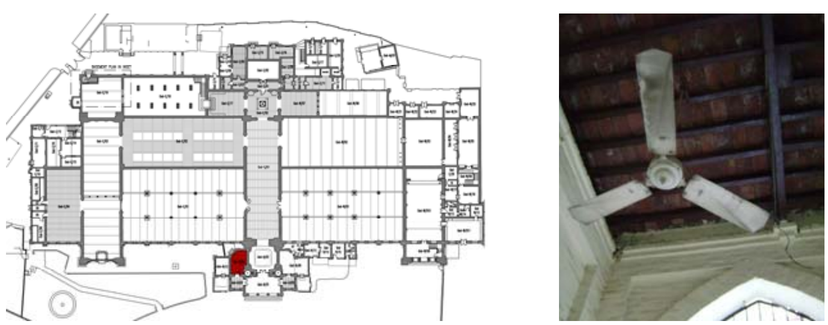

Figure 2.53: Lahore Museum key plans showing location of T-Iron Brick Roof supported on I-Beams in space Gnd-N/04 (left) Looking South at T-Iron Brick Roof in Space Gnd-N/04 (right)

RC Slabs

RC slabs have been the system of choice for the roofs in all post-independence construction (Figure 2.54). It has been indiscriminately used for both new construction as well to carry out all repairs and alteration to the old. The smaller spaces with shorter spans, Gnd-E/05-10, Gnd-S/11-13, Gnd-S/20, Gnd-W/04, Gnd-W/06, Gnd-W/09, Gnd-W/12-24, Gnd-N/07-09, Gnd-N/12-18, Fst-E/06-09, Fst-S/02-04, Fst-W/01, Fst-W/05 & 06, Fst-W/08 and Snd-W/04&05, use two way RC slabs which rest on the masonry walls. In case of larger areas with longer spans the RC roofs are supported with drop beams, as can be seen in spaces Bas-E/01, Gnd-E/11-16, Gnd-E/19, Gnd-S/05&06, Gnd-S/16-19, Gnd-W/08, Gnd-W/11, Gnd-W/25, Gnd-W/05, Fst-W/07, Fst-S/01, Fst-E/10-14 (1974) or with inverted beams as observed in spaces Gnd-W/03, Fst-W/04, Fst-E/15, Fst-E/01-05. Additionally flat RC slab has also been used, though only in one space Gnd-E/18, in the Museum.

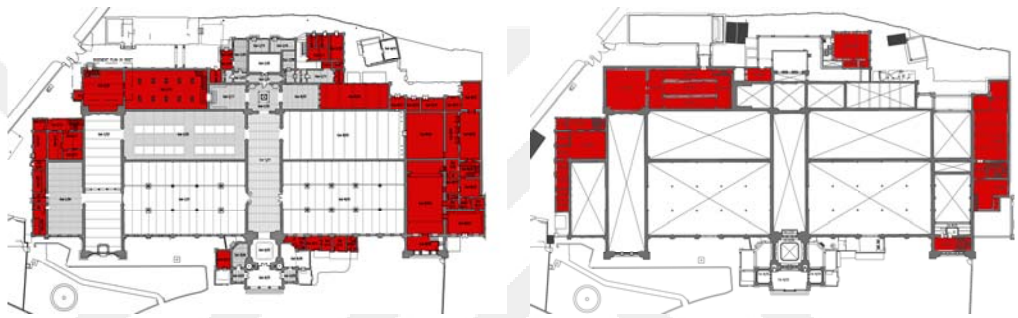

Figure 2.54: Lahore Museum key plans showing locations of RC Slabs
Ground Floor (left) First Floor (right)

False Ceilings

There are three spaces in the Museum, Gnd-N/01, Gnd-N/06 and Gnd-S/01, that have false ceiling and their roofing system cannot be observed (Figure 2.55). For the purpose of this study the roofing system employed and the member sizes used in these spaces is assumed based on their year of construction/ modification and the roofing system employed by the spaces in close proximity, keeping in mind their year of construction and/or modification.

For space Gnd-N/01 which was built in 1893, the same year as its neighboring spaces Gnd-N/03 and Gnd-N/05, it is assumed that the roofing system employed would be the same i.e. I-Beam supporting wooden flat roofs. In case of Gnd-N/06 the roofing system is assumed to be I-Beam supporting T-Iron brick roof which is similar to Gnd-N/04. This assumption is based on the information available in the Lahore Museum Annual report of 1967-68 that roofs of both these spaces was modified in 1965. The roofing system for space Gnd-S/01 is assumed to be I-Beam supporting wooden flat roofs the same as Gnd-C/03. Both these spaces were originally built as one space, in 1929 and divided into two, through a brick masonry wall built in the year 1969.

Figure 2.55: Lahore Museum key plans showing location of False Ceilings Spaces Gnd-N/01, Gnd-N/06 and Gnd-S/01

2.6. Structural Features

No in-situ or laboratory tests have been conducted to determine the material properties of the structural materials used in the Lahore Museum building. In the absence of any experimental data the material properties have been adopted from literature. The basic mechanical properties of the structural materials have been tabulated and are presented in Table 11, while their collection, rationalization and characterization is presented below.

Brick

Lahore Museum building is essentially a brick masonry structure (Figure 2.30, Figure 2.31, Figure 2.32, Figure 2.33 and Figure 2.34). Regardless of the period of construction, brick has been used for building all the load bearing and non-load bearing walls as well as the foundations. The type of brick used in the Museum was first introduced in Lahore for the construction of Lahore Railway Station, by the British in 1861 (M. A. Khan, 2013, p. 189). According to the PWD specifications, bricks used in buildings of any import were to be burnt in Bull's Patent Trench kilns (MacFarlane, 1936, p. 11). The same kiln type is being used in Pakistan till date.

No literature sources were found regarding the mechanical properties of the bricks used during the Colonial era. The information has thus been extrapolated from the data presented in the paper titled *"Qualitative analysis of baked clay bricks available in Larkana Region, Pakistan"*. To determine the brick properties for the purpose of this study some key factors which impact the properties of the bricks were compared like the soluble salt content and PH value of the soil found in Lahore and in Larkana besides the brick firing process used. The Modulus of Elasticity (MoE) value thus used for both pre and post partition bricks is 18050.47 MPa (2618 ksi) (Khoso, Wagan, Khan, Bhatti, & Ansari, 2014, p. 47) while the value of Poisson's ratio used is 0.17 (Khoso et al., 2014, p. 49). The specific weight of the bricks for the purpose of this study is taken as 19 kN/m^3 (121 lb/ft^3) (MacFarlane, 1936, p. XXXIX).

Cast Iron (CI)

Structurally Cast Iron (CI) has only been used in form of columns in the Lahore Museum; in two spaces Gnd-E/01 and Gnd-W/01, built in 1893 (Figure 2.30). According to the PWD specifications CI employed in the Colonial era was tough, close grained, grey metal. The strength of the CI bar of cross section area of 25.4 mm x 50.8 mm (1 in. x 2 in.) placed on bearing 610 mm (2 ft.) apart was such that it could sustain a weight of 1372 kg (27 cwt.) placed at the center, without fracture and with a deflection of no less than 8mm ($^5/_{16}$ in.) (MacFarlane, 1936, p. 36). For the purpose of this study, conservative figures for the ultimate strength of CI have been adopted, the ultimate tensile strength is taken to be 83 MPa (6 $tons/in^2$) while the ultimate compressive strength is considered to be 441 MPa (32 $tons/in^2$) (Bates & British Constructional Steelwork Association, 1984, p. 8). The specific weight of CI for the purpose of this study is taken as 70 kN/m^3 (446 lb/ft^3) (MacFarlane, 1936, p. XXXIX).

The properties and strength of CI given in the PWD specifications were compared with those mentioned in the journal article titled *"Elastic Properties of Cast Iron"*. After the comparison, the MoE value of CI for the purpose of this study was taken from the article as 99974 MPa (14500 ksi) while the value of Poisson's ratio used is 0.2 (Krynitsky & Saeger-Jr., 1939, p. 199).

Wood

Structurally wood has been used in the Lahore Museum as part of the roofing system in various galleries. According to the PWD specifications the wood used during the Colonial era in the Punjab region was Deodar from the forests of Punjab hills or Kashmir (MacFarlane, 1936, p. 35). Deodar is a hardwood and its extensive use during the British period was due to its strength, durability and most importantly its rot-resistant nature. For the purpose of this study the MoE value of Deodar wood is taken as 9315 MPa (1351 ksi) and the Poisson's ratio value used is 0.3 (Rauf, 2006, p. 13) while the specific weight of Deodar wood is taken as 6.3 kN/m^3 (40 lb/ft^3) (MacFarlane, 1936, p. XXXIX).

Steel

Lahore Museum building employs steel only as part of the roofing system in various galleries. Steel is used in the form of I-Beams and railway girders which according to the PWD specifications conformed to the British Standard Specifications for structural steel and was manufactured using the Open Hearth Process (MacFarlane, 1936, p. 36). The steel sections used in the Museum prior to independence were imported from Britain, the I-Beams in gallery Gnd-E/02 and Gnd-W/02 carry the stamp of "Cargo Fleet England." To determine the section sizes and properties attempts were made to acquire a handbook of the company from the early 20th Century, failure to do so lead to the use of Dorman, Long & Co. Ld. Handbook (1906), mentioned in MacFarlane's PWD Specifications (1936). For the purpose of this study, in the pre-independence construction, the ultimate tensile strength of steel is considered to be 441 MPa (32 tons/in^2) while the ultimate compressive strength is taken as 414 MPa (30 tons/in^2) (Bates & British Constructional Steelwork Association, 1984, p. 9).

For the post- independence construction it is considered that ASTM[26]-A36 Structural Steel has been used and the ultimate tensile strength is considered to be 475 MPa (34.5 tons/in^2) while the yield strength is taken as 250 MPa (18 tons/in^2) (ASTM International, 2004, p. 3).

[26] ASTM International, originally known as the American Society for Testing and Materials

Similarly, two MoE values of steel have been used; for the pre-independence construction the MoE is taken as 216,219 MPa (31,360 ksi) (British Engineering Standard Association, 1924, p. 17), while for the post-independence construction the MoE is considered to be 200,000 MPa (29,000 ksi). The value of the Poisson's ratio used is 0.3 (AISC Standard 360, 2005, p. XXX) and the specific weight of steel is taken as 77 kN/m^3 (490 lb/ft^3) (MacFarlane, 1936, p. XXXIX).

Reinforced Concrete

Reinforced Concrete (RC) has only been used in the Lahore Museum building post-independence for the construction of roof slabs, columns, beams and lintels. The value of MoE of RC used for the purpose of this study is taken from the American Concrete Institute code ACI-318 as 24821 MPa (3600 ksi) for construction up to the 1980s and as 21546 MPa (3125 ksi) for the later construction while the value of the Poisson's ratio used is 0.2 (ACI Committee 318, 2011, p. 111) . The compressive strength of concrete is taken as 21 MPa (3000 psi) (ACI Committee 318, 2011, p. 295). The specific weight of RC for the purpose of this study is taken as 23.56 kN/m^3 (150 lb/ft^3) (MacFarlane, 1936, p. XXXIX).

Lime Mortar

Lime mortar has been used in the Lahore Museum for construction of the brickwork masonry till the 1920s. According to the PWD specification the Lime mortar was made from slaked stone lime and the mortar mixture was kept at one part lime to two parts *"surkhi"*[27] (MacFarlane, 1936, p. 31). The value of MoE of Lime Mortar used for the purpose of this study is taken as 3447.38 MPa (500 ksi) and the value of Poisson's ratio used is 0.1 (Palmer & Parsons, 1934, p. 627) while its specific weight is considered to be 17 kN/m^3 (109 lb/ft^3) (MacFarlane, 1936, p. XXXIX).

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[27] "*Surkhi*" is an Indian term used for brick-dust. It is used as a substitute for sand and is made from grinding burnt brick to powder.

Cement Mortar

Cement mortar has been used in the Lahore Museum for construction of the brickwork masonry from the 1920s till date. The cement used in Lahore Museum is Portland cement and the mortar ratio used is one part cement to four parts sand (MacFarlane, 1936, p. 33). For the purpose of this study the MoE value of the cement mortar is assumed as 2654.5 MPa (385 ksi) and the value of Poisson's ratio used in 0.12 (NESPAK, 2015a, p. 14) while its specific weight is considered to be 20.4 kN/m^3 (131 lb/ft^3).

Brick Masonry

Brick Masonry used in the museum is of two types, in the earlier construction stages it is formed with brick units and lime mortar while in the later stages it comprises of brick units and cement mortar. The MoE of the brick masonry was calculated for both binding agents using the equation:

$$E^{*} = E_m \frac{1+{}^{s}/_{h_b}}{{}^{E_m}/_{E_b}+{}^{s}/_{h_b}} \qquad \text{(Como, 2013, p. 43)}$$

Where

E^* = MoE of brick masonry;

E_b = MoE of brick; (18050.47 MPa)

E_m = MoE of Mortar; (Lime: 3447.38MPa and Cement: 2654.5 MPa)

h_b = Height of brick; (76 mm) and

s = Joint thickness; (6 mm)

The MoE value of Brick masonry with Lime Mortar thus calculated is 13789 MPa (2000 ksi) and MoE value of Brick masonry with Cement Mortar is 9653 MPa (1400 ksi) while the Poisson's Ratio, for the purpose of this study, is taken as 0.17.

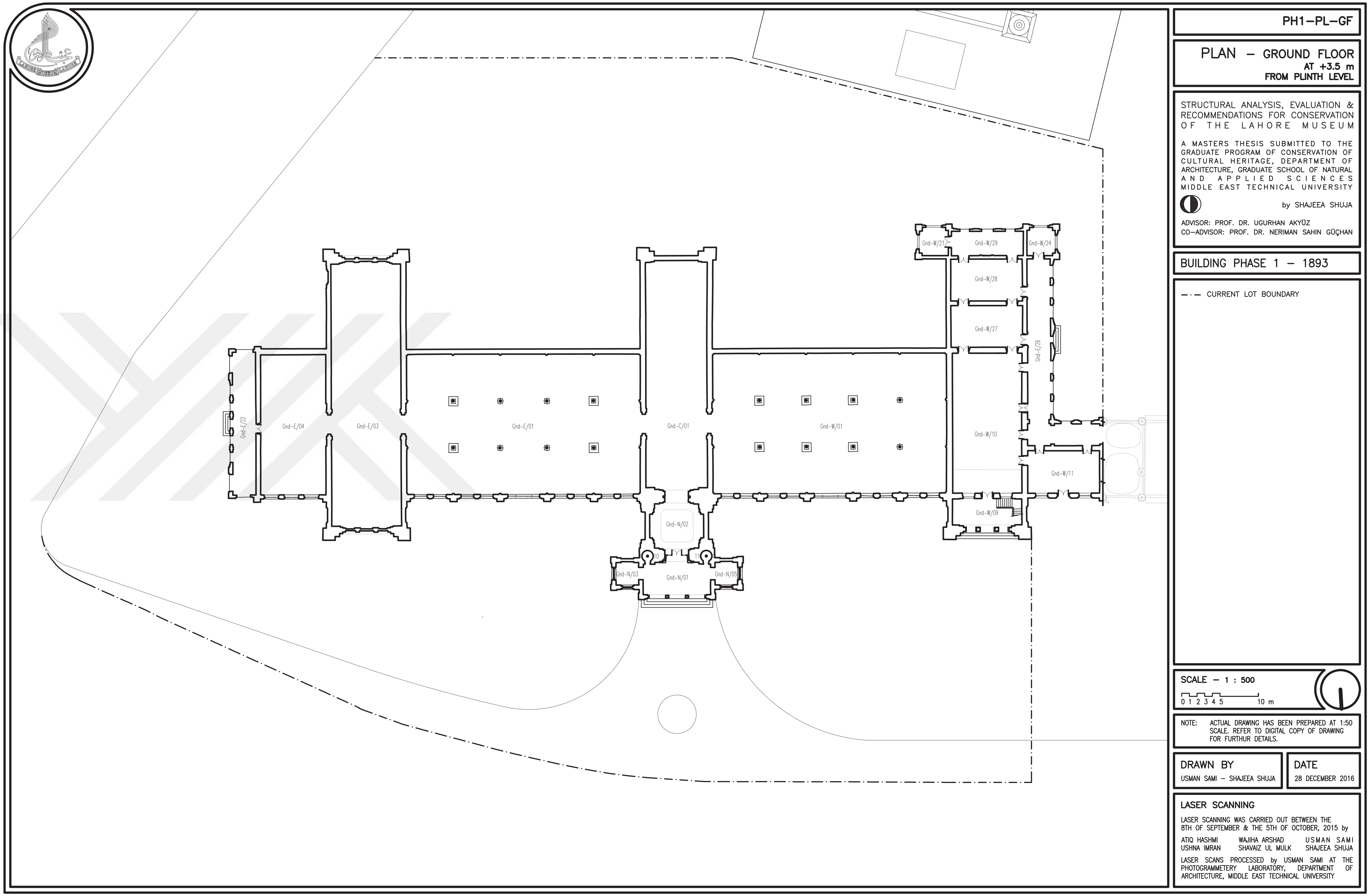

Figure 2.56: PH1-PL-GF – Building Phase 1 – 1893 Plan – Ground Floor (2016)

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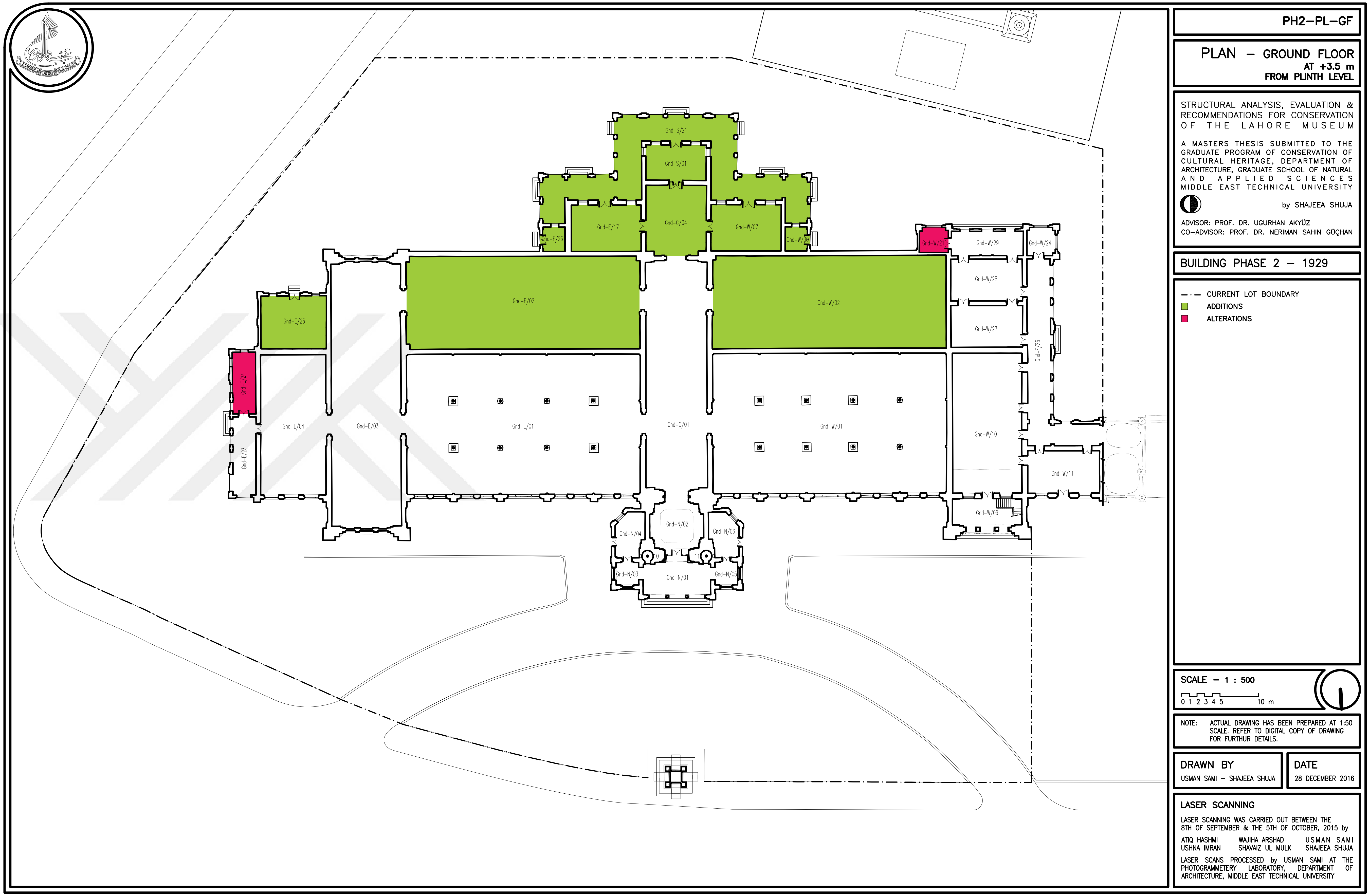

Figure 2.57: PH2-PL-GF – Building Phase 2 – 1929 Plan – Ground Floor (2016)

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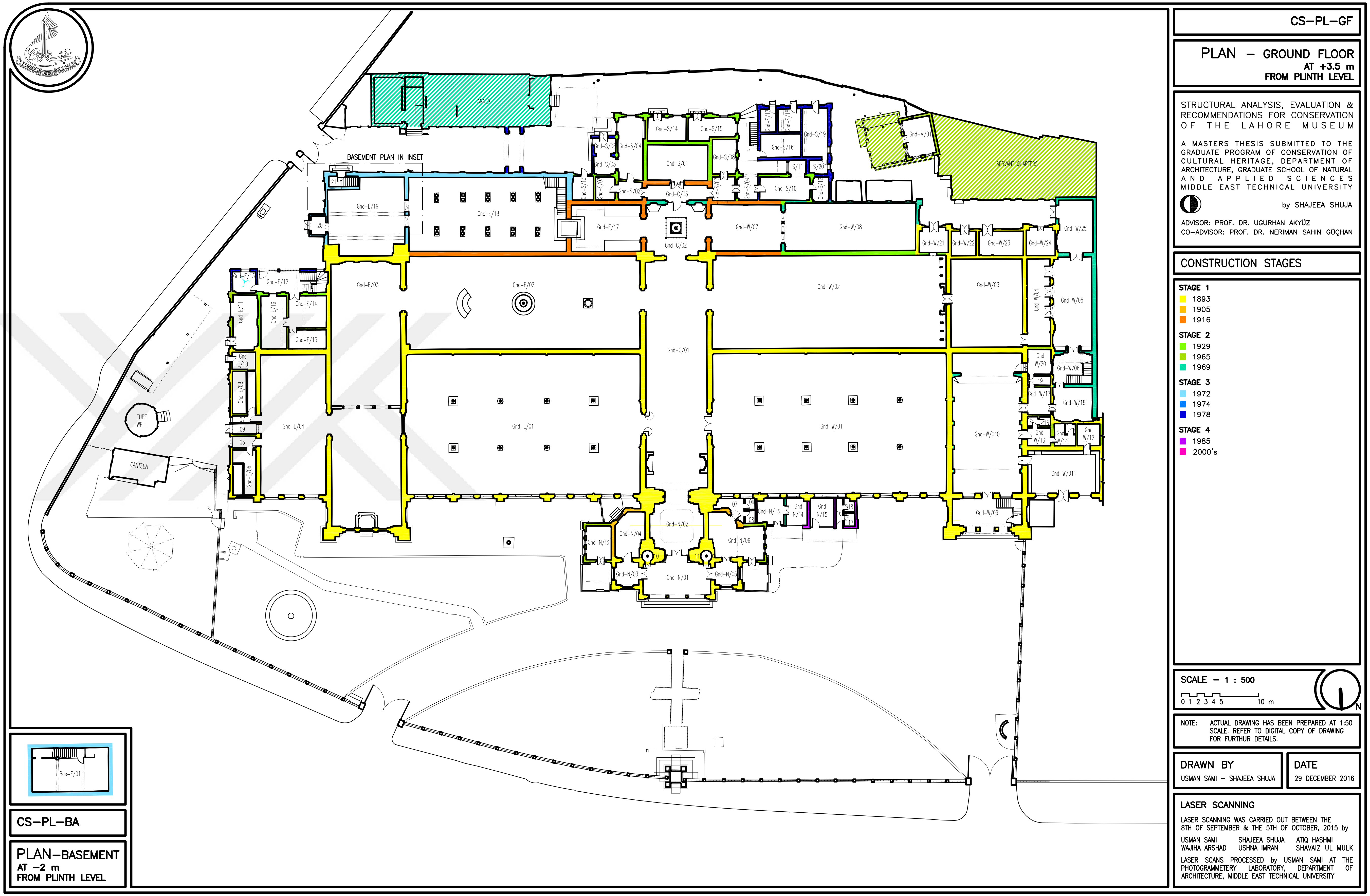

Figure 2.58: CS-PL-GF / BA – Construction Stages – Plan – Ground Floor / Basement (2017)

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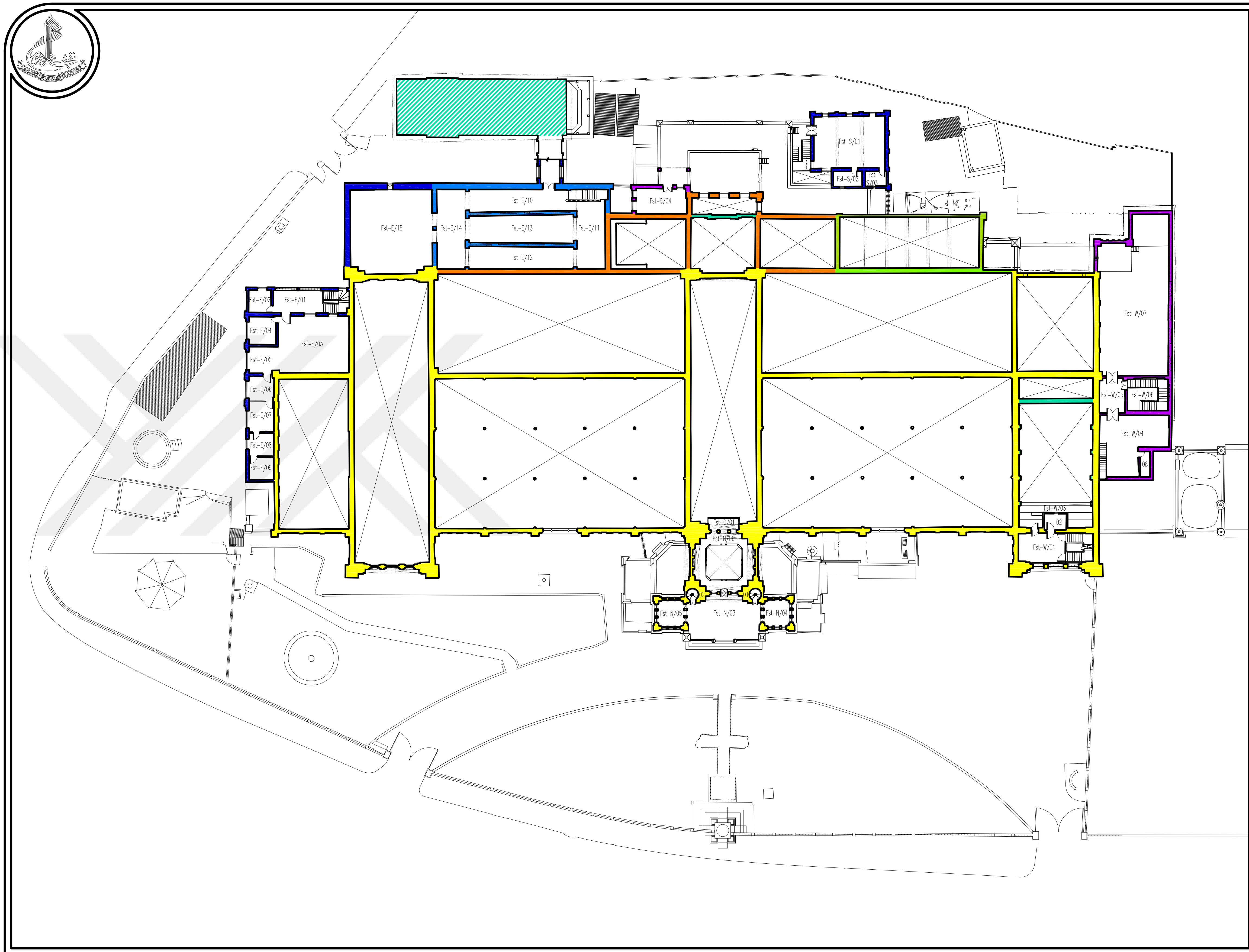

CS–PL–1F

PLAN – FIRST FLOOR
AT +6.45 m
FROM PLINTH LEVEL

STRUCTURAL ANALYSIS, EVALUATION & RECOMMENDATIONS FOR CONSERVATION OF THE LAHORE MUSEUM

A MASTERS THESIS SUBMITTED TO THE GRADUATE PROGRAM OF CONSERVATION OF CULTURAL HERITAGE, DEPARTMENT OF ARCHITECTURE, GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES MIDDLE EAST TECHNICAL UNIVERSITY

by SHAJEEA SHUJA

ADVISOR: PROF. DR. UGURHAN AKYÜZ
CO–ADVISOR: PROF. DR. NERIMAN SAHIN GÜÇHAN

CONSTRUCTION STAGES

STAGE 1
- 1893
- 1905
- 1916

STAGE 2
- 1929
- 1965
- 1969

STAGE 3
- 1972
- 1974
- 1978

STAGE 4
- 1985
- 2000's

SCALE – 1 : 500
0 1 2 3 4 5 10 m

N

NOTE: ACTUAL DRAWING HAS BEEN PREPARED AT 1:50 SCALE. REFER TO DIGITAL COPY OF DRAWING FOR FURTHUR DETAILS.

DRAWN BY
USMAN SAMI – SHAJEEA SHUJA

DATE
29 DECEMBER 2016

LASER SCANNING

LASER SCANNING WAS CARRIED OUT BETWEEN THE 8TH OF SEPTEMBER & THE 5TH OF OCTOBER, 2015 by

USMAN SAMI SHAJEEA SHUJA ATIQ HASHMI
WAJIHA ARSHAD USHNA IMRAN SHAVAIZ UL MULK

LASER SCANS PROCESSED by USMAN SAMI AT THE PHOTOGRAMMETERY LABORATORY, DEPARTMENT OF ARCHITECTURE, MIDDLE EAST TECHNICAL UNIVERSITY

Figure 2.59: CS-PL-1F – Construction Stages – Plan – First Floor (2017)

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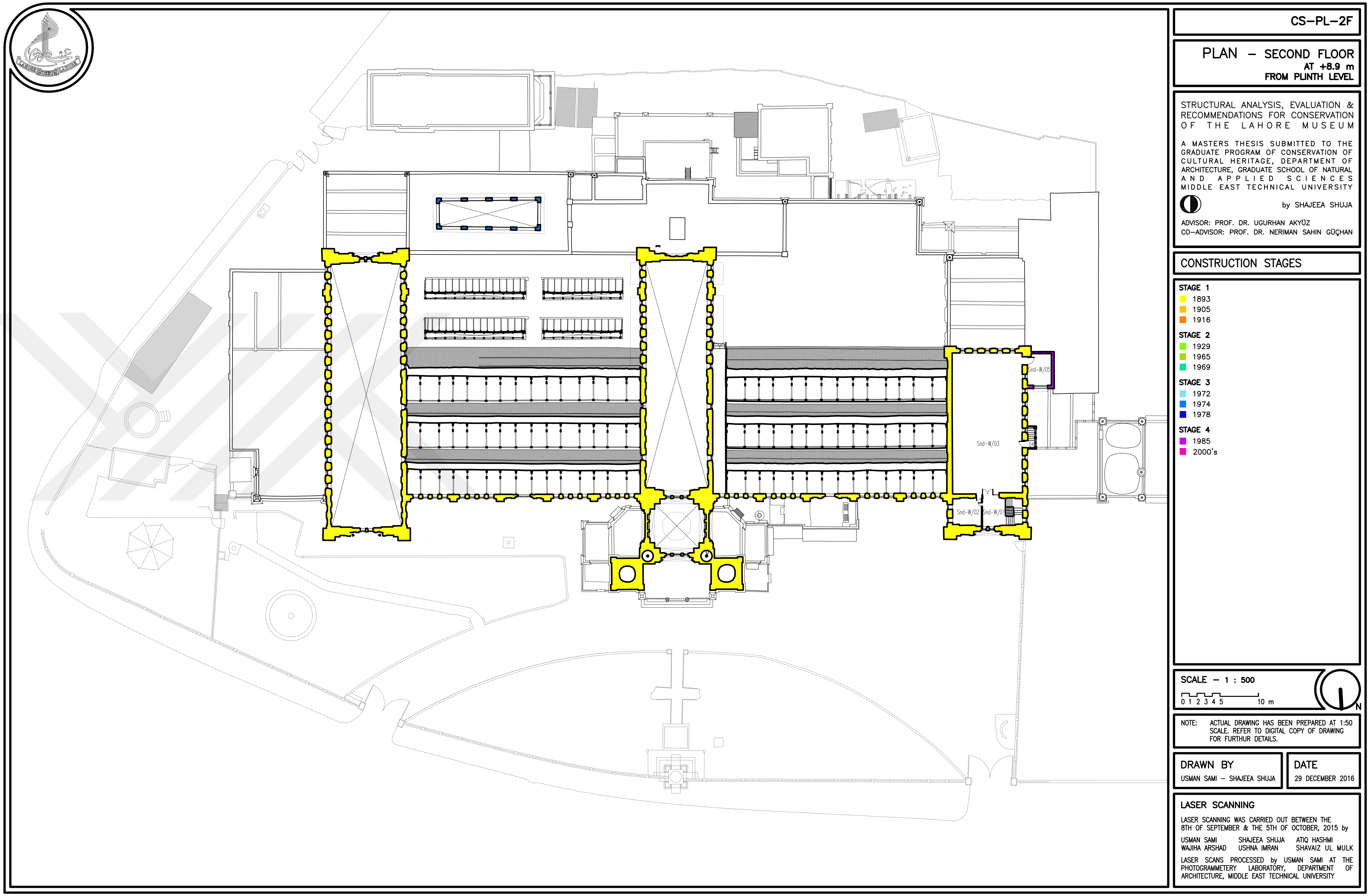

Figure 2.60: CS-PL-2F – Construction Stages – Plan – Second Floor (2017)

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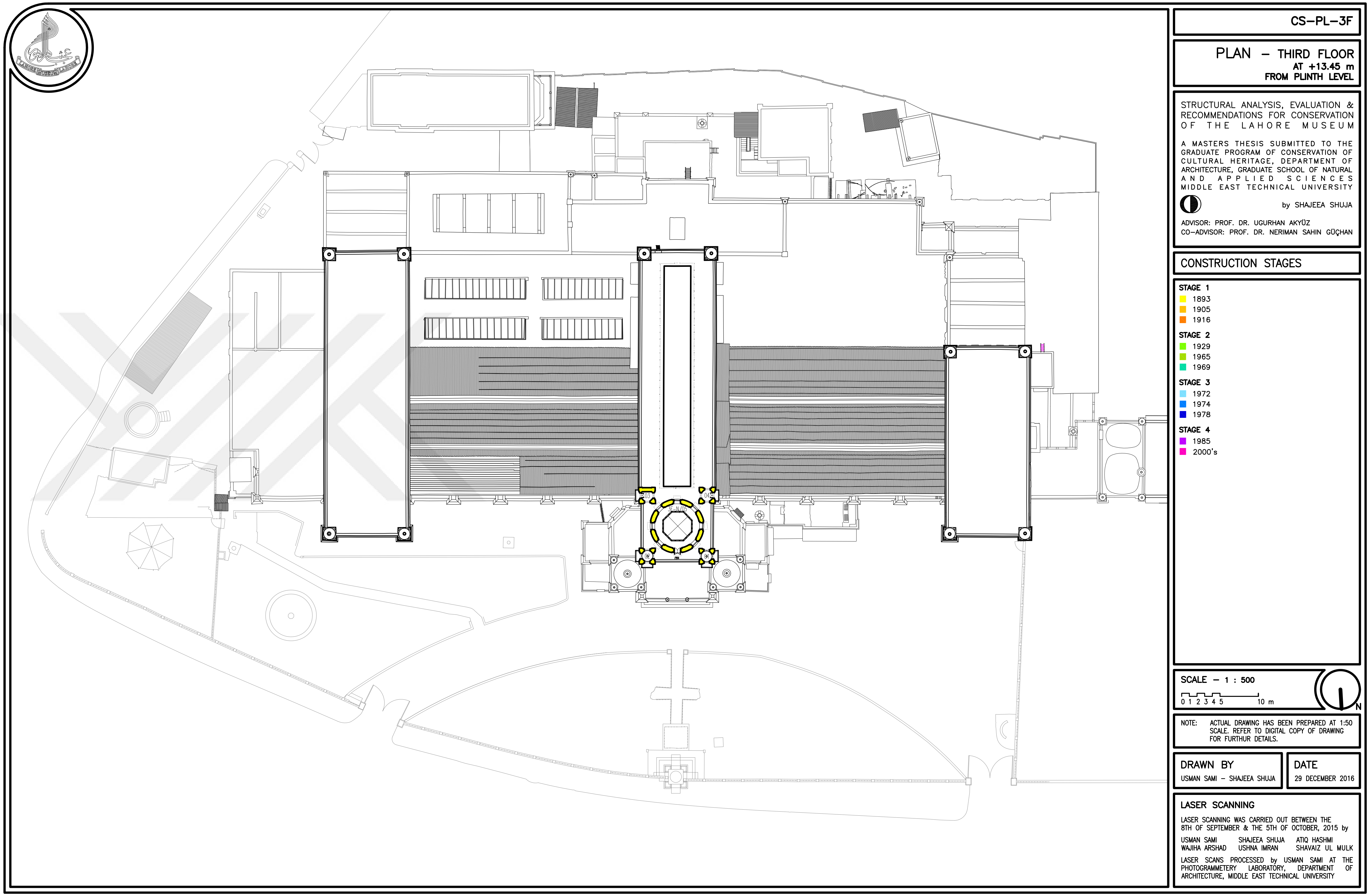

Figure 2.61: CS-PL-3F – Construction Stages – Plan – Third Floor (2017)

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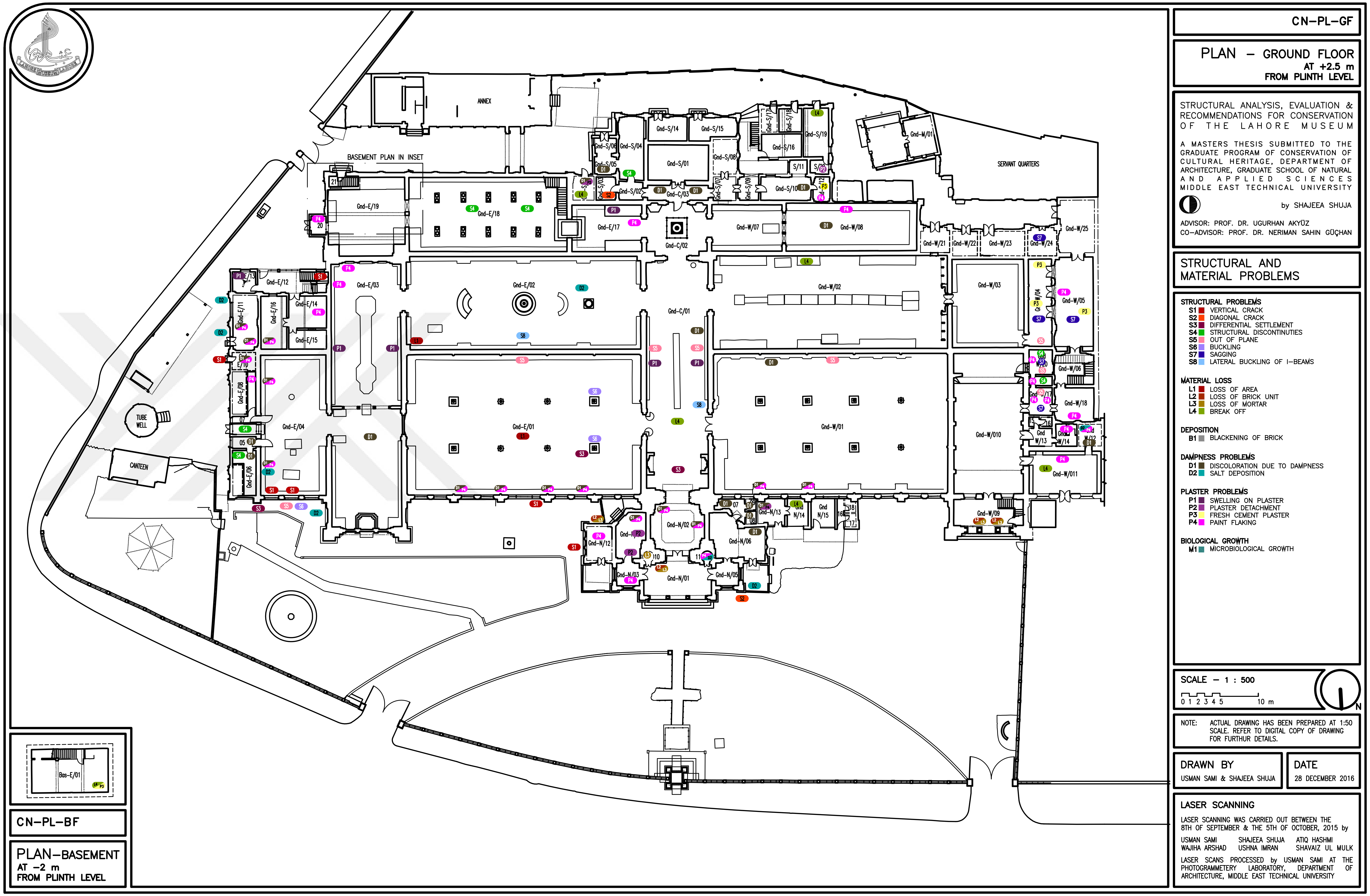

Figure 2.62: CN-PL-GF / BA – Structural and Material Problems – Plan – Ground Floor (2016)

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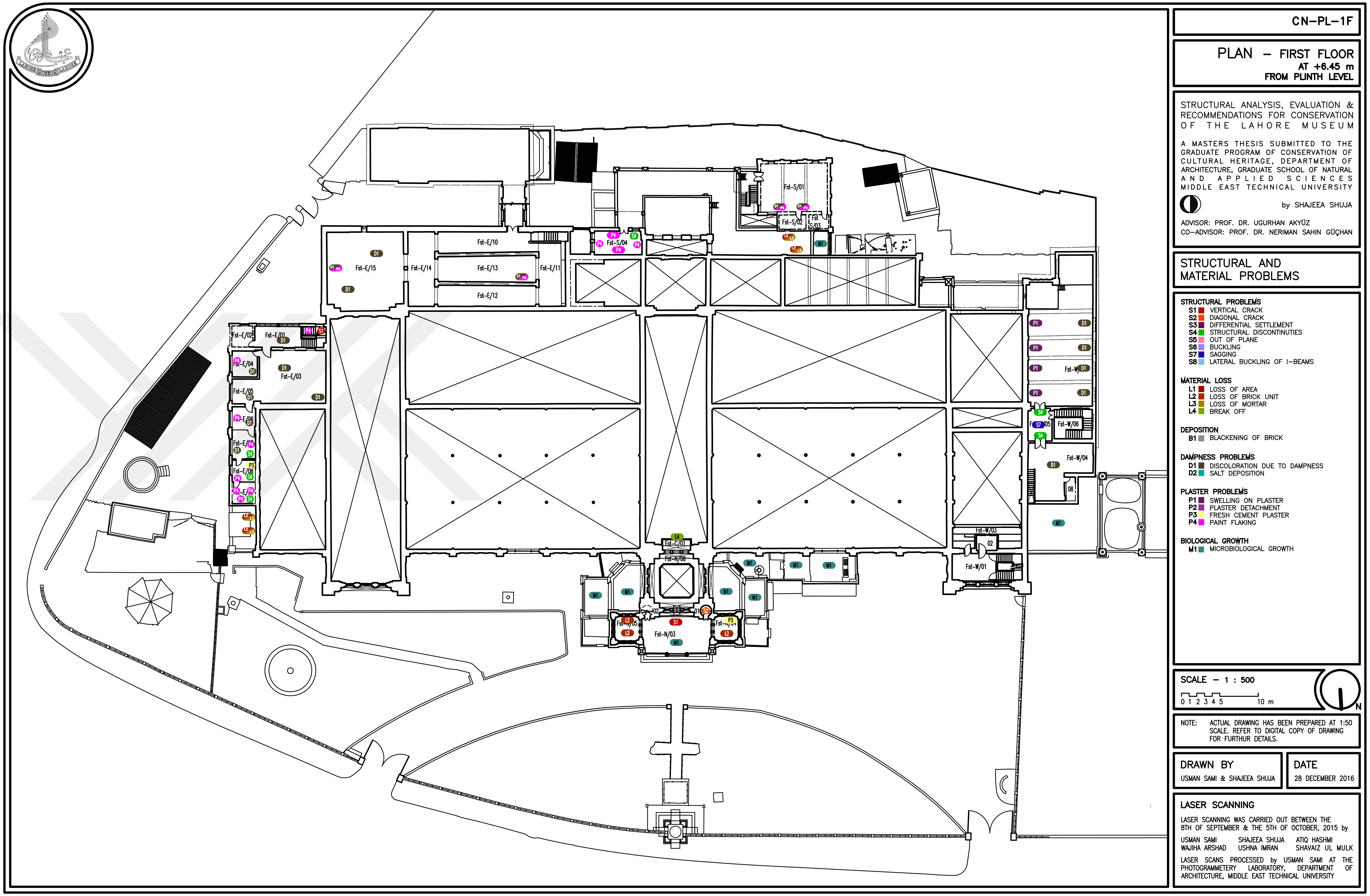

Figure 2.63: CN-PL-1F – Structural and Material Problems – Plan – First Floor (2016)

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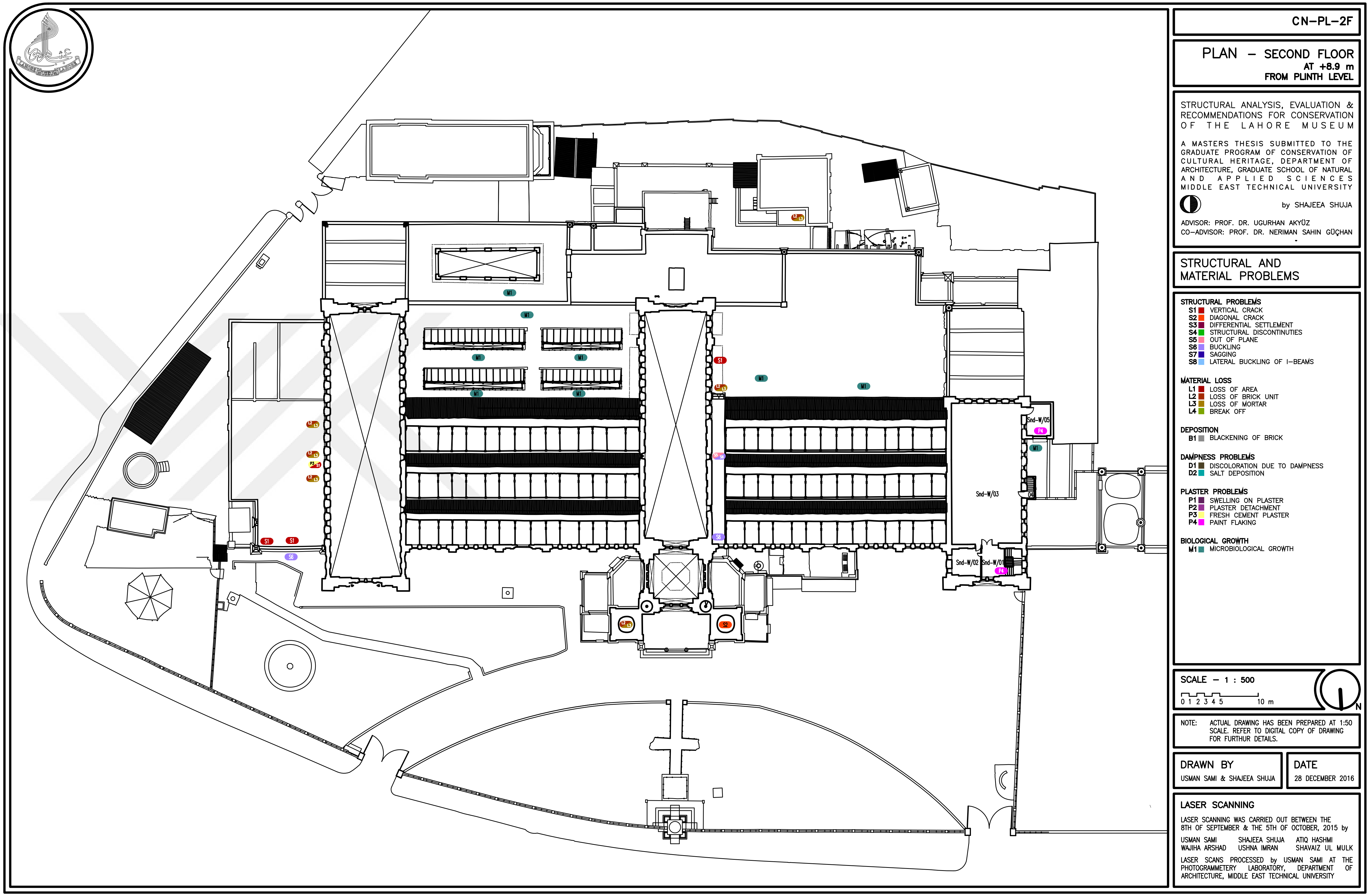

Figure 2.64: CN-PL-2F – Structural and Material Problems – Plan – Second Floor (2016)

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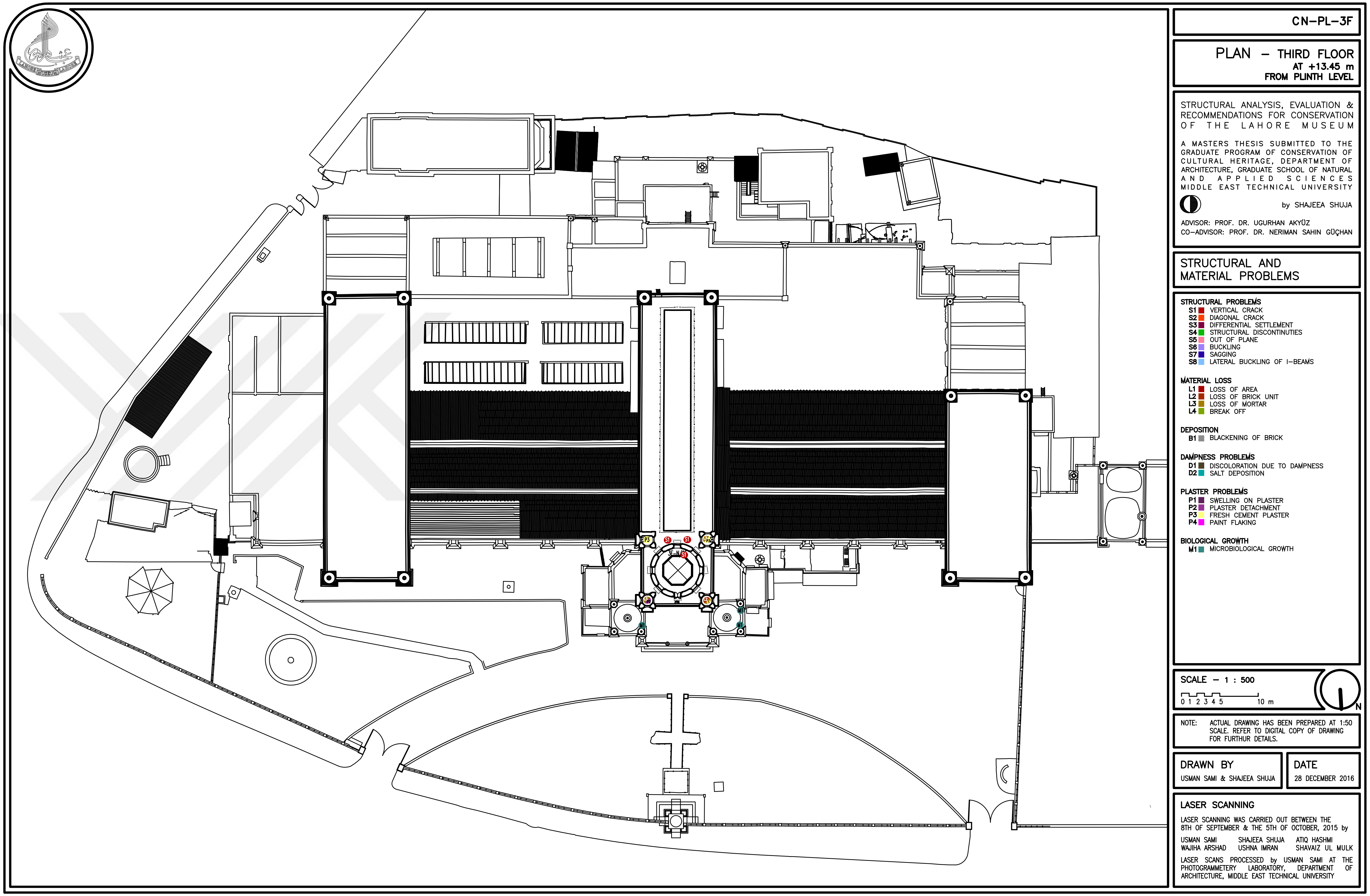

Figure 2.65: CN-PL-3F – Structural and Material Problems – Plan – Third Floor (2016)

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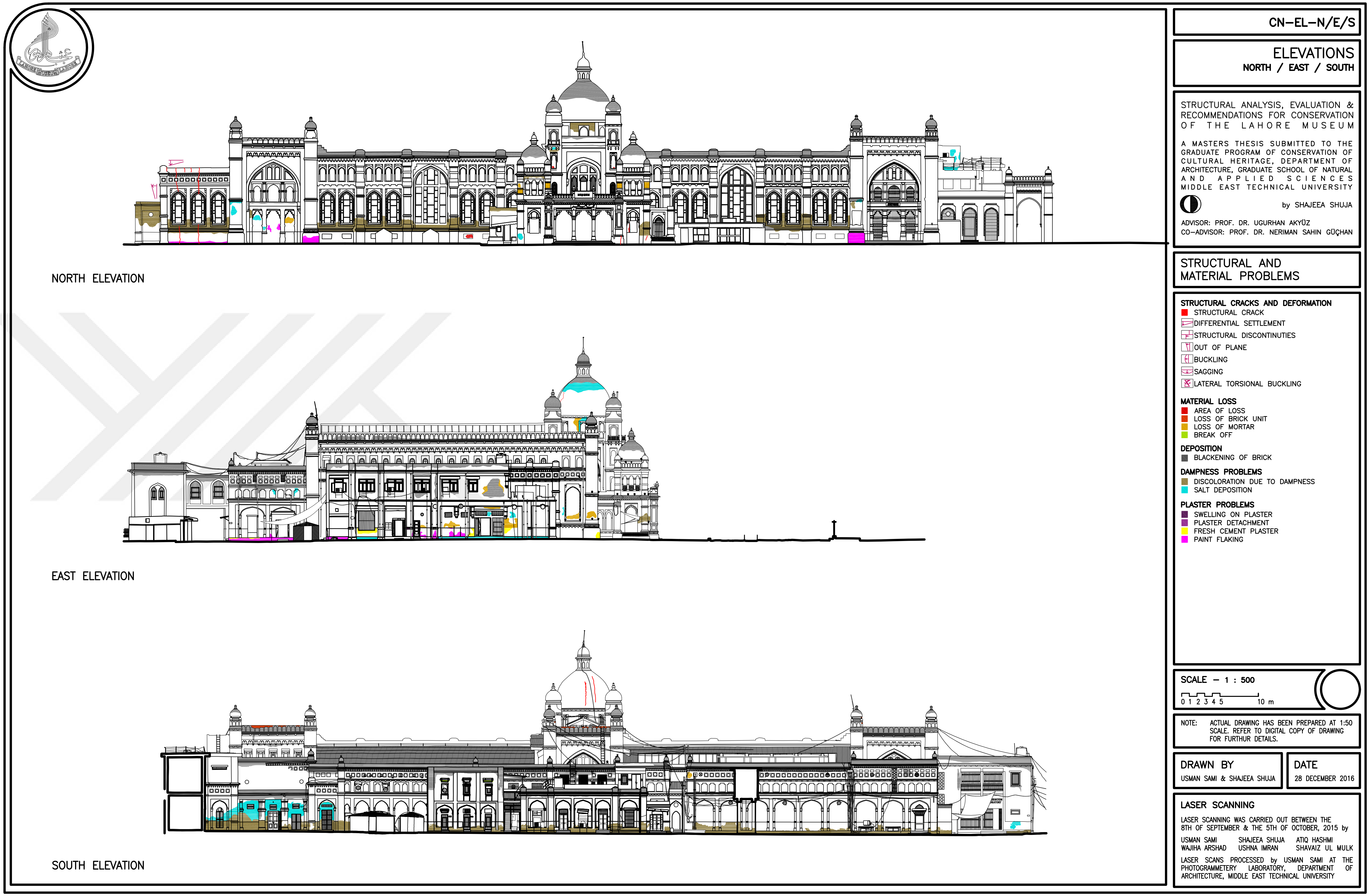

Figure 2.66: CN-EL-N/E/S – Structural and Material Problems – Elevations – North / East / South (2016)

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Figure 2.67: CN-SE-1/2/3 – Structural and Material Problems – Sections – 1 / 2 / 3 (2016)

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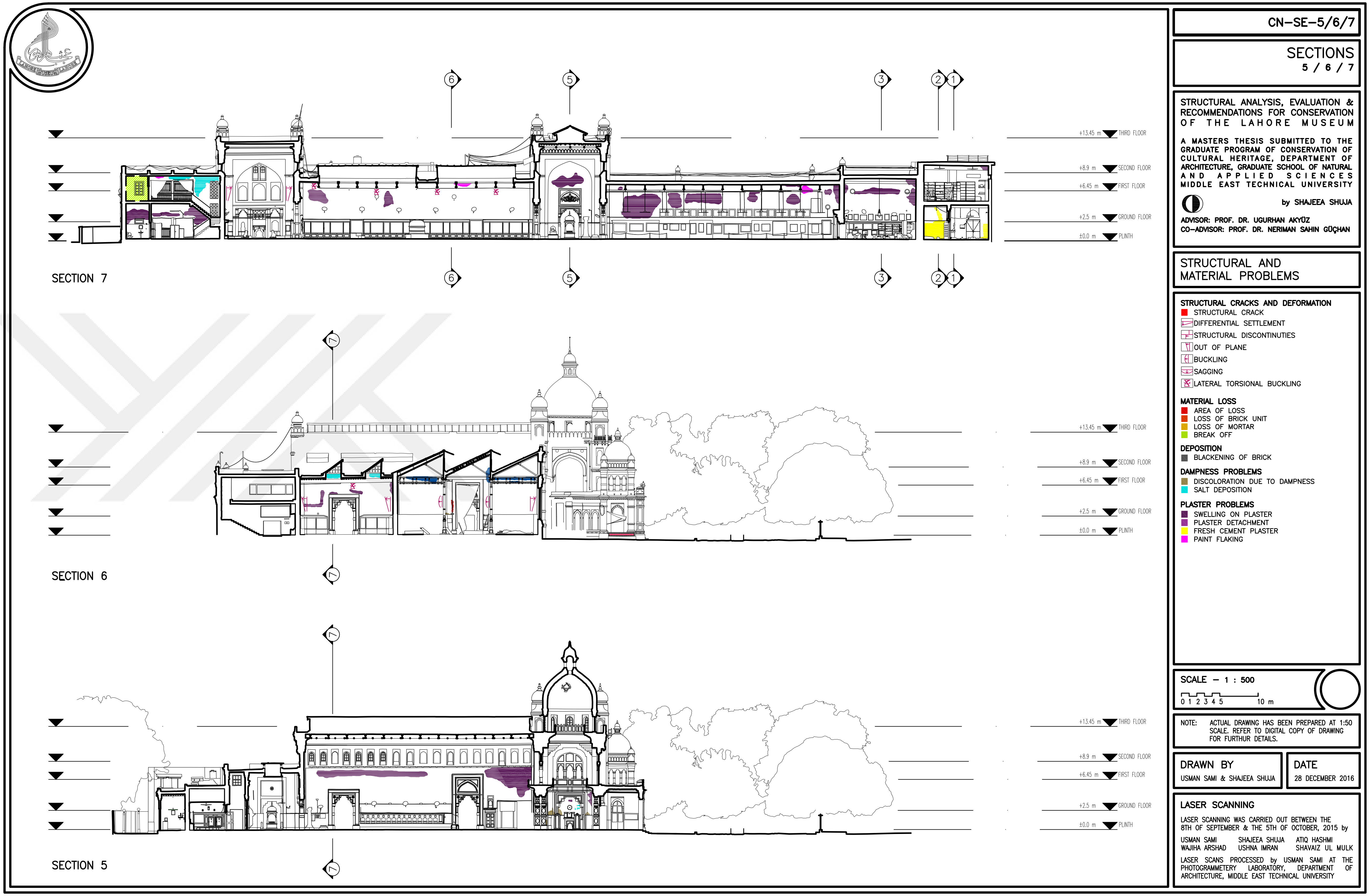

Figure 2.68: CN-SE-5/6/7 – Structural and Material Problems – Sections – 5 / 6 / 7 (2016)

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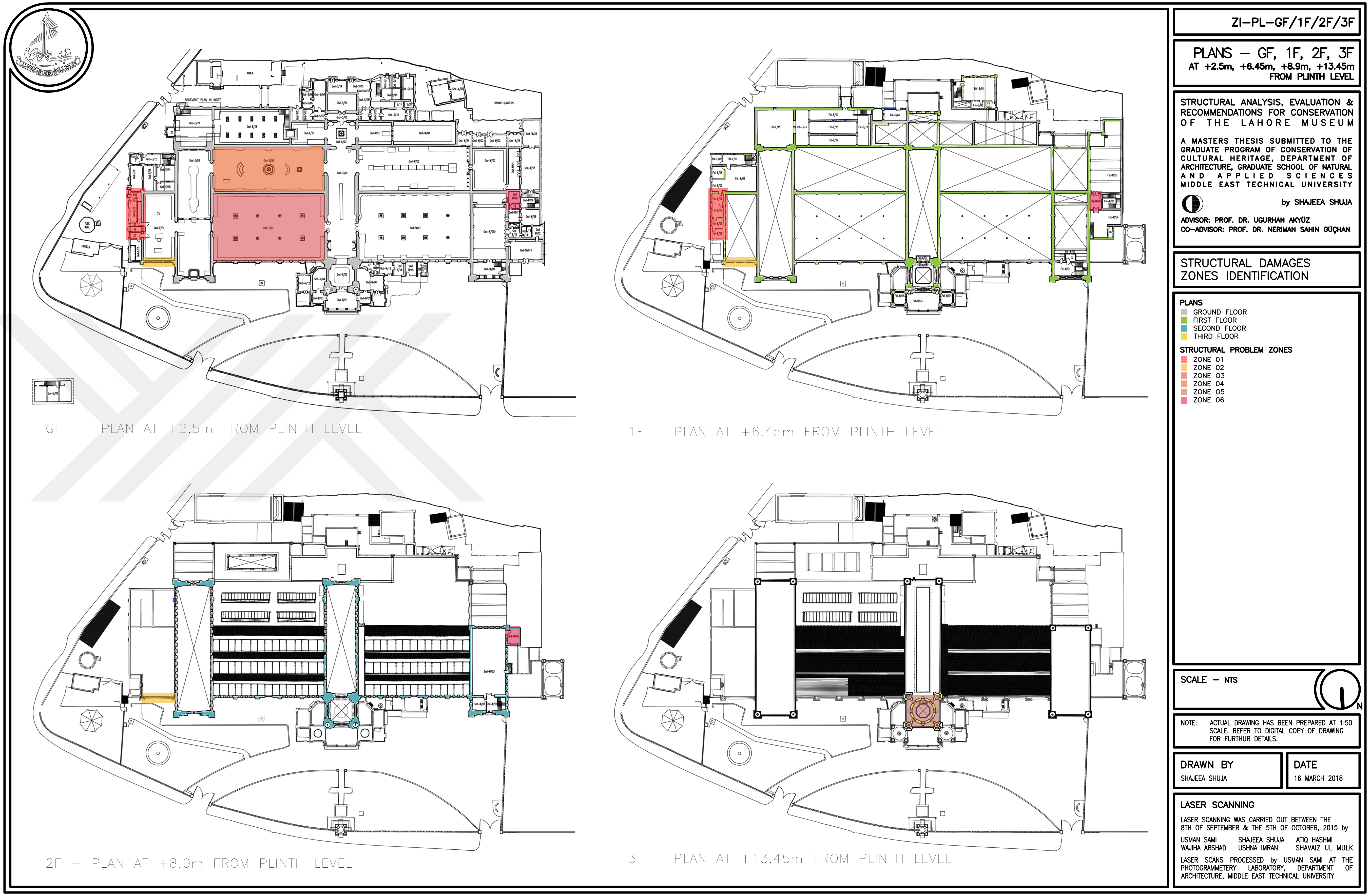

Figure 2.69: ZI-PL-GF/1F/2F/3F – Structural Damages Zone Identification – Plans – GF / 1F / 2F / 3F (2018)

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2.7. Qualitative Assessment

The Museum building exhibits signs of physical deterioration and structural deformation and faces a multitude of problems arising from a variety of factors. This section based on historical research, visual observations and documentation carried out on the building defines the construction stages experienced by the building during its service life and the interventions with a potential to structurally damage the building. It also presents the structural and material problems faced by the building and their probable causes.

2.7.1. *Spatial Evolution of the Lahore Museum Building*

The Lahore Museum building since its construction in 1893, has seen constant additions and alterations. The spatial growth of the Museum building has been retraced using primary sources, mainly the sketch plans from 1908 and 1929, Lahore Museum's *Annual Reports* (tabulated in APPENDIX A) and the archival documents from the Museum which include details and cost estimates for the construction/ alteration/ additions carried out on the building. Information has also been derived from secondary sources such as the *Imperial Gazetteers (1894 & 1916),* Government of India – Department of Education Report No. 6 *Educational Buildings in India (1911)* and Syed Muhammad Latif's book *Lahore: Its History, Architectural Remains and Antiquities (1892).* Additionally period photographs of the Museum collected during the course of this thesis were used to fill the information gaps in the written accounts.

The collated information from these sources reveals that, from the initial construction of the purpose built premise to its current form, the interventions though sporadic can be grouped and studied in four distinct stages (Figure 2.58, Figure 2.59, Figure 2.60 and Figure 2.61).

Stage I – 1893 till 1905

This stage correlates to the initial state of the building when it was completed in the year 1893. The plan for Stage I (Figure 2.56) has been reconstructed using the early written sources, explaining the spatial organization of the museum, and the earliest available sketch plan from the 1908 Descriptive Guide by Percy Brown (Figure 2.9). This plan drawn for the guidance of the visitors only shows areas of the museum which were accessible to the general public. At the time of the museum's inauguration, the building consisted of 21 spaces all of which have been listed along with their functions and sizes in Table 5.

Table 5**:** *List of Museum Spaces in 1893*

Space Code	**Room Name**	**Function**	**Size**		
			L (N/S)	**W** (E/W)	**H**
Gnd-N/01	Entrance Portico	Transition Space	-	-	-
Gnd-N/02	Entrance Vestibule	Staging Area	20 ft. 6 m	20 ft. 6 m	65ft. 19.8m
Gnd-N/03	Room	-	-	-	-
Gnd-N/05	Room	-	-	-	-
Gnd-N/10	Stairwell	Circulation Space	4.75 ft. ø 1.45 m ø	-	-
Gnd-N/11	Stairwell	Circulation Space	4.75 ft. ø 1.45 m ø	-	-
Gnd-C/01	Central Gallery	Industrial Arts Display	96.5 ft. 29.4 m	26.5 ft. 8 m	39 ft. 11.9 m
Gnd-E/01	Gallery	Industrial Arts Display	60 ft. 18.2 m	100 ft. 30.5 m	25 ft. 7.6 m
Gnd-E/03	Gallery	Antiquities Display	60 ft. 18.2 m	100 ft. 30.5 m	25 ft. 7.6 m
Gnd-E/04	Office	Office/ Library/ Sale Room	60 ft. 18.2 m	28 ft. 8.5 m	25 ft. 7.6 m
Gnd-E/22	-	Eastern Verandah	-	-	-
Gnd-W/01	Gallery	Economic Products & Natural History Display	60 ft. 18.2 m	100 ft. 30.5 m	25 ft. 7.6 m
Gnd-W/09	Lobby	Transition Space	-	-	-
Gnd-W/10	Lecture Hall	Auditorium	60 ft. 18.2 m	30 ft. 9.1 m	40 ft. 12.2 m
Gnd-W/11	Classroom	Room for storing slides and preparation of gas for the working of the Magic Lantern used in the lecture hall	-	-	-
Gnd-W/21	Room	-	-	-	-
Gnd-W/24	Room	-	-	-	-

Table 6: Continued

Space Code	Room Name	Function	Size		
			L (N/S)	**W** (E/W)	**H**
Gnd-W/26	-	Western Verandah	-	-	-
Gnd-W/27	Classroom	MSA repoussé and blacksmith class	18 ft. 5.5 m	30 ft. 9.1 m	25 ft. 7.6 m
Gnd-W/28	Classroom	MSA repoussé and blacksmith class	18 ft. 5.5 m	30 ft. 9.1 m	25 ft. 7.6 m
Gnd-W/29	-	Southern Portico	-	-	-

Note: These sizes have been copied from the source documents without any modification. The values do not match those obtained during measured survey, as they have been rounded off to whole numbers in the archival documents.

Source: Department of Education, 1911, p. 166; Walker, 1894, p. 301

Stage II – 1906 till 1965

The annual reports for the Lahore Museum, from 1889 to 1944, record that the curatorial needs of the ever growing museum collection lead to the building being subjected to multiple additions and modifications. Additions to the museum building started as early as 1906 and the building expansion continued in keeping with the symmetrical design logic of the original scheme till 1929. The Museum was to keep this spatial configuration for approximately the next 40 years. Hence, the layout of the Museum in 1929 was considered as the most appropriate state for Stage II of the building. The plan for Stage II (Figure 2.57), has been generated through the sketch plan of 1929 and its cross-comparison with the building documentation carried out for this thesis.

The plan for Stage II, highlighting the additions and alterations made between the years 1893 to 1929, shows the building comprised of 34 spaces at this stage. The list of the museum spaces along with their functions and year of construction in tabular form is presented in Table 6. Most of the additions were made on the south side of the building behind existing galleries and hence had little or no impact on the northern façade of the building. The only change to the northern façade and also the first addition to the building was the construction of two cloak rooms (Gnd-N/04 & 06) in 1906.

Table 6: *List of Museum Spaces in 1929*

Space Name	Function in 1929	Construction Year	Space previously part of…..
Gnd-N/01	Entrance Portico	1893	
Gnd-N/02	-	1893	
Gnd-N/03	-	1893	
Gnd-N/04	Cloak Room	1906	
Gnd-N/05	Entrance Vestibule	1893	
Gnd-N/06	Cloak Room	1906	
Gnd-N/10	Stairwell	1893	
Gnd-N/11	Stairwell	1893	
Gnd-C/01	Industrial Arts Gallery	1893	
Gnd-C/04	Library	1916	
Gnd-E/01	Applied Arts Gallery	1893	
Gnd-E/02	Gandhara Sculpture Gallery	1916	
Gnd-E/03	Brahmanical Sculpture Gallery	1893	
Gnd-E/04	Tibetan & Nepalese Gallery	1893	
Gnd-E/17	Curator's Office	1916	
Gnd-E/23	Eastern Verandah	1893	Gnd-E/22
Gnd-E/24	Room	1893	Gnd-E/22
Gnd-E/25	Godown	1929	
Gnd-E/26	Toilet	1929	
Gnd-W/01	Punjab Gallery	1893	
Gnd-W/02	Picture Gallery	1929	
Gnd-W/07	Office	1916	
Gnd-W/09	Western Entrance Portico	1893	
Gnd-W/10	Arts & Crafts Depot	1893	
Gnd-W/11	Office	1893	
Gnd-W/21	-	1893	
Gnd-W/24	-	1893	
Gnd-W/26	Western Verandah	1893	
Gnd-W/27	-	1893	
Gnd-W/28	Store	1893	
Gnd-W/29	Southern Portico	1893	
Gnd-W/30	Toilet	1929	
Gnd-S/01	Coin Room	1929	
Gnd-S/21	Southern Verandah	1929	

Stage III – 1966 till 1978

After the partition in 1947 the Museum building fell into disrepair till funds were made available for its renovation and re-organization in 1965 (Lahore Museum, 1968, p. 1). The next ten years saw extensive additions and modifications and by 1978 the building had gained its maximum footprint. Hence, the layout of the Museum in 1978 was considered as the most appropriate state for Stage III of the building.

Stage IV – 1979 till Present

In the year 1985, a handful of rooms attached to the northern façade were built, along with Reserve Stores at the western end of the building, over existing spaces. The changes between 1985 and 2000's include modifications to the roofs and addition of partition wall. The current spatial configuration of the building is thus considered as Stage IV of the building. The current condition of the building with detailed description of each space is provided in APPENDIX B of this thesis.

2.7.2. *Structural Interventions*

The museum building over the past 114 years has been subjected to many expedient **Spatial Changes**, which have lead footprint of the building to grow from 2587.35 m^2 (27,850 ft^2) to 5225 m^2 (56,241.5 ft^2) (Figure 2.58, Figure 2.59, Figure 2.60 and Figure 2.61) (See APPENDIX A for chronological list of these works). The myriad of additions and alterations, governed purely by the need for additional space, were all designed and executed by PWD[28] engineers in strict adherence to building codes and specifications without any clear vision or a master plan. These changes discussed in detail in Sections 2.2 and 2.7.1, and in APPENDICES A. & B., have caused shifts in loading patterns and in many instances have resulted in over burdening of walls and foundations.

Additionally the **Roofing Systems**, have had frequent repairs and changes being made to them. In the early days of the building these changes were primarily driven by the leaking roofs and gutters which caused damage to the exhibits almost every year

[28] Re-designated as Communications and Works Department (C&W) in 1962

(Central Museum, 1919, 1923, 1926; Lahore Museum, 1908; Revenue and Agricultural Department, 1894, 1895a, 1897, 1900, 1901, 1902, 1903, 1904, 1905, 1906). The entire roofs were completely overhauled between 1907 – 1908 (Lahore Museum, 1908) but the problem of the roof leakage persisted for the first quarter of the 20th Century.

The distribution and placement of the steel I-Beam in galleries Gnd-C/01, Gnd-E/02, Gnd-E/03, Gnd-E/04, Gnd-W/02 and Gnd-W/10, that have been retained in their original positions till date, point to the fact that the initial roofing system employed in the Museum was jack-arch vaulted roofs[29] (Figure 2.76). This is evidenced by the mention of the "arched" roof of the Central Gallery (Gnd-C/01) in an annual report (Central Museum, 1921) besides the faint details that can be seen of the roof of gallery Gnd-E/03 in the photograph from the year 1938 (Figure 2.70). These roofs over the years were replaced with flat wooden roofs with skylights to control leakage and to provide more light into the galleries (Central Museum, 1921). During the renovation in the 1960s, most damaged of the wooden roofs in galleries Gnd-E/03 and Gnd-W/02 were replaced with RC roofs (Lahore Museum, 1968).

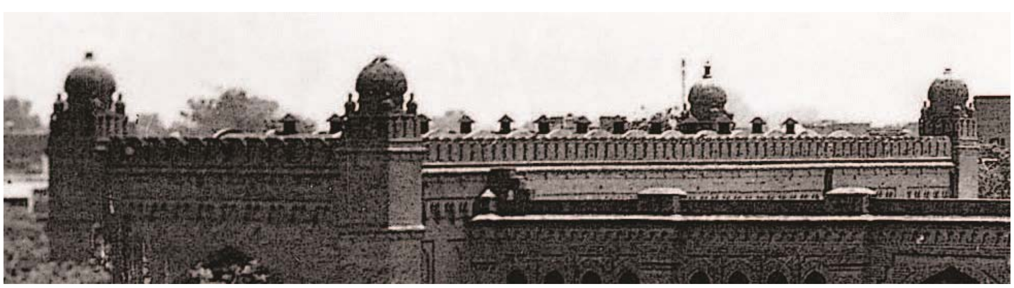

Figure 2.70: Gnd-E/03 – Hindu and Buddhist Gallery – Jack-arched Roof (1938)
Initially the jack-arch vaults were replaced with flat wooden roof. The roof was further modified in 1965when the wooden beam and batten were by replaced with an RC slab.
Source: NCA Archives

The roof of gallery Gnd-E/04 was opened in 2013 to replace the wooden battens that had been severely damaged by termite. The wooden roofs of both the eastern and

[29] Jack arch roofs are formed by a series of parallel (shallow) brick vaults which are supported on steel I-Beam sections.

western verandahs have also been replaced by RC roofs. The roofs of galleries Gnd-W/01 and Gnd-E/01 were opened up in year 1983 and 2015 respectively, to remove the brick tiles and lime concrete layers that were part of the initial roofing details.

The use of multiple roofing systems in the building with large variations in height when coupled with frequent changes and alterations to the roofs, brings with it its own set of problems.

As far as the **Construction Materials** are concerned during the various construction stages of the Museum, the brick type has remained the same while different mortar types have been used. Lime mortar was used in the initial construction stage but as early as 1918 Portland cement came into use. The first documented use of the "Portland cement" in the Museum building is for plastering of the walls in one of the Museum galleries (Central Museum, 1919, p. 5). Over time, as the availability of Portland cement became commonplace, it completely replaced Lime as a binding agent and has been used both for repair works as well as new constructions. The continuous introduction of salts carried by the Portland cement is causing damage to the exposed brickwork.

2.7.3. *Current Damages and Probable Causes*

The damages observed in the Museum building are classified as per the Recommendations of International Scientific Committee for Analysis and Restoration of Structure of Architectural Heritage (ISCARSAH)[30] (2003). According to the Recommendations, **Structural Damage** is the change and worsening of structural behavior that is produced by mechanical actions that affect the structure. These actions produce stresses and strains that can result in cracking, crushing and/or movement. While **Material Damage** is defined as the change and worsening of material characteristics that is produced by physical, chemical or biological actions that affect the materials. It can result in loss of material, deterioration of surfaces and reduction of strength.

[30] ISCARSAH is an International Scientific Committee of the International Council on Monuments and Sites (ICOMOS)

Structural Damages

Multiple structural damages are observed in the Museum building such as Vertical Cracks (S1) and Diagonal Cracks (S2) and Differential Settlement (S3). In places Structural Discontinuities (S4), Out of Plane (S5) behavior, Buckling (S6) and Sagging (S7) are also observed. Lateral Buckling of I-Beams (S8) is also detected in a couple of galleries.

The structural damages are generally localized although multiple phenomenon occur simultaneously in each location. In order to diagnose the cause of damage, it is of paramount importance that damages be discussed in their context, as context and symptoms of damages are inextricably linked. Six zones have been identified in the building where the problems are concentrated, their locations can be seen in Figure 2.69. While, Table 7 shows the location as well as the problems that exist in those zones. For the ease of cross-referencing the drawings, showing structural and material problems, have also been pinpointed in the table.

Table 7: *Zone Identification of Structural Damages in Lahore Museum*

Zone	Location		Structural Problem Type	Reference Drawings
	Block	Space Code		
01	B	Gnd-E/04	S1, S3, S5, S6	CN-PL-GF/ BA; CN-EL-N/E/S
02	D	Gnd-E/01	S3, S5, S6	CN-PL-GF/ BA; CN-SE-5/6/7
03	H	Gnd-W/04 Gnd-W/19 Gnd-W/20 Fst-W/05 Snd-W/05	S4, S5, S7	CN-PL-GF/ BA; CN-PL-1F; CN-SE-1/2/3
04	D	Gnd-E/02	S5, S8	CN-PL-GF/ BA; CN-SE-5/6/7
05	E	Thd-N/05	S1	CN-PL-3F; CN-EL-N/E/S
06	A	Gnd-E/05 Gnd-E/07 Fst-E/08 Fst-E/09	S4, S5	CN-PL-GF/ BA; CN-PL-1F

The zones have been classified qualitatively, according to their level of importance with regards to the safety of the building and are discussed below beginning with the most critical.

Zone 01

Most critical of the structural damages are observed in Zone 01 where the wall Gnd-E/04-N-W is host to a myriad of problems. Two Vertical Cracks (S1) are observed on the wall, one passing through the central arch and the other passing through the eastern arch (Figure 2.66). These cracks starting at the parapet do not follow the mortar line but have broken brick units and travel all the way to the ground (Figure 2.71). Both cracks are greater in width at the top of the wall as compared to the bottom.

Figure 2.71: Vertical Crack going through Central Arch of Gnd-E/04-N-W (2015)
Crack starts from the parapet (left) and reaches till the base of the wall (right)

The crack through the central arch, near the top of the wall, is visible both in the interior as well as the exterior. This crack was first observed by the Author in 2013 and close inspection of a photograph from the year 2007 confirms the presence of the crack from an earlier date (Figure 2.72). However no prior documentation of the crack could be found.

Figure 2.72: Slight crack is observed in the wall Gnd-E/04-N-W (2007)
Source: Fawad Raza

The crack seems to be expanding and in 2017 the second crack passing through the eastern arch was observed for the first time. Also in 2017, a Vertical Separation Crack (S1) was observed at the junction of the wall and the pier at the eastern end of the wall (Figure 2.66). The pier also exhibits out of plane behavior (S5) and is displaced in the North-eastern direction (Figure 2.73). The wall Gnd-E/04-N-W is also showing signs of Lateral Buckling (S6) coupled with out of plane behavior (S5) (Figure 2.73) besides being approximately 50 mm (2 in.) lower at the eastern end in comparison to its western end, which points towards Differential Settlement (S3).

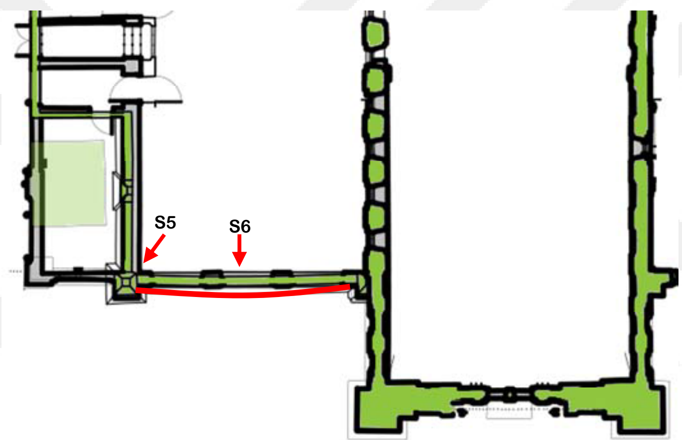

Figure 2.73: Out of Plane behavior (S5) and Buckling (S6) in Zone 01
Seen through the overlapping of Plans
Plan at +2.5m ▭ Plan at +6.45m ▭

In an interview conducted by the author with the PWD engineer mentioned earlier in the thesis, the author was told that the building suffered slight damage as the result of the October 2005 earthquake, with its epicenter at 34.493°N and 73.629°E, about 10 km northeast of the city of Muzzaffarad, and nearly 324 km (201 miles) north-north east of Lahore. The earthquake had moment magnitude 7.6 (M_w) and focal depth of 26 km (16 miles) (Rossetto & Peiris, 2008, p. 2). Strong ground motion recordings during the earthquake are available in Abbottabad, Murree and Nilore; the location details and PGA values are summarized in Table 8.

Table 8: *Location details of strong ground motion records and PGA*

Location	Epicentral distance (km)	PGA (g)		
		NS	EW	Vertical
Abbottabad	48.0	0.197	0.231	0.087
Murree	64.0	0.078	0.075	0.069
Nilore	100.0	0.026	0.023	0.30

Source: Rossetto and Peiris (2008, p. 3)

According to the interviewee the cracks that appeared in the building were examined by the Building Research Station of the Punjab Building Department which deemed them "minor …… and easily repairable" (Haque, 2014). Though the location of the cracks were not confirmed but the crack passing through the central arch of Gnd-E/04-N-W could have resulted as a consequence of the 2005 earthquake. The problem would have aggravated when the roof was opened up for repairs in 2012. The roof boards and earth-fill were removed without providing any external support to the wall, moreover a crane was placed in line with the central arch, on top of the wall, to hoist repair materials.

Additionally, adjacent to the gallery Gnd-E/04 on the Eastern side are the public toilets Gnd-E/06. The movement in wall Gnd-E/04-N-W could have resulted in cracking or rupturing of the water pipes embedded in the walls. Signs of rising damp on wall Gnd-E/04-E-W (Eastern wall) adds weight to this argument. Based on this argument it can be assumed that the local soil conditions have been impacted which could explain the differential settlement (S3) observed in Gnd-E/04-N-W and the Out of Plane behavior (S5) of the Eastern pier.

Zone 02

During the documentation survey, a crack was observed in the terrazzo floor (Gnd-E/01-F), running in the East-West direction of the northern aisle of space Gnd-E/01 (Figure B.10). Beyond the crack, in the northern direction, it was noticed that the floor was slightly sloping down towards the northern end, pointing towards Differential Settlement (S3) of the floor. The documentation drawings revealed three other problems, in Zone 02, which were not perceptible with the naked eye. Firstly, the wall Gnd-E/01-N-W is exhibiting Out of Plane behavior (S5) and tilting away from the base in the Northern direction. Similarly the wall Gnd-E/01-S-W is also seen to exhibit Out of Plane behavior (S5) and is tilting away from the base in the Southern direction. Lastly, the CI columns are showing signs of slight deformation of shape i.e. Local Buckling (S6) (Figure 2.68).

The Out of Plane behavior (S5) of the northern wall (Gnd-E/01-N-W) of space Gnd-E/01 and the Differential Settlement (S3) of the floor seem to be interconnected problems and could be the result of localized worsening of the soil conditions. This argument is supported by the fact that the wall is an exterior wall which shows signs of rising damp. There are downspouts, at the Eastern and the Western end, discharging water directly onto the ground near the base of the wall. Additionally there are no drains in the near vicinity and the slope of the concrete walkway is inadequate to move the water away from the wall (Figure 2.74). As the rainwater collects at the base of the wall it could seep into the ground through the cove joint. This problem would be compounded by the fact that the walkway is made of an impervious material, which would trap the moisture seeping in through the cove joint into the soil. Furthermore, historically heavy moisture rose from the floors of different galleries in the Museum during rainy seasons (Central Museum, 1928), which points to high moisture content of the soil.

Thus the worsening of the soil conditions could have caused slight settlement of foundations of Gnd-E/01-N-W, resulting in the titling of the wall and also the differential settlement (S3) of the floor which is inseparably linked to the soil conditions.

While the out of plane behavior (S5) of the wall Gnd-E/01-S-W in space Gnd-E/01, could be due to the additions of 1916 when the adjacent space Gnd-E/02, south of this space, was constructed (Table 6 and Figure 2.57). The new construction lead to a “serious crack” in the wall of the gallery, which then had to be opened and rebuilt (Central Museum, 1916). The additional load of the roof of space Gnd-E/02 on the wall Gnd-E/01-S-W, could have resulted in the crack. Although the wall was repaired no measures were taken to strengthen the wall or the foundations. Additionally, the roofing system of space Gnd-E/02 was frequently changed due to the persisting roof leakage. Thus the recurring changes in the loading pattern could have resulted in the out of plane behavior (S5) observed in the wall.

Figure 2.74: Two downspouts one at the eastern end (left) and the other at the western end (right) of the wall Gnd-E/01-N-W.
Concrete walkway can also be seen in the images

The deformation noticed in the CI column may originate due to inaccuracies of casting and/ or because the material is fatigued due to imposed loads.

Zone 03

Sagging (S7) of the roof, was observed during the site survey in spaces Gnd-W/04, Gnd-W/20, Gnd-W/19 and Gnd-W/17 along with Out of Plane behavior (S5) in walls Gnd-W/04-N-W, Gnd-W/20-N-W, Gnd-W/19-N-W and Gnd-W/17-N-W. The tilt of the walls was cross checked with the help of a plumb line and it was observed that all walls were tilting away from the base in the southern direction. The documentation drawings also confirmed the above mentioned observations in Zone 03 (Figure 2.67). No cracks or settlement of the floor was detected and the only plausible reason seemed to be the construction over these spaces. This argument gained more credence when the historical survey revealed that spaces Gnd-W/04, Gnd-W/20, Gnd-W/19 and Gnd-W/17 were carved out of the Western Verandah in 1965 while the spaces Fst-W/05 and Snd-W/05 were built in 1985 (Figure 2.58, Figure 2.59 and Figure 2.60).

Overlaying of the plan drawn at +2.5 m (8 ft. 3in.) with the plan drawn at +6.45 m (21 ft. 2 in.) further revealed vertical structural discontinuities (S4) (Figure 2.75).

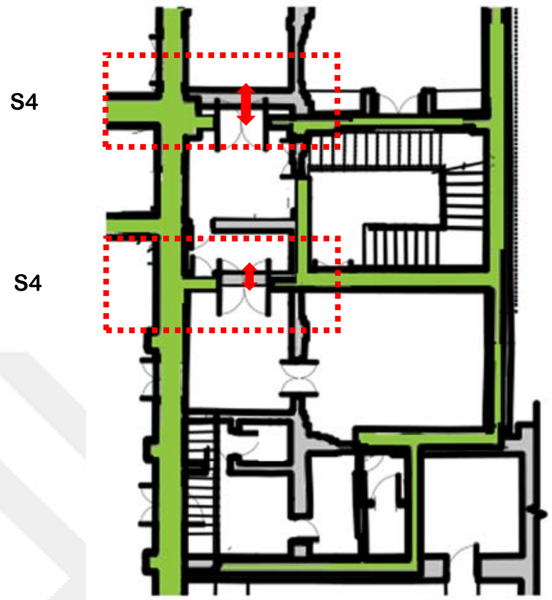

Figure 2.75: Structural Discontinuities in Zone 03 seen by overlapping of Plans
Plan at +2.5m ▭ Plan at +6.45m ▭

In case of the sagging of the roofs another fact to consider is the change in the roofing system of the Western Verandah from wooden beam and batten to RC during the 1965 renovation. No provisions were made to accommodate the first floor, which houses the reserves stores and library storage. The change in the loading conditions could have resulted in the sagging of the roofs in Zone 03.

The walls Gnd-W/04-N-W, Gnd-W/20-N-W, Gnd-W/19-N-W and Gnd-W/17-N-W were built as partition walls only and there is a high possibility that they were built on-grade. This combined with the additional load due to the construction of the first floor could have caused the tilt observed in the walls in Zone 03.

Zone 04

During the documentation survey Out of Plane Behavior (S5) of wall Gnd-E/02-S-W and Lateral Buckling of I-Beams (S8) was observed in Zone 04.

The Lateral Buckling of I-Beams (S8) in space Gnd-E/02 can be attributed to the change of roofing system from the Jack Arch to I-Beam supporting the wooden flat roof with skylights. In the colonial era, when the appearance of the roofing system was given due consideration, as would have been the case of the Museum gallery, Jack Arch sprang from the bottom flange of the I-Beam (MacFarlane, 1936, p. 166) (Figure 2.76). Hence, load was applied below the shear center of the I-Beam, which reduced the susceptibility of the section to lateral buckling. Whereas, the use of wooden flat roof meant that the load was applied above the shear center making it prone to Lateral Buckling (S8).

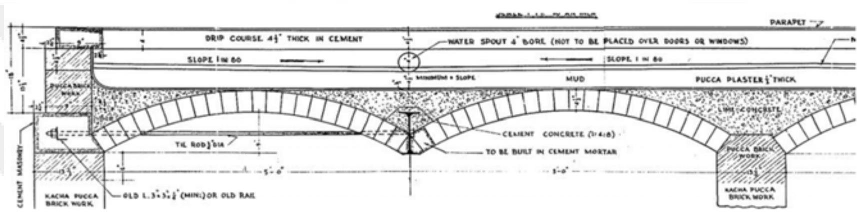

Figure 2.76: Jack Arch Roofing System used in India during the Colonial Era
From the Railway Archives at Railway Headquarters Lahore
Source: M. A. Khan (2013, p. 187)

In case of the wall Gnd-E/02-S-W it was observed that the wall titled from its base in the southern direction. This was cross checked with the help of a plumb line and was also confirmed through the documentation drawings (Figure 2.68). This behavior can be attributed to the construction of the adjacent space Gnd-E/18, south of space Gnd-E/02 in 1972, and later in 1974 the addition of gallery spaces above Gnd-E/18. Additionally, the roofing system of space Gnd-E/02 was frequently changed due to the persisting roof leakage. Thus the increased gravity load due to the new constructions and the addition of slab approximately at mid-height of the wall Gnd-E/02-S-W coupled with recurring changes in the loading pattern due to roof changes could have resulted in the Out of Plane Behavior (S5) observed in wall Gnd-E/02-S-W .

Zone 05

Two meridional cracks are observed on the exterior of the main dome (Thd-N/05) at the southern end (Figure 2.66). The cracks generally follow the mortar line but in places have broken brick units (Figure 2.77). The starting point of the cracks could not be observed but they extend till the circular wall of the drum. The cracks have been grouted a few times in the past but keep reappearing.

These cracks are also attributed to the October 2005 earthquake which could have caused the initial crack in Zone 01 discussed earlier.

Figure 2.77: The meridional cracks observed on the Main Dome (left) Close-up showing the crack breaking brick unit (right)

Zone 06

Slight out of plane behavior (S5) was detected in Gnd-E/05-N-W and Gnd-E/07-N-W during the documentation survey in Zone 06. This observation was cross checked with the help of a plumb line and it was observed that the walls were tilting away from the base in the southern direction. As no cracks or settlement of the floor was seen the only plausible reason seemed to be the construction over these spaces. This argument gained more credence when the historical survey revealed that spaces Gnd-E/05 and Gnd-E/07 were carved out of the Eastern Verandah in 1965 while the spaces Fst-E/08 and Fst-E/09 were built in 1978 (Figure 2.58 and Figure 2.59). Overlaying of the plan drawn at +2.5 m (8 ft. 3in.) with the plan drawn at +6.45 m (21 ft. 2 in.) further revealed vertical structural discontinuities (S4) (Figure 2.78). Additionally as the walls Gnd-E/05-N-W and Gnd-E/07-N-W were built as partition walls only there is a high possibility that they were built on-grade. The combination of these two actions could have caused the tilt observed in the walls in Zone 06.

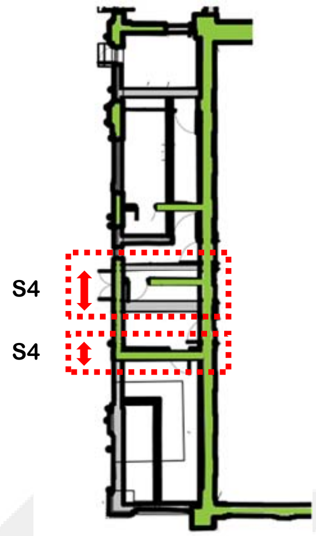

Figure 2.78: Structural Discontinuities in Zone 06 seen through the overlapping of Plans
Plan at +2.5m Plan at +6.45m

Besides the structural problems mentioned above, vertical and diagonal cracks are observed all over the building with the highest concentration in the northern part of the building. The widths of the cracks vary and though they seem minor it is impossible to tell if they are live or static cracks, as no long term monitoring has been carried out on them.

Material Damage

Multitude material deterioration problems are observed in the Museum. There are some parts of the building that have experienced Loss of Area of fabric (L1) and Areas where brick units have been lost (L2). Mortar Loss (L3) is found all over the building fabric while in some places parts of the building fabric has Broken off (L4). Another problem recurring all over the building is the Dampness Problems, causing Discoloration (D1) and Salt Deposition (D2). Plastering in the building also suffers with problems such as Swelling of Plaster (P1), Plaster Detachment (P2) and Flaking of Paint (P4) due to dampness. In some areas walls have been Re-plastered with Cement (P3) where the plaster had completely detached from the building. Furthermore, Blackening of Brick (B1) is observed on the building exterior while Microbiological growth (M1) is observed on many parts of the roof (Figure 2.62, Figure 2.63, Figure 2.64, Figure 2.65, Figure 2.66, Figure 2.67 and Figure 2.68).

The principal cause of material damage in the building seems to be the presence of moisture from inadequately contained rainwater. The roof drainage in Lahore Museum is particularly problematic as the sloping roof monitors drain into gutters, which then discharge onto the flat roofs (Figure 2.79).

Figure 2.79: Sloping roofs draining into gutter which discharge onto flat roof (left)
Roof draining directly onto Southern Façade through scuppers (right)

As the roof heights in the museum building vary, hence the higher roofs drain onto the lower roofs through scuppers. The in-built drains on the lower roofs are connected to drain pipes which runs along the ceilings of galleries. These pipes on occasion are connected to downspouts which discharge directly onto the ground at the base of the exterior walls (Figure 2.74) while in some cases the roofs drain directly onto the exterior walls through scuppers (Figure 2.79).

This problem is best exemplified in the case of the two galleries with trusses i.e. Gnd-E/01 (Islamic Arts Gallery and Gnd-W/01 (General Gallery). The design of the roof in these spaces is inherently flawed as the trusses, oriented in the east-west direction, abut much higher building blocks on either side. Catchment channels in the middle of the roof collect rainwater from the two drainage valleys (Figure 2.80) and evacuates it into drain pipes. The pipes then drop below the soffit into the gallery spaces from there they run along the eastern wall of Gnd-W/01 and western wall of Gnd-E/01 concealed behind the plaster of Paris cornices that slope towards the north. The water is finally channeled out of the building through spouts on the upper levels of the northern façade of the building.

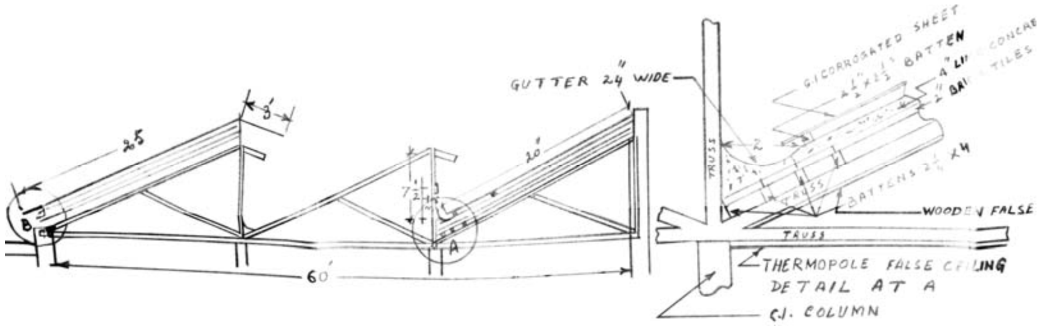

Figure 2.80: Section through the General Gallery Roof – Existing (1980)
Drawing extracted from: Butt, Q. u. H., Executive Engine^{er}, 4th Provincial: Building Division, Lahore. (1980). Estimate for: Re-construction of corrugated sheet roofing & drains over existing trusses of Islamic & General gallery in Lahore Museum Lahore. To: Director Lahore Museum. Letter No. E-50-0/50-LM-5915 dated. 10.9.1980. p. 52

The badly designed roof drainage has caused discoloration and blackening of the exposed brickwork and opening of masonry joints especially at the upper part of the walls on the building exterior. It has also resulted in microbiological growth on various flat roofs of the building.

Another source of moisture in the building is rainwater penetration from the roof which has led to the appearance of water stains on the ceiling as well as upper parts of the walls along with swelling of plaster and flaking of paint. This is the direct result of the worn out and peeling waterproof coating over the brick tiles on the flat roofs and the dilapidated condition of the corrugated iron sheets covering the sloping skylight monitors. In case of the sloping roof not only has the material worn out but the overlaps are insufficient and in many places the joints have opened up.

Furthermore, rising damp has caused significant spalling or loss of material on the building exterior and has also resulted in damage to the interior finishes. The surfaces at the base of the exterior walls are paved with impervious materials such as concrete or asphalt and therefore are unable to absorb the rainwater discharge. Furthermore, there are only a few very small drains in the vicinity and even they are clogged with debris. The slope of paved areas also appears inadequate to move the water away from the base of the walls. As a result of all these factors the rainwater collects at the base of the wall. The concrete parging applied to external as well as internal faces of the exterior walls compounds the problem. As the application of this impervious material has driven dampness up the walls. Above the parging where water can finally migrate through the walls, visible powdering of brick is observed on the exterior of the building. While swelling and even detachment of plaster is observed in the interior of both the exhibit areas as well as the reserve godowns.

Another problem the museum building faces is the continuous reintroduction of salts to the brickwork. As Portland cement became readily available, the building initially built with brick masonry laid in lime mortar saw a steady shift to cement based construction. Currently, PWD unreservedly uses Portland cement for the construction of additions as well as repair and maintenance of the earlier structures. As the building in parts and at times is completely repointed with red tinted Portland cement mortar, the salts carried by the cement are repeatedly introduced to the brickwork. The moisture from rainwater or leaking sewage pipes may carry other types of salt, which are introduced to the brickwork through rainwater penetration and rising damp. The presence of salt in the brickwork is causing powdering of the brick edges which are then pointed with thicker layers of mortar in an unending cycle.

Figure 2.81: Powdering of Brick / Detachment of Pointing on the exterior wall of Fst-W/01 (2017)

The presence of moisture and salts in the brickwork, together with the wetting and drying cycles due to heavy monsoon rains, has led to material degradation all over the building.

CHAPTER 3

MODELLING AND STRUCTURAL ANALYSES OF THE LAHORE MUSEUM

This chapter aims to assess the Museum building through quantitative approach and contains three sections. The approach takes historical background of the building into account, by developing four analytical models based on the reconstituted geometries of the building. The first section provides a review of the computational strategies available for modelling of historic masonry structures. It discusses in detail the possibilites and limitations of each strategy. The next section opens with the rationalization of the approach taken up for modelling of the Musuem building in light of the discussion presented in the previous section and concisely states the rationale for choosing to study the building through four reconstituted geometries of the structure. It then proceeds with step by step description of the process used for developing the models and ends with a brief discussion apropos structural load cases and analyses carried out to understand the global structural behavior of the building. It also lists the various load combinations applied in the analyses. The third and the concluding section presents the results of analyses carried out. It sequentially presents the findings of the Modal Analysis, followed by the Seismic Analysis. It then discusses in general the results of the analysis conducted on the predominant structural system i.e. the solid brick masonry walls; moving on to an in-depth discussion of the localized problem zones identified through the masonry wall analysis and ends with a brief discussion of sub-structural system i.e. the columns.

3.1. Review of Computational Strategies for Analytical Modelling of Historic Masonry Structures

Historical masonry structures inherently have complex geometries and there exist many uncertainties in regards to their material characterization, structural details and internal morphologies. In addition to this, masonry construction typified by its anisotropic nature and complex composite character (composed of materials with different physico-mechanical properties) (Figure 3.5-a), poses an overwhelming challenge in rationalizing the structural behavior of historic masonry structures with mathematical methods. Analytical modelling eases the task of solving these complex mathematical relations posed by historical masonry structures.

Analytical Modelling Methods

Nowadays several methods and computational tools are available to analyze the structural behavior of historic masonry structures. The basic differences amongst these methods lie in their approach to element formulation, assembly of numerical equations and how these equations are solved. The most widely used approach for modelling of masonry structures is the Finite Element Method (FEM). Other methods used are the Discrete Element Method (DEM) and its formulation the Discontinuous Deformation Analysis (DDA). The choice of a particular method of analysis depends on the objectives of the analysis as well as the compatibility of the analysis tool and the desired results. Another key consideration is the availability of input data vis-à-vis the material properties and structural configuration.

Finite Element Modelling (FEM)

In FEM, the complex structure defining a continuum is discretized into simpler parts called finite elements. These elements are then re-connected at nodes. This process establishes equations for static equilibrium which are then solved for obtaining displacements and stresses for each finite element. These results are interpolated over the entire structure to give the approximate behavior of the structure (Cook, Malkus, & Palesha, 1989, pp. 1-4).

The basic origin of FEM lies in the displacement based stiffness method of analysis. In this approach the displacements of the structural nodes or degrees of freedom (DOF), are represented as a dependent on the stiffness matrix and load matrix. A general form of simpler stiffness matrix equation for the structural solution is shown in Figure 3.1.

$$\begin{Bmatrix} f_1 \\ f_2 \\ f_3 \\ . \\ . \\ . \\ f_n \end{Bmatrix} = \begin{bmatrix} k_{11} & k_{12} & k_{13} & \dots & k_{1n} \\ k_{21} & k_{22} & k_{23} & \dots & k_{3n} \\ k_{31} & k_{32} & k_{33} & \dots & k_{3n} \\ . & & & & . \\ . & & & & . \\ . & & & & . \\ k_{n1} & k_{n2} & k_{n3} & \dots & k_{nn} \end{bmatrix} \begin{Bmatrix} d_1 \\ d_2 \\ d_3 \\ . \\ . \\ . \\ d_n \end{Bmatrix}$$

Figure 3.1: General form of stiffness matrix equation for the structural solution in FEM

Three types of finite elements; line, plane and solid elements are used to represent linear, planar and 3D elements of the structure respectively (Figure 3.2, Figure 3.3 and Figure 3.4).

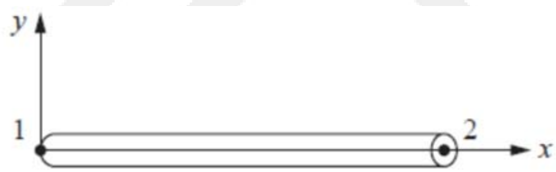

Figure 3.2: Linear element discretization to Line element in FEM

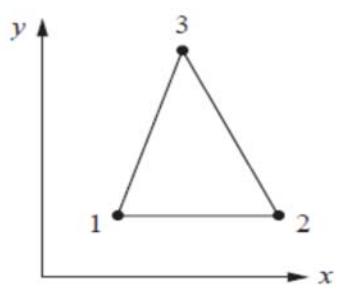

Figure 3.3: Planar element discretization to Plane element in FEM

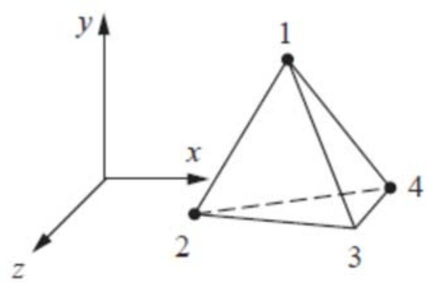

Figure 3.4: 3D element discretization to solid element in FEM

The accuracy of the FEM model depends on the type and number of element used, assumptions about the behavior of the elements as well as the data input for defining the material, geometric properties, constraints and boundary conditions of the actual phenomena.

FEM based approaches for Modelling

To represent masonry, different strategies and several solution methods have been developed in the last few decades. Currently, depending on the need and complexity of the historical masonry structure to be modelled, three main strategies for modelling masonry in FEM are - detailed micro-modelling, simplified micro-modelling and macro-modelling (Lourenço, 1996; Lourenço, Rots, & Blaauwendraad, 1995).

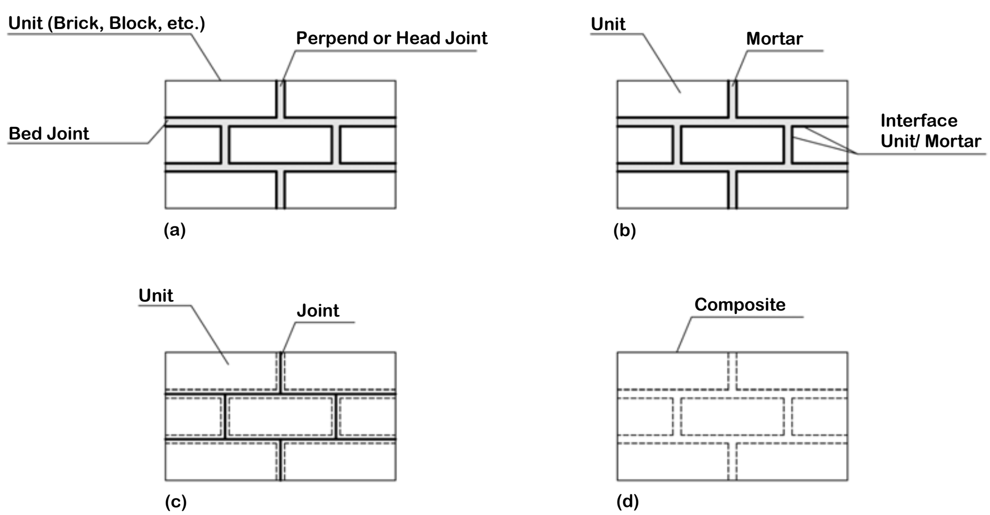

Figure 3.5: Modelling strategies for masonry structures: (a) masonry sample; (b) detailed micro-modelling; (c) simplified micro-modelling; (d) macro-modelling
Source: Lourenço (1996, p. 12)

In *detailed micro-modelling* all the elements of masonry; the units, mortar and unit/mortar interface are modelled separately (Figure 3.5-b) and the anisotropic mechanical properties of both mortar and unit are taken into account (Lourenço et al., 1995, p. 315). This approach provides the most accurate representation of masonry in an analytical environment, as it allows us to understand different failure mechanisms of masonry structures. However, this simulation strategy with its large number of joints and hence degrees of freedom, requires an intensive computational effort. Additionally, the structural parameters required for detailed micro-modelling may not be accurately known due to the uncertainties attached to the material characterization of the historic structures. Hence this type of modelling is best applied to structural elements or part models (Lourenço, 2002, p. 304).

In case of *simplified micro-modelling*, the units are expanded to represent both units and mortar material while the behavior of mortar joints and unit/mortar interface are massed together (Figure 3.5-c). The expanded units ensure that the geometry remains unchanged (Lourenço et al., 1995, p. 316). This representation enables a reduction of degree of freedom but accuracy is lost as mechanical properties of mortar are ignored.

For the *macro-modelling* approach, units, mortar and unit/mortar interface are modelled together in a homogeneous continuum (Figure 3.5-d) as the interaction between units and mortars is negligible for the global structural behavior (Lourenço et al., 1995, p. 316). This approach minimizes the number of degrees of freedom also mesh generation is easier and its intensity is reduced, as the location of the masonry units is not considered. It is appropriate to use macro-modelling when the structures are made of sufficiently large solid walls, as the stresses would be more or less uniform across or along the macro-length (Lourenço, 2002, pp. 304-305). Though the homogenization could lead to inappropriate damage simulation it is the best approach when dealing with buildings with large halls where collapse is generally caused by the loss of equilibrium in limited portions of the building.

Discrete Element Method (DEM)

DEM models are formed by representing the masonry units as an assemblage of distinct blocks and the joints are modelled as contact surfaces between blocks. It is possible to model the non-linear behavior of the masonry including large displacements and even complete detachment in this approach. As DEMs are non-linear in solution, the iterations requires intensive computational effort. Hence this kind of analysis is best suited for small structures with simple geometry and uniformly shaped masonry elements rather than large complex structures. Furthermore, this approach requires detailed material properties, including those pertaining to the inelastic behavior, of both the masonry units as well as the mortar.

Principles of Analytical Modelling

In analytical modelling the aim is to represent the behavior of a real structure in mathematical terms. The simulation of historical masonry constructions pose challenges due to the complexity of their geometry and construction material. Independent of the approach used, idealization of geometry and structural behavior are needed, to successfully represent and analyze the behavior of the historical structures (Lourenço, 2002, p. 319).

Idealization of Geometry

The geometry can be represented through the use of linear elements, two-dimensional elements, shell elements or fully three-dimensional elements (Lourenço, 2001, p. 98). As historical structures have complex geometry it is difficult to concretize under what circumstances it is appropriate to apply a particular idealization of geometry. Therefore, as long as the representation is considered acceptable for the problem being analyzed, the geometric idealization should be kept as simple as possible (Lourenço, 2002, p. 312).

Idealization of Structural Behavior

For the analysis of masonry structures, the basic idealizations of structural behavior are linear elastic behavior, plastic behavior and non-linear behavior (Lourenço, 2002, p. 313).

Linear Elastic Analysis assumes that the material obeys Hooke's Law, and is only able to trace the response of the structure within the elastic range. It fails to simulate the realistic behavior of masonry structures, which have minimal tension carrying capacity. Masonry due to its low tensile strength exhibits a complex non-linear response even at low stress levels (Roca et al., 2010, p. 310). Notwithstanding, this analysis technique has been effectively used in defining the structural behavior of large masonry structures with complex geometries. The technique has been used amongst others, to study the effect of the ongoing settlement of the Tower of Pisa's colonnade (Maachi, Ruggeri, Eusebio, & Moncecchi, 1993) and to understand the global structural behavior of the Colosseum (Croci, 1995).

Plastic or Limit Analysis is performed to assess the structural load at failure. This technique can be used for the analysis of historical masonry structures if a zero tensile stress is assumed while ignoring the effects of previous loadings. Its application is impractical for larger structures (Lourenço, 2002, p. 314).

Non-Linear Analysis is the most accurate idealization technique for the analysis of masonry structures. It allows the behavior of the structure to be observed from the elastic range till complete failure. It allows for the construction sequence to be included in the analysis and can also assist in understanding the structural problems related to material degradation. However, this technique requires non-linear properties of materials which can only be assessed through laboratory and/or in-situ mechanical tests.

The stress-strain curves followed in linear and non-linear analysis can be seen in Figure 3.6. Linear analysis follows first linear approach and the results are verified within allowed elastic limit states. While non-linear analysis continues to analyses structure even after some local elements have breached elastic limit and redistributes forces accordingly. Hence with non-linear analysis the complete behavior of the structure including stress distribution, deformational behavior and the failure mechanism can be studied. While linear elastic analysis, only provides general information about stress distribution and deformational behavior of the structure (Lourenço, 2002, p. 316).

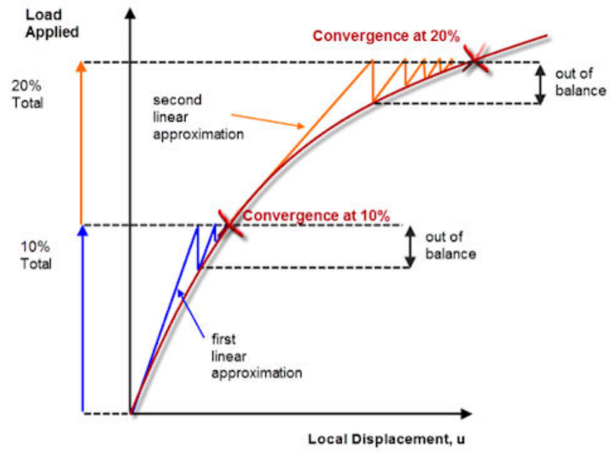

Figure 3.6: Stress-Strain curves followed in linear and non-linear analysis
Source: Digital Engineering

However, the number of parameters required for linear elastic analysis is much less in comparison to those required by non-linear analysis. To carry out linear elastic analysis only elastic properties of the materials and maximum allowable stresses are required while non-linear analysis requires besides elastic properties, strength of the materials as well as inelastic information; the stress–strain diagrams, material dilation data, mohr-coulomb material failure criteria etc. (Lourenço, 2001, 2002; Roca et al., 2010).

The choice of idealization of structural behavior is thus dependent on the availability of the material properties, the objectives and the scale of the problem being analyzed.

3.2. Analysis Techniques and Tools

Lahore Museum with a footprint of 5225 m^2 (56,241.5 ft^2), predominantly has a Masonry Bearing Wall system that is active in carrying all or most vertical loads such as gravity loads and live loads as well as lateral loads such as seismic loads. The masonry unit is fired clay solid brick while both lime and cement mortar have been used as binding agent. The building houses various structural elements that can be broadly classified into Continuum entities such as slabs, walls, domes etc. and Frame entities such as Beams, Columns etc. It is subjected to normal occupancy loads such as storage, accessible roofs etc. Detailed discussion has been presented in Chapter 2.

There was no experimental data available for the material characterization of the building. Hence, for the purpose of this study, the basic mechanical properties of the materials i.e. unit weight, Modulus of Elasticity, and Poisson's Ratio have been adopted from literature. For details see Section 2.6.

The main objective of the study was to simulate the structure, from the available structural configuration information, adopted material properties and applied loads, to understand the global structural behavior and obtain results for stresses and deformations of the main load bearing system i.e. masonry walls.

In light of the discussion presented in Section 3.1, and keeping in mind the scale of the building and the available material data, FEM macro-modelling is the best suited approach for developing analytical model of the Lahore Museum building. Furthermore, linear elastic analysis was conducted. Non-linear analysis was considered unsuitable for the purpose of this study as detailed mechanical properties pertaining to inelastic behavior of the materials, which are a pre-requisite, were missing. Also due to the structural non-uniformity in geometry and stiffness, this technique would render convergence issues among iterations for the museum building. Last but not the least as the scale of the building is very large, application of non-linear FEM analysis would require intensive computational time and large storage space.

As an attempt to examine the impact of the historical architectural and structural interventions, four models were developed, each corresponding to the subsequent construction stages experienced by the building in its service life (Figure 2.56, Figure 2.57, Figure 2.58, Figure 2.59, Figure 2.60 and Figure 2.61). The analysis was independently carried out on the four reconstituted geometries, to better understand the phenomenon of deformation and possibly damage.

Interaction of the structure with the soil has also been taken into account by modelling the support conditions of the structure with springs at the base. The stiffness characteristics of the spring have been kept equivalent to those presented by the considered soil type.

For study and evaluation of the analytical models CSI-SAP2000 software has been used. The software, based on FEM approach, has an integrated graphical user interface for structural analysis and design.

To understand the global structural behavior, all structural elements and their respective geometries housed in the museum building have been modeled in SAP2000. The brief details of the representation of structural elements used in SAP2000 is presented later in this section.

All imposed loads; self-weight, superimposed dead loads, live loads and seismic loads, were modelled in SAP2000, as per UBC97/ BCP-2007 codes. The load combinations formed by coupling the various loads, based on principle of linear superposition have been applied in SAP2000.

Structural Sections

As stated earlier Lahore Museum houses multiple structural elements that can be broadly classified as 1-Dimensional Line entities and 2-Dimensional Continuum entities.

In case of continuum elements such as masonry walls and domes, shell elements can be used in SAP 2000. Shell modelling yield results in the form of stresses based on which quantitative assessments can be made. They also prove advantageous in the creation of geometrical model by reducing computational effort.

Shell element can be a four node quadrilateral or a three node triangular formulation, with the quadrilateral formulation being more accurate of the two (Figure 3.7) (CSI, 2013, p. 161). Each shell element has its own local coordinate system used to define section properties, loads, and output. All six degrees of freedom are active at each of its connected joints (CSI, 2013, p. 164).

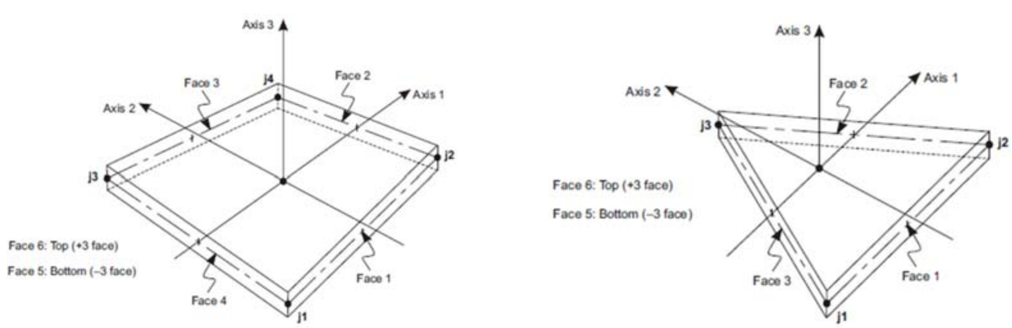

Figure 3.7: Area Element Joint Connectivity and Face Definitions
Source: CSI (2013, p. 160)

The analytical notations and sign conventions used in SAP2000 for shell elements can be seen in Figure 3.8. In the analytical model, quadrilateral formulation has been used. Furthermore, shell-thin elements were applied for roofing, slabs etc., while shell-thick elements were applied for masonry bearing walls in order to include the stiffness contributed by shear deformations.

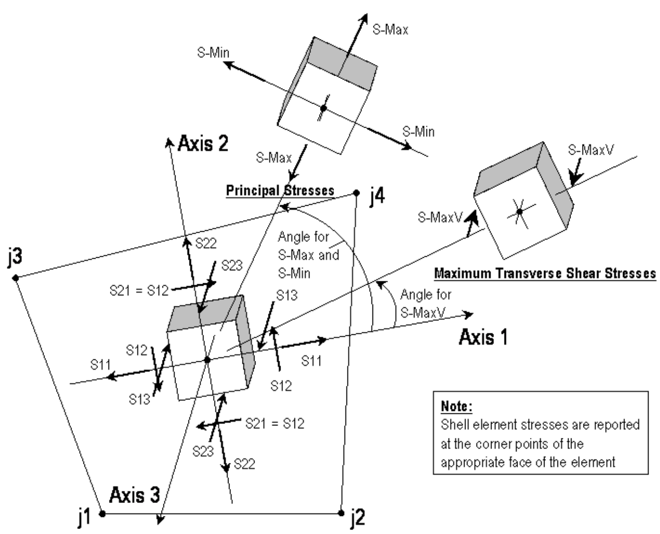

Figure 3.8: Shell Element In plane and Out of Plane Stresses
Source: CSI (2013, p. 191)

For line elements SAP2000 offers Frame elements. A Frame element is modelled as a straight line connecting two points (CSI, 2013, p. 90). Like shell elements, each frame elements has its own local coordinate system used to define section properties, loads, and output, with six degrees of freedom active at both of its connected joints. If a member has to be modelled that does not transmit moments at the ends, then both bending rotations can be released at both ends while the torsional rotation is released at either end (CSI, 2013, pp. 91-92). The analytical notations and sign conventions used in SAP2000 for frames elements can be seen in Figure 3.9.

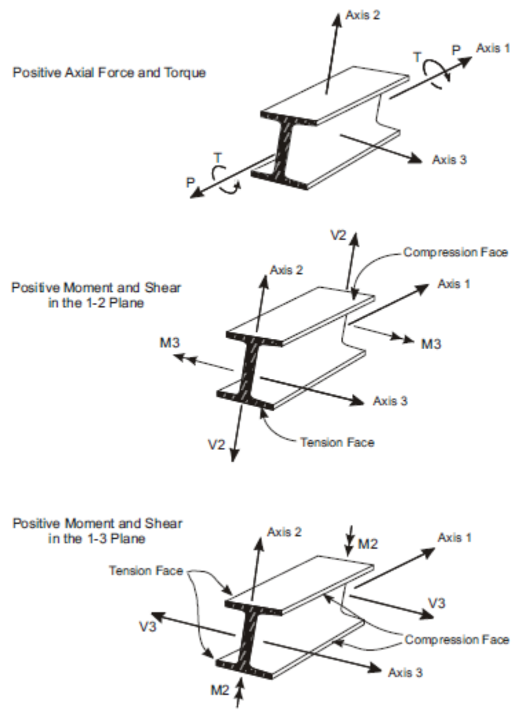

Figure 3.9: Frame Element Internal Forces and Moments
Source: CSI (2013, p. 127)

The data gathered from the site survey was used for definitions of frame and shell elements. The various frame and shell sections defined on the basis of existing structural entities are presented in Table 9 and Table 10 respectively.

Table 9: *Frame Section Properties*

Section Name	Material	Shape	Depth mm	Width mm	t_f mm	t_w mm
ST1-C-R-CI-12	ST1-Cast Iron	Pipe	304.8			6.3
ST1-C-S-B-33X33	ST1-Masonry-Old	Rectangular	838.2	838.2		
ST1-C-S-B-36X36	ST1-Masonry-Old	Rectangular	914.4	914.4		
ST1-C-S-B-63X63	ST1-Masonry-Old	Rectangular	1600.2	1600.2		
ST1-CB-S 2x4	ST1-Steel A36	Channel	101.6	50.8	6.1	4.3
ST1-DIB-S-DxW 8x4 SD	ST1-Steel A36	SD Section				
ST1-IB-S-DxW 12x6	ST1-Steel A36	I/Wide Flange	304.8	152.4	18.2	10.2
ST1-IB-S-DxW 16x6	ST1-Steel A36	I/Wide Flange	406.4	152.4	21.5	14.0
ST1-IB-S-DxW 6x2	ST1-Steel A36	I/Wide Flange	152.4	50.8	8.8	6.4
ST1-IB-S-DxW 8x4	ST1-Steel A36	I/Wide Flange	203.2	101.6	10.2	7.1
ST1-P-W DxW 3x2	ST1-Deodar Wood	Rectangular	76.2	50.8		
ST1-P-W DxW 4x2.5	ST1-Deodar Wood	Rectangular	101.6	63.5		
ST1-P-W-DxW 3x2	ST1-Deodar Wood	Rectangular	76.2	50.8		
ST1-P-W-DxW 4x4	ST1-Deodar Wood	Rectangular	101.6	101.6		
ST1-P-W-DxW 5x3	ST1-Deodar Wood	Rectangular	127.0	76.2		
ST1-P-W-DxW 5x7	ST1-Deodar Wood	Rectangular	127.0	177.8		
ST2-IB-S-DxW 12x6	ST2-A36	I/Wide Flange	304.8	152.4	18.2	10.2
ST2-IB-S-DxW 16x6	ST2-A36	I/Wide Flange	406.4	152.4	21.5	14.0
ST2-IB-S-DxW 20x7.5	ST2-A36	I/Wide Flange	508.0	190.5	25.7	15.2
ST2-IB-S-DxW 6x2	ST2-A36	I/Wide Flange	152.4	50.8	8.8	6.4
ST2-P-W DxW 4x4	ST2-Deodar Wood	Rectangular	101.6	101.6		
ST2-P-W DxW 6x3	ST2-Deodar Wood	Rectangular	152.4	76.2		
ST2-TI-S DxW 3x3	ST2-A36	Tee	76.2	76.2	9.7	9.7

Table 10: Continued

Section Name	Material	Shape	Depth mm	Width mm	t_f mm	t_w mm
ST2-P-W DxW 6x6	ST2-Deodar Wood	Rectangular	152.4	152.4		
ST3-C-C-C-15	ST3-Concrete	Circle	381.0			
ST3-C-C-RC-15	ST3-Concrete	Circle	381.0			
ST3-C-S-B-13.5x13.5	ST3-Masonry	Rectangular	342.9	342.9		
ST3-C-S-B-24x18	ST3-Masonry	Rectangular	457.2	609.6		
ST3-C-S-C-19x19	ST3-Concrete	Rectangular	482.6	482.6		
ST3-DB-RC-DxW 12x6	ST3-Concrete	Rectangular	304.8	152.4		
ST3-DB-RC-DxW 18x12	ST3-Concrete	Rectangular	457.2	304.8		
ST3-DB-RC-DxW 24x12	ST3-Concrete	Rectangular	609.6	304.8		
ST3-InB-RC-DxW 12x9	ST3-Concrete	Rectangular	304.8	228.6		
ST3-InB-RC-DxW 24x12	ST3-Concrete	Rectangular	609.6	304.8		
ST3-LtB-DxW-12x22.5	ST3-Concrete	Rectangular	304.8	571.5		
ST3-LtB-DxW-6x13.5	ST3-Concrete	Rectangular	152.4	342.9		
ST3-LtB-DxW-6x18	ST3-Concrete	Rectangular	152.4	457.2		
ST3-LtB-DxW-6x22.5	ST3-Concrete	Rectangular	152.4	571.5		
ST3-LtB-DxW-6x27	ST3-Concrete	Rectangular	152.4	685.8		
ST3-LtB-DxW-6x9	ST3-Concrete	Rectangular	152.4	228.6		
ST4-C-S-B-9x9	ST4-Masonry	Rectangular	228.6	228.6		
ST4-DB-RC-DxW 18x12	ST3-Concrete	Rectangular	457.2	304.8		
ST4-DB-RC-DxW 24x12	ST4-Concrete	Rectangular	609.6	304.8		
ST4-IB-S-DxW 9x4	ST4-A36	I/Wide Flange	228.6	101.6	11.7	7.6
ST4-InB-RC-DxW-18x9	ST4-Concrete	Rectangular	457.2	228.6		
ST4-InB-RC-DxW-24x12	ST4-Concrete	Rectangular	609.6	304.8		
ST4-LtB-DxW-6x13.5	ST3-Concrete	Rectangular	152.4	342.9		
ST4-LtB-DxW-6x18	ST4-Concrete	Rectangular	152.4	457.2		
ST4-LtB-DxW-6x9	ST4-Concrete	Rectangular	152.4	228.6		

Note: ST1, ST2, ST3 and ST4 stands for Construction Stage 1, 2, 3 and 4 respectively

Table 10: *Area Section Properties*

Section Name	Material	Type	Thickness (mm)
ST1-3D-W-B-13.5	ST1-Masonry-Old	Shell-Thick	342.9
ST1-3D-W-B-18	ST1-Masonry-Old	Shell-Thick	457.2
ST1-3D-W-B-22.5	ST1-Masonry-Old	Shell-Thick	571.5
ST1-3D-W-B-27in	ST1-Masonry-Old	Shell-Thick	685.8
ST1-3D-W-B-31.5	ST1-Masonry-Old	Shell-Thick	800.1
ST1-3D-W-B-54	ST1-Masonry-Old	Shell-Thick	1371.6
ST1-3D-W-B-67.5	ST1-Masonry-Old	Shell-Thick	1714.5
ST1-3D-W-B-9	ST1-Masonry-Old	Shell-Thick	228.6
ST1-DECK	-	Shell-Layered	120.65
ST1-Deck Change ST3	-	Shell-Layered	95.25
ST1-Deck Change ST4	-	Shell-Layered	95.25
ST1-S1	-	Shell-Thin	101.6
ST1-S2	-	Shell-Layered	120.65
ST1-S3	-	Shell-Layered	69.85
ST1-S4	ST1-Lime Concrete	Shell-Thin	101.6
ST1-SVT-L1	-	Shell-Layered	69.85
ST1-SVT-L2	-	Shell-Layered	69.85
ST2-3D-W-B-13.5	ST2-Masonry	Shell-Thick	342.9
ST2-3D-W-B-18	ST2-Masonry	Shell-Thick	457.2
ST2-3D-W-B-22.5	ST2-Masonry	Shell-Thick	571.5
ST2-3D-W-B-27	ST2-Masonry	Shell-Thick	685.8
ST2-3D-W-B-9	ST2-Masonry	Shell-Thick	228.6
ST2-S1	ST2-Lime Concrete	Shell-Thin	101.6
ST2-S2	-	Shell-Layered	120.65
ST2-S3	ST2-Lime Concrete	Shell-Thin	101.6
ST3-3D-W-B-13.5	ST3-Masonry	Shell-Thick	342.9
ST3-3D-W-B-18	ST3-Masonry	Shell-Thick	457.2
ST3-3D-W-B-22.5	ST3-Masonry	Shell-Thick	571.5
ST3-3D-W-B-27	ST3-Masonry	Shell-Thick	685.8
ST3-3D-W-B-9	ST3-Masonry	Shell-Thick	228.6
ST3-3D-W-C-22.5	ST3-Concrete	Shell-Thick	571.5
ST3-S5-RC-6C+6F	ST3-Concrete	Shell-Thin	152.4
ST3-S6-RC-6C+6F	ST3-Concrete	Shell-Thin	152.4
ST3-S7-RC-4C+6F	ST3-Concrete	Shell-Thin	101.6
ST4-3D-W-B-13.5	ST4-Masonry	Shell-Thick	342.9

Table 11: Continued

Section Name	Material	Type	Thickness (mm)
ST4-3D-W-B-18	ST4-Masonry	Shell-Thick	457.2
ST4-3D-W-B-22.5	ST4-Masonry	Shell-Thick	571.5
ST4-3D-W-B-9	ST4-Masonry	Shell-Thick	228.6
ST4-S5-RC-6C+6F	ST4-Concrete	Shell-Thin	152.4
ST4-S6-RC-6C+6F	ST4-Concrete	Shell-Thin	152.4
ST4-S7-RC-6C	ST4-Concrete	Shell-Thin	152.4

Note: ST1, ST2, ST3 and ST4 stands for Construction Stage 1, 2, 3 and 4 respectively

Formation of Model Geometry

Lahore Museum is a complex structure. Though there are certain regularities but the building houses various structural systems, which are quite difficult to follow and formulate in SAP2000 alone. AutoCAD was used in the modeling phase to draw complete geometry using centerline modeling principles. The structural geometry was detailed in AutoCAD as 3D faces for Continuum elements such as walls and slabs, and as lines for frame elements like beams, columns etc. The models were then imported into SAP2000, using AutoCAD and SAP2000 interoperability, to carry out the analysis. The meshing chosen in SAP2000 was the best choice with regards to computational time and the desired results. The joint connectivity issue was addressed using SAP2000 in-built “Edge Constraint” command.

Four separate models were created, each corresponding to a structural configuration experienced by the building at a certain historical moment. 3D models of each stage in AutoCAD and the resultant SAP2000 models can be seen in Figure 3.10, given below.

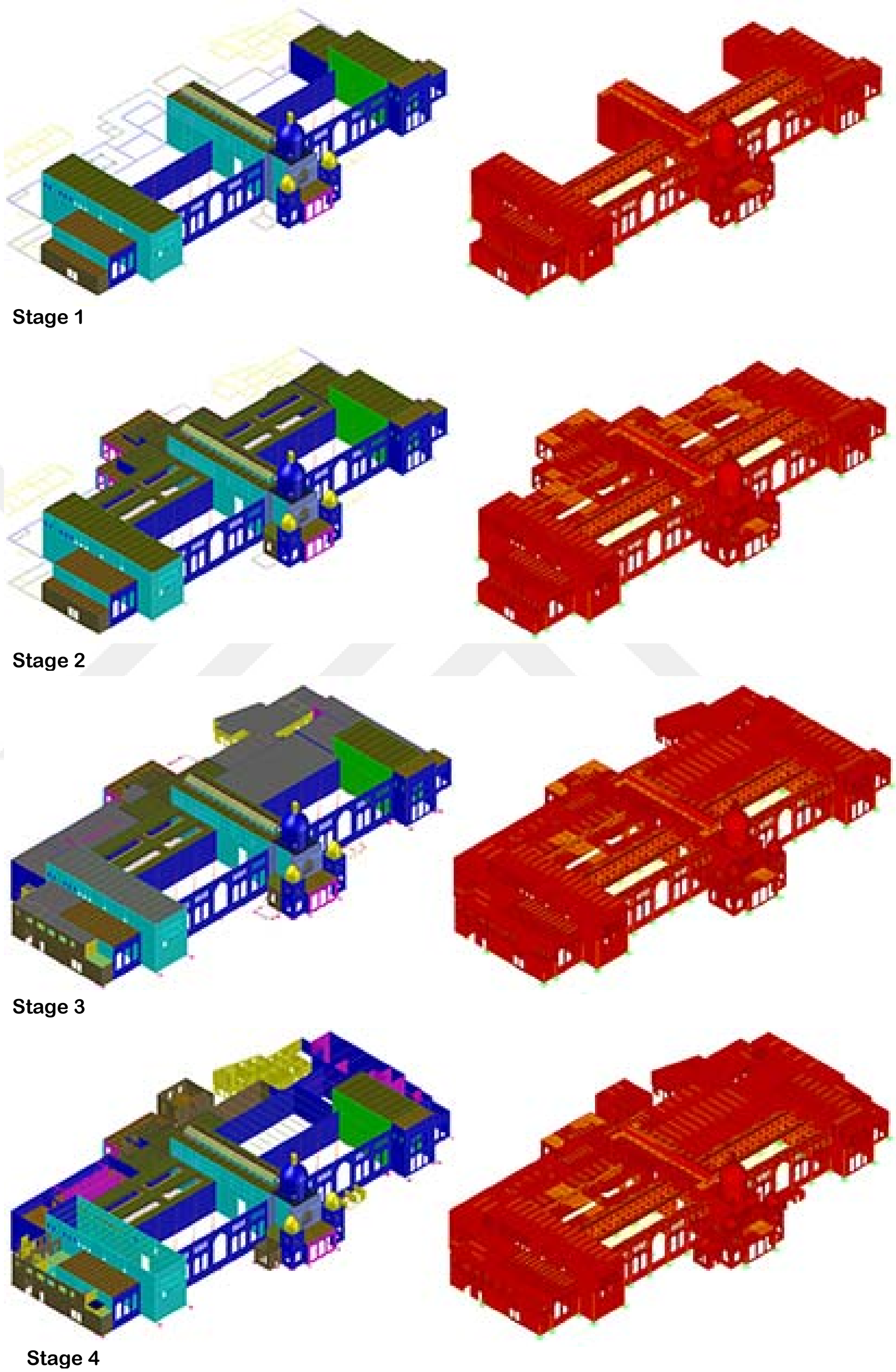

Figure 3.10: 3D Models of the four reconstituted geometries of the building
AutoCAD models (left) SAP2000 models (right)

Material Properties

For the adopted approach i.e. FEM macro modelling, only basic mechanical properties like unit weight, MoE, Poisson's ratio and Shear Modulus were required by SAP2000. Material properties, their collection, rationalization etc. has been discussed in detail in Chapter 2, Section 2.6. The basic material properties applied are presented here in tabular form and can be seen from Table 11.

Table 11: *Basic Mechanical Properties of Materials*

Material	**Unit Weight (kg/m^3)**	**Poisson Ratio**	**Modulus of Elasticity (MPa)**
Brick Masonry (Brick + Lime Mortar)	1939	0.17	13789
Brick Masonry (Brick + Cement Mortar)	1939	0.17	9653
Reinforced Concrete (Old)	2404	0.2	24821
Reinforced Concrete (New)	2404	0.2	21546
Cast Iron	7147	0.2	99974
Steel	7852	0.3	206842
Wood (Deodar)	641	0.3	9315

As analytical models for the museum building have been developed in four distinct stages corresponding to four alterations in its service life. The material aging, degradation and creep were simulated using a simplified approach involving reduction of MoE in subsequent stages.

Boundary Conditions

The boundary conditions for structural solution needed is the sub-structure foundations for the analytical model. Initially the model was evaluated with pin and fixed supports. But to simulate the approximate behavior of soil, springs were applied at the base of walls and columns.

The allowable bearing capacity of the soil was calculated at 145.95 kPa (1.52 tons/ft^2). Corresponding Modulus of Subgrade reactions were calculated and applied to structural models in the form of joint and line springs, under columns and wall supports respectively. Various moduli of subgrades calculated and applied for modelling are presente in Table 12 and Table 13.

Table 12: *Line Spring values for various wall thickness*

Wall Thickness (W) (m)	**Foundation Width (2W) (m)**	**Line Spring (Gravity Direction) (kN/m/m)**	**Line Spring (Lateral Direction) (kN/m/m)**
0.229	0.457	7900.0	2633.3
0.343	0.686	11850.0	3950.0
0.457	0.914	15800.1	5266.7
0.571	1.143	19750.1	6583.4
0.686	1.372	23700.1	7900.0
0.800	1.600	27650.1	9216.7
1.372	2.743	47400.2	15800.1
1.714	3.429	59250.2	19750.1

Table 13: *Joint Spring values for various column sizes*

Column Size Diameter Length x Width (mm)	**Foundation Area (m^2)**	**Joint Spring - Gravity (Z Direction) (kN/m)**	**Joint Spring - Lateral (X & Y Direction) (kN/m)**
300	0.581	10032.5	3344.2
838 x 838	2.810	48557.5	16185.8
914 x 914	3.344	57787.5	19262.5
1600 x 1600	10.242	176974.2	58991.4

Maximum Allowable Stresses

The basic intrinsic property used in codes for the evaluation of the Masonry is its ultimate compressive strength, f'_m. As no experimental data was available the value for compressive strength, f'_m, of masonry for the purpose of this study has been taken from literature. A conservative approach was adopted and the value corresponding to the weakest form of masonry was used. The value for compressive strength, f'_m, of masonry used is 11,031 kPa (1600 psi) (International Conference of Building Officials, 1997, p. 203, Volume 2, Table 21-D).

The limit states for the stresses in masonry were also adopted from UBC-97. The allowable compressive strength threshold for masonry was taken was 0.25 f'_m, which equals to 2758 kPa (400 psi) (International Conference of Building Officials, 1997, p. 218, Volume 2, Section 2107.3).

The allowable tensile strength threshold for the masonry used is 207 kPa (30 psi) normal to the head joints and 104 kPa (15 psi) normal to the bed joints (International Conference of Building Officials, 1997, p. 232, Volume 2, Table 21-I).

Structural Analysis Definitions

Various structural load cases were applied for the analysis of the Museum building.

Modal Analysis was carried out to evaluate the natural vibration frequencies of the building. The time periods and modes of vibration were calculated using Eigen vectors type and 30 modes were calculated for each stage of the building.

Linear Static Analysis was carried out using the self-weight of the building for the **Dead Loads**. The **Superimposed Dead Loads (SDL)** were calculated using the structural geometries and roof/ floor finishes while **Live Loads** of the structure were adopted from UBC-97/BCP-2007 based on the occupancy criteria. Intensities of SDL and Live loads are presented in Table 14.

Table 14: *Applied Area Loads*

Section Name	SDL (psf)	Live (psf)	Details	Remarks
ST1-DECK	27	20	4" Lime concrete and wood included in section definition, load applied for metal and brick tiles	Roof Load
ST1-Deck St3 change	5	20	Nominal	Roof Load
ST1-Deck St4 change	5	20	Nominal	Roof Load
ST1-S1	40	20	Self-weight of 4" lime from model. Brick tiles+ Mud applied with 120 psf density	Roof Load
ST1-S2	40	20	Self-weight of 4" lime from model. Brick tiles +Soil +Board applied with 120 psf density	Roof Load
ST1-S3	25	20	Lime + wood from model. GI and Brick tile applied	Roof Load
ST1-S4	40	20	4" from model. Rest Applied.	
ST1-SVT-L1	20	0	Lime and Wood from Model. Brick Tiles applied.	Inaccessible roof
ST1-SVT-L2	20	0	Lime and Wood from Model. Brick Tiles applied.	Inaccessible roof
ST1-SVT-L2+Domes Load	1200	0	Applied at localized area where domes were present	Inaccessible roof
ST2-S1	40	20	Refer ST1-S1	Roof Load
ST2-S2	40	20	Refer ST1-S2	Roof Load
ST2-S3	27	20	Refer ST1-S3	Roof Load
ST3-S5-RC-6C+6F	60	20	Concrete from model. 6" Finishes applied at 120psf	Roof Load
ST3-S6-RC-6C+6F	60	100	Concrete from model. 6" Finishes applied at 120psf	Service Floor

Table 15: Continued

Section Name	SDL (psf)	Live (psf)	Details	Remarks
ST3-S7-RC-4C+6F	60	100	Concrete from model. 6" Finishes applied at 120psf	Service Floor
ST4-S5-RC-6C+6F	60	20	Concrete from model. 6" Finishes applied at 120psf	Roof Load
ST4-S6-RC-6C+6F	60	100	Concrete from model. 6" Finishes applied at 120psf	Service Floor
ST4-SX-RC-6C	40	250	On top only	Water Load

For **Seismic Loads** both the Equivalent Lateral Static Procedure as well as Response Spectrum Analysis were carried out. The Design Spectra used was as per UBC-97/BCP-2007 (Figure 3.11). For the Museum building C_a and C_v values were adopted from BCP-2007 for Seismic Zone 2A with Seismic Zone Factor (Z) of 0.15. The values C_a and C_v are 0.22 and 0.32 respectively (Table 15 & Table 16).

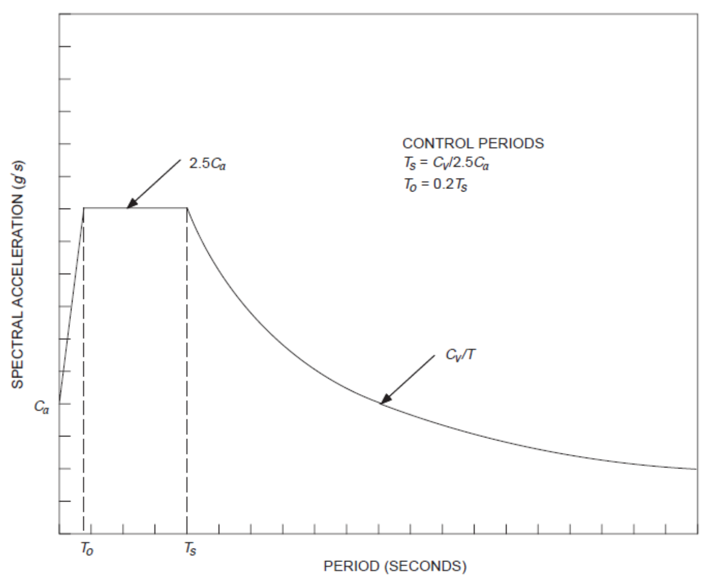

Figure 3.11: Design Response Spectra
Source: Uniform Building Code (UBC 97), Volume 2, p. 38

Table 15: *Seismic Coefficients C_a*

Soil Profile Type	Seismic Zone Factor, Z				
	Z = 0.075	**Z = 0.15**	**Z = 0.2**	**Z = 0.3**	**Z = 0.4**
S_A	0.06	0.12	0.16	0.24	$0.32N_a$
S_B	0.08	0.15	0.20	0.30	$0.40N_a$
S_C	0.09	0.18	0.24	0.33	$0.40N_a$
S_D	0.12	**0.22**	0.28	0.36	$0.44N_a$
S_E	0.19	0.30	0.34	0.36	$0.36N_a$
S_F	See Footnote				

Footnote: Site specific geotechnical investigation and dynamic response analysis shall be performed to determine seismic coefficients for soil type S_F
Source: NESPAK (2007, p. 54)

Table 16: *Seismic Coefficients C_v*

Soil Profile Type	Seismic Zone Factor, Z				
	Z = 0.075	**Z = 0.15**	**Z = 0.2**	**Z = 0.3**	**Z = 0.4**
S_A	0.06	0.12	0.16	0.24	$0.32N_v$
S_B	0.08	0.15	0.20	0.30	$0.40N_v$
S_C	0.13	0.25	0.32	0.45	$0.56N_v$
S_D	0.18	**0.32**	0.40	0.54	$0.64N_v$
S_E	0.26	0.50	0.64	0.84	$0.96N_v$
S_F	See Footnote				

Footnote: Site specific geotechnical investigation and dynamic response analysis shall be performed to determine seismic coefficients for soil type S_F
Source: NESPAK (2007, p. 54)

The loads were coupled as per code to form load combinations. Different load combinations applied in the analysis are as follows

1.0D

1.0D + 1.0L

1.0D + 1.0L ± 1.0EQX ± 0.3EQY

1.0D + 1.0L ± 0.3EQX ± 1.0EQY

3.3. Analyses of the Results

The predominant structural system in the museum building is the masonry load bearing walls system. Thus foremost attention was given to this main load bearing system to narrow down the concerns for the structure based on structural behavior and performance depicted by results. Other structural systems are localized and will need to be studied in detail with the help of detailed material properties and part models.

3.3.1. *Modal Analysis*

As discussed, FEM modelling involves assembling and solving mathematical matrices. The prominent matrices are the mass and stiffness matrices and although load vectors and boundary conditions also come into play but global stability is dependent upon mass and stiffness distribution. Modal Analysis, which provides time periods and corresponding mode shapes should give an overview of the structural behavior and should be realistic. The first 30 modes, calculated during the modal analysis, for each stage provided the cumulative mass participation ratios (MRP) of more than 90% in both the X and Y direction. For the developed analytical models, modal time periods, mode shapes and mass participation ratio (MRP) corresponding to the first 12 modes are presented in Table 17 while the first mode shape for all four stage can be seen in Figure 3.12.

The most important observation from the mode shapes is that for all four stages, the governing fundamental mode of vibration involves the main dome over space Thd-N/05. Although the dome vibrates but the time periods depict adequate stiffness for the dome. Hence, any activity in the future involving dynamic loads and resonance effects (such as jack hammering etc.) should be taken up with due consideration as it can lead to excitation of forced vibrations in dome. If such an activity is unavoidable, adequate measures should be taken in advance for minimizing the effects.

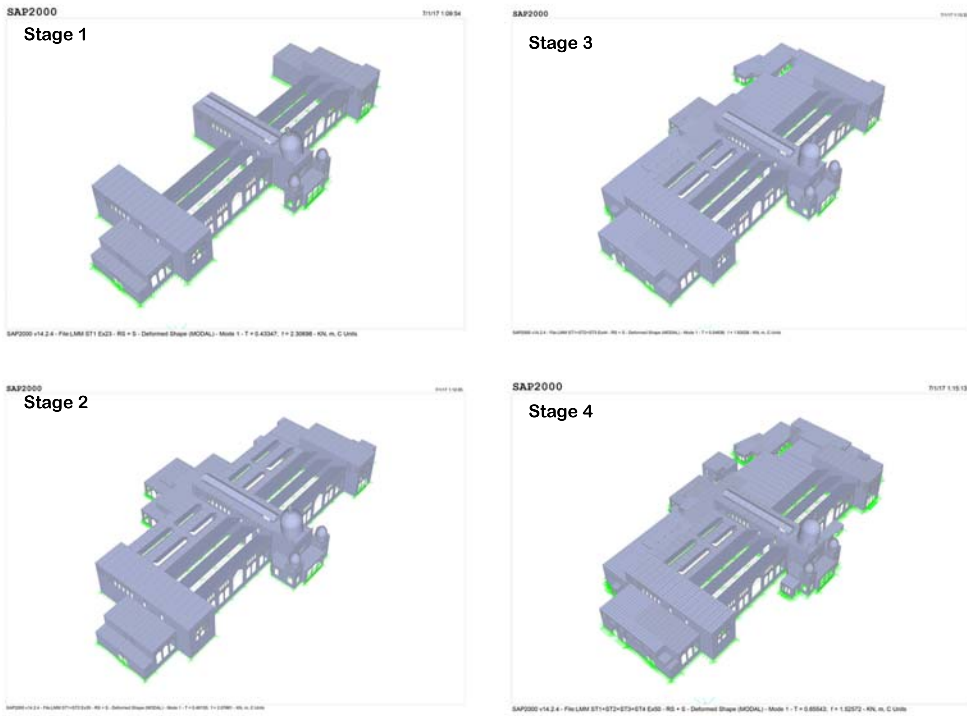

Figure 3.12: First mode shape of all four stages.
Stage 1 (Top Left) Stage 2 (Bottom Left), Stage 3 (Top Right) and Stage 4 (Bottom Right)

Table 17: *Modal Periods and Mass Participation Ratio (MRP)*

Output Case	Mode Number	Stage I			Stage II			Stage III			Stage IV		
		Period (Sec)	Direction (Unitless)	MPR (%)	Period (Sec)	Direction (Unitless)	MPR (%)	Period (Sec)	Direction (Unitless)	MPR (%)	Period (Sec)	Direction (Unitless)	MPR (%)
MODAL	1	0.4335	X-Dir.	3	0.4816	X-Dir.	4	0.5464	X-Dir.	2	0.6554	X-Dir.	1
MODAL	2	0.3701	X-Dir.	15	0.3561	Y-Dir.	35	0.4262	Z-Dir.	1	0.4832	Z-Dir.	1
MODAL	3	0.3434	Y-Dir.	49	0.3391	X-Dir.	17	0.3911	Y-Dir.	1.5	0.4732	X-Dir.	1
MODAL	4	0.3209	X-Dir.	9	0.3274	Y-Dir.	20	0.3907	Y-Dir.	8	0.4624	Y-Dir.	3
MODAL	5	0.3120	Y-Dir.	11	0.3208	Y-Dir.	7	0.3872	X-Dir.	2	0.4449	Z-Dir.	1
MODAL	6	0.2983	X-Dir.	6	0.3131	X-Dir.	36	0.3599	Y-Dir.	0.25	0.4407	X-Dir.	0.001
MODAL	7	0.2945	X-Dir.	1	0.3113	X-Dir.	19	0.3587	Y-Dir.	5	0.4374	Y-Dir.	1
MODAL	8	0.2891	Y-Dir.	3	0.3101	X-Dir.	0.5	0.3519	Z-Dir.	0.01	0.3992	Z-Dir.	0.012
MODAL	9	0.2856	Y-Dir.	4	0.3051	Z-Dir.	2	0.3446	Y-Dir.	18	0.3878	Z-Dir.	1
MODAL	10	0.2819	X-Dir.	17	0.3050	Z-Dir.	1	0.3370	Z-Dir.	1	0.3638	Z-Dir.	0.25
MODAL	11	0.2806	X-Dir.	1	0.2993	Y-Dir.	14	0.3259	X-Dir.	10	0.3469	Y-Dir.	46
MODAL	12	0.2786	X-Dir.	7	0.2982	X-Dir.	1	0.3242	X-Dir.	58	0.3425	X-Dir.	58

3.3.2. *Seismic Analysis*

For seismic analysis, as mentioned earlier, two approaches of application of seismic loads known as "Equivalent Lateral Static Procedure" and "Response Spectrum Analysis" were studied and their results were compared. The parameters used to define the seismic weights is 100% Dead Loads and 20% Live Loads as per UBC-97 clause no. 1630.1.1. The Seismic Response Modification Factor - R is taken as 4.5 (International Conference of Building Officials, 1997, p. 32, Volume 2, Table 16-N) and Importance Factor - I is taken as 1.00 (International Conference of Building Officials, 1997, p. 30, Volume 2, Table 16-K). For the current state of the building i.e. Stage 4, the structural weight of the building is therefore of the order 170,000 kN. The Response Spectrum Analysis applied base shears of the order 13,000kN while the Equivalent Static Procedure yields 20,000kN of base shear. These base shears are 8% and 12% of the structural weight of the building respectively. As Response Spectrum Analysis yields more realistic results of the two approaches its results were used in the study.

When load combinations involving seismic loads are compared with the gravity load combinations, the stress values in case of earthquake load combinations (APPENDIX D; Figure D.1to Figure D.32) are comparable to the results reported for gravity load combinations (Figure 3.16 to Figure 3.19). The seismic loads thus contribute very little to the governing stresses. One of the reason could be that the seismic forces are only 8% to 12% of the structural weight of the building, therefore the vertical/ gravity load combinations are governing the behavior of the building. This is due to the fact that the building is primarily composed of thick Masonry Walls that act as shear walls in resisting lateral loads effectively. Additionally, the building is not a slender structure. Although the height of the galleries is quite high; the building is largely a single storey structure. The base footprint area covered is larger in proportion to its height. Hence, larger length of restraining members is available against the overturning caused by the lateral seismic loads. Furthermore, Lahore city lies in a moderate seismic risk zone due to which the structure exhibits low stress values in case of seismic activity.

3.3.3. *Stress Analysis of Masonry Walls*

Masonry is a brittle structural material that is weak in tension compared to its compressive strength. Unlike ductile materials, its tension behavior is not symmetrical to its compression behavior.

A ductile material, like steel, in case of bending continues to carry both tension and compression stresses till all the fibers along neutral axis yield at the ultimate moment capacity (Figure 3.13).

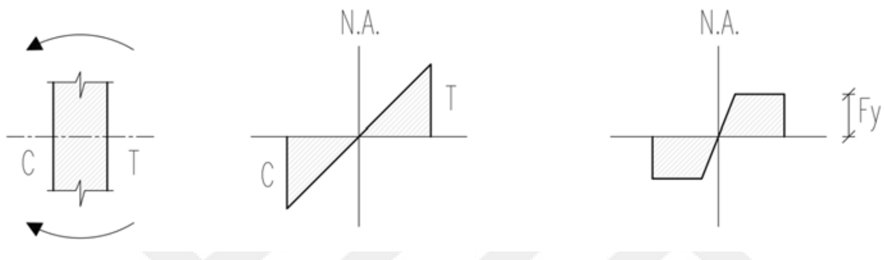

Figure 3.13: Behavior of ductile material – Steel
(a) Under Elastic Stage (b) At Ultimate Stage

On the other hand, brittle materials, like masonry, do not exhibit tension stresses of such magnitudes. In case of unreinforced masonry when tension arises cracks are initiated, generally at right angles to the stresses that cause tension, and stresses are redistributed (Figure 3.14).

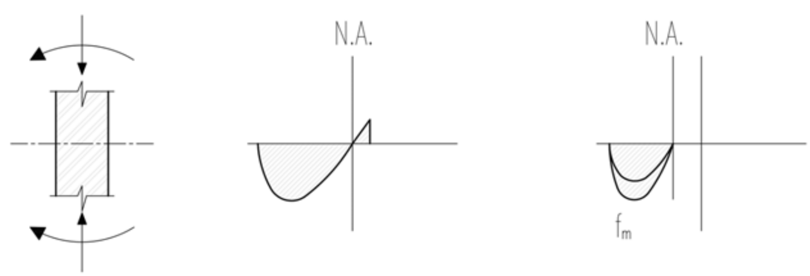

Figure 3.14: Behavior of brittle material – Masonry
(a) Crack Initiation (b) at Ultimate Stage

Hence, the actual behavior of masonry shows that masonry is a non-linear entity. However, the way SAP2000 solves with the Linear FEM approach, the redistribution or the actual cutoff for tensile stresses beyond tension limit is not catered for and the stresses in case of bending increases symmetrically as if for a ductile material (Figure 3.15).

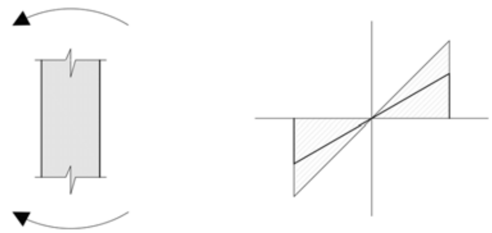

Figure 3.15: Behavior of SAP2000 Shell Element under bending in Linear FEM approach

The stress analysis has been carried out in the light of the discussion presented above. First and foremost the stress results for all four stages show that none of the masonry structure is overstressed in compression, despite the threshold being based on conservative assumptions.

It is observed that stress results for seismic loads combinations are almost identical to the gravity load combination results. Hence, for the purpose of this study the gravity load combinations are considered to present the behavior of the structure. The resulting stresses for gravity load combinations in horizontal (S11) and vertical (S22) directions for the masonry walls are shown in Figure 3.16 to Figure 3.19, while the results for all the seismic load combinations can be seen in APPENDIX D (Figure D.1 to Figure D.32).

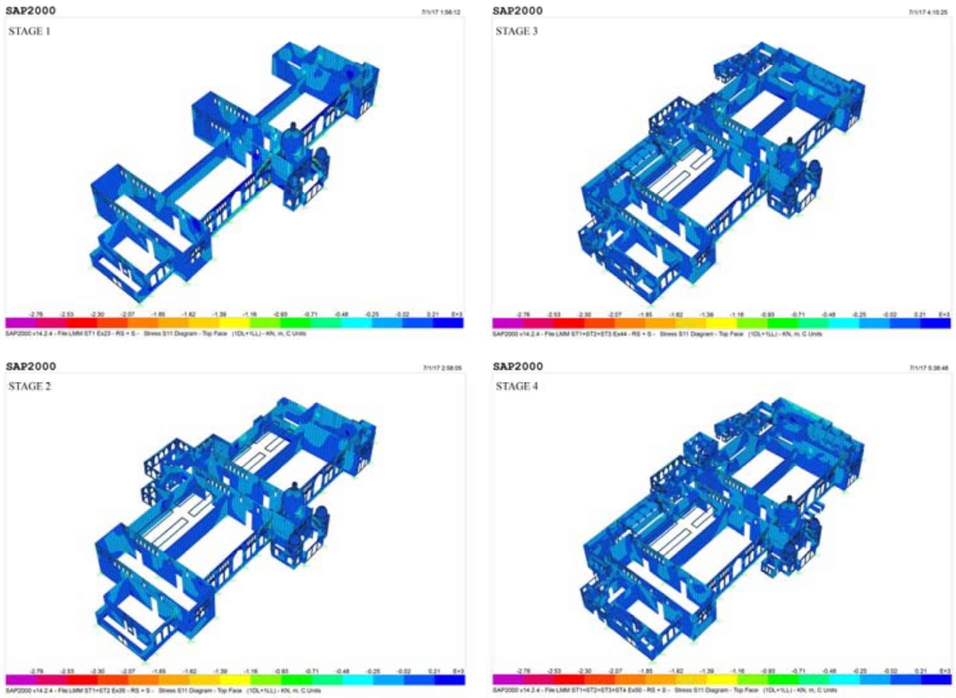

Figure 3.16: Load Combo 1D+1L In-plane Normal Stresses – Horizontal Direction (Top Face)

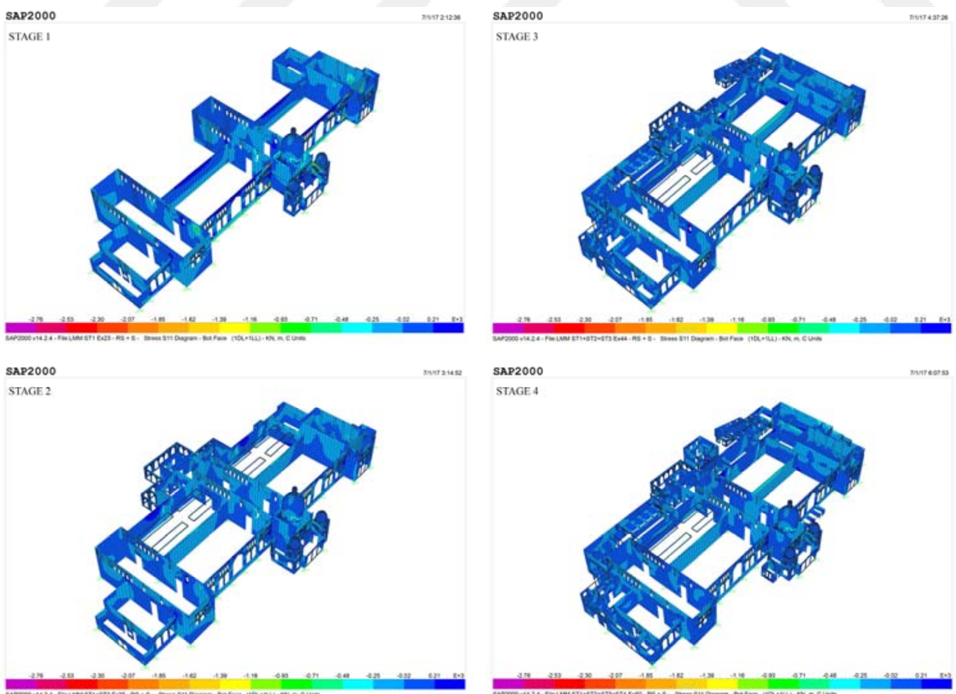

Figure 3.17: Load Combo 1D+1L In-plane Normal Stresses – Horizontal Direction (Bottom Face)

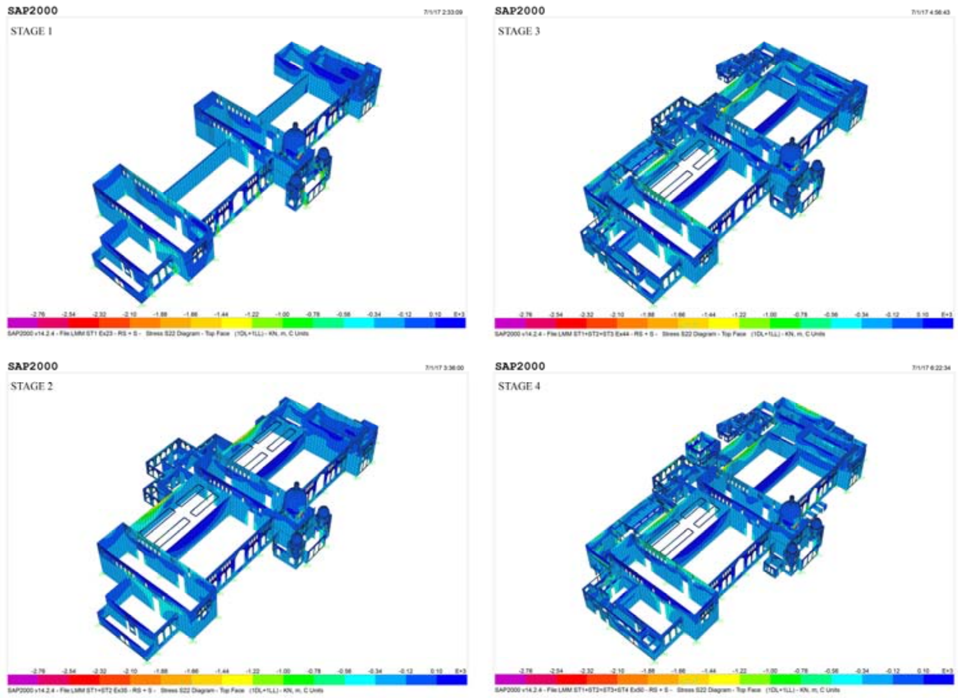

Figure 3.18: Load Combo 1D+1L In-plane Normal Stresses – Vertical Direction (Top Face)

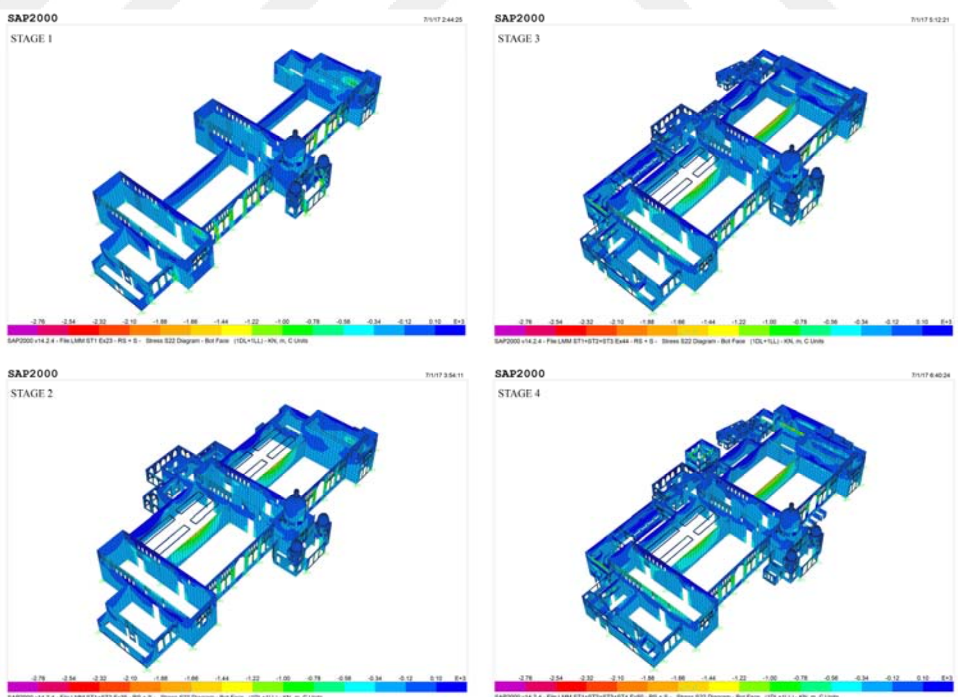

Figure 3.19: Load Combo 1D+1L In-plane Normal Stresses – Vertical Direction (Bottom Face)

From the gravity load combination results (Figure 3.16 to Figure 3.19) critical locations were identified. The stress values observed in the critical area elements were tabulated (Table 18). These localized results along with the global behavior of the associated walls were studied in detail. The stress results for the walls can be seen in APPENDIX D (Figure D.33 to Figure D.46) while the discussion is presented below.

Table 18: *Results for In-Plane stresses in KPa, -ive is compression*

Location	In-plane Stresses	Stage 1		Stage 2		Stage 3		Stage 4	
		Top Face	Bot. Face	Top Face	Bot. Face	Top Face	Bot. Face	Top Face	Bot. Face
Gnd-E/01-N-W **4258**	Horizontal Direction	-1760	-2471	-548	-724	-511	-651	-196	-380
	Vertical Direction	**120**	-110	49	-72	47	-70	59	-63
Gnd-W/01-N-W **3961**	Horizontal Direction	-261	-362	-189	-188	-66	-84	27	-9
	Vertical Direction	-186	-161	-61	-63	-48	-56	-65	-63
Gnd-E/01-S-W **16260**	Horizontal Direction	**292**	**258**	175	-259	189	-247	134	-313
	Vertical Direction	-52	29	**1212**	-1429	**1199**	-1409	**1220**	-1440
Gnd-W/01-S-W **3813**	Horizontal Direction	99	**261**	164	-229	114	-285	118	-269
	Vertical Direction	-249	**133**	**711**	-1021	**862**	-1155	**834**	-1134
Gnd-E/02-S-W **18617**	Horizontal Direction	N.A.	N.A.	-94	191	-234	149	-213	157
	Vertical Direction	N.A.	N.A.	-1074	**828**	-815	**542**	-878	**603**
Gnd-W/02-S-W **17751**	Horizontal Direction	N.A.	N.A.	198	-216	**241**	-252	**278**	-243
	Vertical Direction	N.A.	N.A.	-115	-129	-130	-191	-154	-198

Table 19: Continued

Location	In-plane Stresses	Stage 1		Stage 2		Stage 3		Stage 4	
		Top Face	Bot. Face	Top Face	Bot. Face	Top Face	Bot. Face	Top Face	Bot. Face
Gnd-E/03-W-W North End **9469**	Horizontal Direction	**934**	-887	**280**	-306	**244**	-268	64	-72
	Vertical Direction	**345**	-492	7	-198	-56	-186	-86	-155
Gnd-E/03-W-W South End **9297**	Horizontal Direction	-134	20	-136	-27	-149	20	-132	41
	Vertical Direction	-328	**206**	-347	**241**	-534	**389**	-554	**411**
Gnd-E/03-E-W North End **9146**	Horizontal Direction	-198	**288**	-233	**216**	-109	111	-36	31
	Vertical Direction	-471	**134**	-427	**199**	-359	63	-230	-45
Gnd-E/03-E-W South End **16073**	Horizontal Direction	-87	6	-73	32	-40	20	-35	17
	Vertical Direction	-211	**208**	-213	**119**	-129	43	-112	-20
Gnd-W/10-W-W **12341 / 27788**	Horizontal Direction	**370**	-438	**231**	-256	65	-151	17	-91
	Vertical Direction	**306**	-562	**127**	-409	**227**	-461	**187**	-352
Gnd-W/05-W-W **56899**	Horizontal Direction	N.A.	N.A.	N.A.	N.A.	39	-59	**255**	41
	Vertical Direction	N.A.	N.A.	N.A.	N.A.	-74	-45	-161	-258

Note: The In-plane Stress Values marked in Red exceed the considered threshold values; N.A. stands for Not Applicable

The in plane normal stresses for the horizontal direction (S11) can be a result of in plane displacements of walls in the horizontal direction due to diagonal action of the lateral loads, faying in or out of walls due to foundations, bending in the horizontal axis, as shown in Figure 3.20.

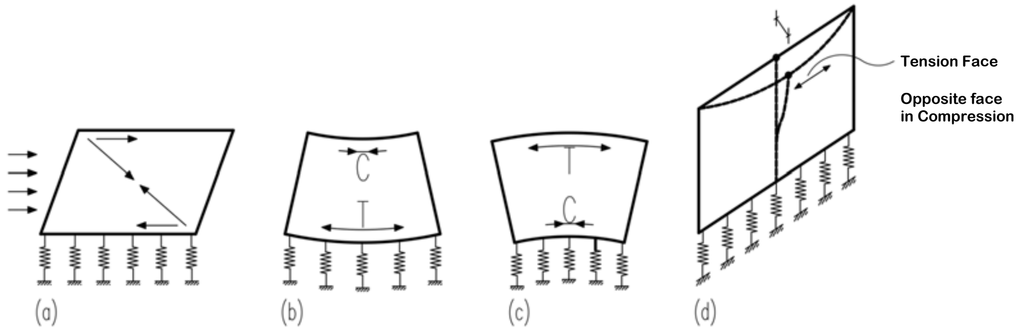

Figure 3.20: In-plane normal stresses – Horizontal Direction (S11)
(a) Displacement of wall in the horizontal direction due to diagonal action of the lateral loads,
(b) Faying in of wall due to foundation, (c) Faying out of wall due to foundation,
(d) Bending in the horizontal axis

Similarly, the in plane normal stresses for the vertical direction (S22) can be a result of in plane displacements of walls in the vertical direction due to diagonal action because of lateral loads, bearing loads of the supported elements, bending in the vertical axis, as shown in Figure 3.21.

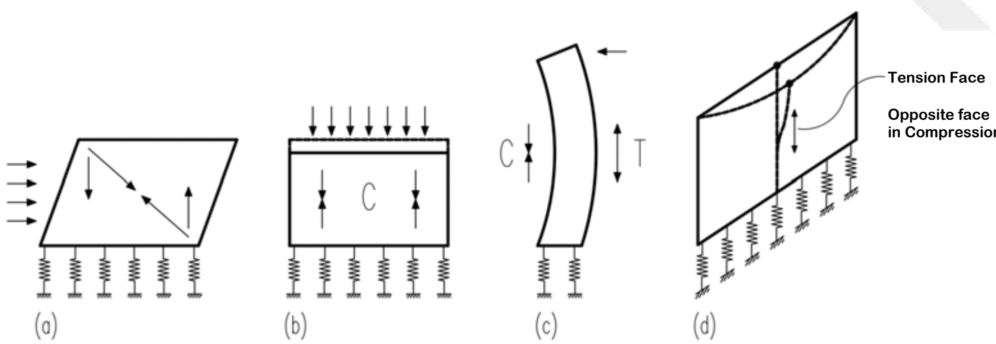

Figure 3.21: In-plane normal stresses – Vertical Direction (S22)
(a) Displacement of wall in the vertical direction due to diagonal action of the lateral loads,
(b) Bearing loads of the supported elements, (c) Bending in vertical direction,
(d) Bending in the horizontal axis

Gnd-E/01 North Wall

The critical location in the wall Gnd-E/01-N-W is observed near the top western corner of the wall.

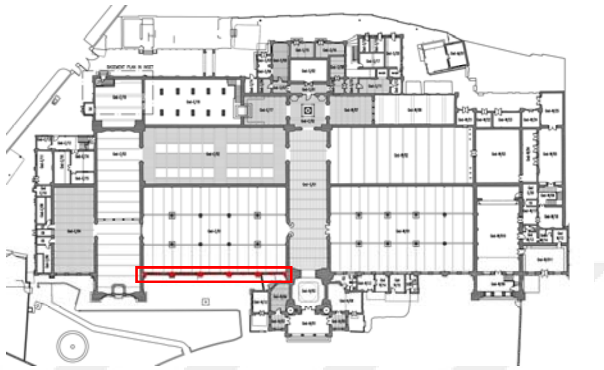

Figure 3.22: Key Plan showing wall Gnd-E/01-N-W

In Stage 1, the S11 results for the selected location show high values of compression on both faces, while the overall wall exhibits in plane bending with tension in the top zone and compression in the bottom zone for both faces (Figure 3.20-c). This could be credited to the settling of the wall at the ends due to the adjacent heavier load bearing galleries Gnd-E/03 and Gnd-C/01 on the eastern and the western end respectively as well as due to the settling of the truss roofing system which ties the wall at the top and causes it to sway towards the northern direction. In the next two stages stress values tend to lower which can be attributed to the addition of space Gnd-N/04, that arrests the neighboring wall to relieve and redistribute the stresses observed in Stage 1. Moreover, a marked reduction is observed in the stress values in Stage 4 which could have resulted due to the change in roof loads in this stage of the building life.

In case of the S22 results for Stage 1 we observe difference in the nature of stresses, with the north (top) face in tension and the south (bottom) face in compression, indicating that the segment of the wall is undergoing bending (Figure 3.21-c). The stress values tend to lower in the subsequent stages for the area element. This behavior is reflected in the overall behavior of the wall as well and can also be ascribed to the construction of space Gnd-N/04 and change in the roof loading.

The behavior of the wall observed in the analytical model corresponds with the behavior observed for the actual wall in the documentation stage of the building. As the actual wall exhibits out of plane behavior and is titling towards north (Figure 2.68).

Gnd-W/01 North Wall

The critical location for wall Gnd-W/01-N-W is observed near the top eastern corner of the wall.

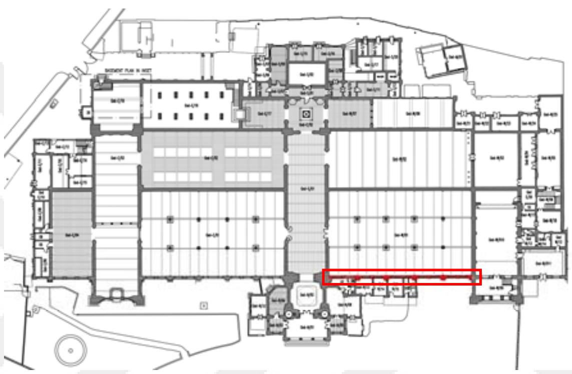

Figure 3.23: Key Plan showing wall Gnd-W/01-N-W

In Stage 1, the S11 results for the selected location show compression on both faces, while the overall wall exhibits tension in the top zone and compression in the bottom zone for both faces pointing to in plane bending (Figure 3.20-c). One of the reasons that can be ascribed to reflect the observed behavior in Stage 1 is settling of the wall ends due to adjacent heavier load bearing galleries Gnd-C/01 and Gnd-W/10 on the eastern and the western end respectively. Another reason could be that the wall tied at the top with the truss roofing sways to the north as the roofing structure settles and attains equilibrium. The amount of stresses diminish in the next two stages for the segment of the wall as well as the entire wall. This could be due to the addition of space Gnd-N/06 in Stage 2, which arrests the neighboring wall to relieve and redistribute the stresses observed in Stage 1 and to the change in roof loads in Stage 3. While in Stage 4, reversal of stress values is observed in the area element which can be due to the construction of spaces Gnd-N/07-09 and Gnd-N/13-18. These new constructions could have restricted any further out of plane deformation of the wall near the bottom but at the top of wall the inward pull of the roof towards south might govern, resulting in the observed stress reversal.

The S22 results of the selected segment of the wall shows compression on both faces of the wall in all stages with ever diminishing values. While the overall wall exhibits that the north (top) face is in tension while the south (bottom) face is in compression, implying that the wall is undergoing bending (Figure 3.21-c).

In the analytical model the global behavior of wall Gnd-W/01-N-W is similar to wall Gnd-E/01-N-W, which is almost symmetrical in its general configuration to the discussed wall. During the visual inspection this behavior was not checked on-site and as no section has been cut through this part of the building. Hence, it cannot be said with any certainty whether this behavior reflects the on-site condition.

Gnd-E/01 South Wall

The critical location in the wall Gnd-E/01-S-W is observed in the middle of the wall near the top.

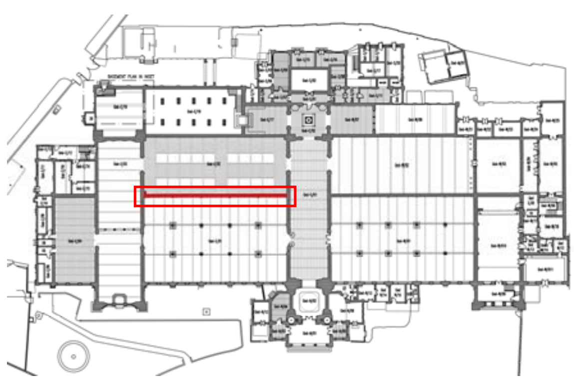

Figure 3.24: Key Plan showing wall Gnd-E/01-S-W

In Stage 1, the S11 results for the selected location exhibits tensile stresses on both faces, while the overall wall exhibits tension in the top zone and compression in the bottom for both faces (Figure 3.20-c). This could be credited to the settling of the wall at the ends due to the adjacent heavier load bearing galleries Gnd-E/03 and Gnd-C/01 on the eastern and the western end respectively as well as due to the settling of the truss roofing system which ties the wall at the top and causes it to sway. In Stage 2 the nature of stresses for the south (bottom) face is reversed from tension to compression while the north (top) face retains tension. The results of the overall wall also show that the entire wall is exhibiting similar behavior which indicates that the wall is exhibiting out of plane behavior (Figure 3.20-d). This could be attributed to the construction of space Gnd-E/02 on the southern side of the wall. As the roofing system of the new space settles it causes the wall to bulge towards north. Moreover, in Stage 3 an increase in tension is observed on the north (top) face while the behavior is reversed for the south (bottom) face this could be due to the construction of spaces Gnd-E/18 and Fst-E/10-14. The roofing systems of all the additions in Stage 2 and Stage 3 play a vital role in the behavior of the wall Gnd-E/01-S-W, for as the horizontal diaphragms settle and attain equilibrium they cause the wall to experience bending due to the shear forces at the interface. In Stage 4, a decrease in tension is observed on the north (top) face whereas the south (bottom) face experiences an increase in compression. This could have resulted due to the change in roof loads in Stage 4.

In case of the S22 results for Stage 1 the wall segment exhibits compression in north (top) face and tension in the south (bottom) face. In the subsequent stages the nature of stress is reversed with the north (top) face now experiencing tension and the south (bottom) face in compression along with a drastic increase in the magnitude of the stresses. This behavior is reflected in the overall behavior of the wall as well and can also be ascribed to the construction of spaces Gnd-E/02, Gnd-E/18 and Fst-E/10-14 and change in the roof loading.

The behavior of the wall observed in the analytical model corresponds with the behavior observed for the actual wall in the documentation stage of the building (Figure 2.68).

Gnd-W/01 South Wall

The critical location in the wall Gnd-W/01-S-W is observed in the middle of the wall near the top.

Figure 3.25: Key Plan showing wall Gnd-W/01-S-W

The behavior exhibited by the wall segment as well as the entire wall for both S11 and S22 results is identical to that seen for wall Gnd-E/01-S-W, which is almost symmetrical in its general configuration to the discussed wall. One of the reasons that can be ascribed to reflect the observed behavior in Stage 1 is settling of the wall ends due to adjacent heavier load bearing galleries Gnd-C/01 and Gnd-W/10 on the eastern and the western end respectively. Another reason could be that the wall tied at the top with the truss roofing sways to the south as the roofing structure settles and attains equilibrium. Moreover in Stage 2, the construction of space Gnd-W/02, south of the wall, can be the cause of the observed stress reversal, indicating out of plane behavior of the wall. The further increase in stress values in Stage 3 can be attributed to the construction of space Gnd-W/08 and changes to the roofing structure for both spaces Gnd-W/01 and Gnd-W/02.

During the visual inspection this behavior was not checked on-site and as no section has been cut through this part of the building it is unclear if this behavior reflects the on-site condition.

Gnd-E/02 South Wall

The critical location in the wall Gnd-E/02-S-W, constructed in Stage 2, is observed near the middle of the wall at the top.

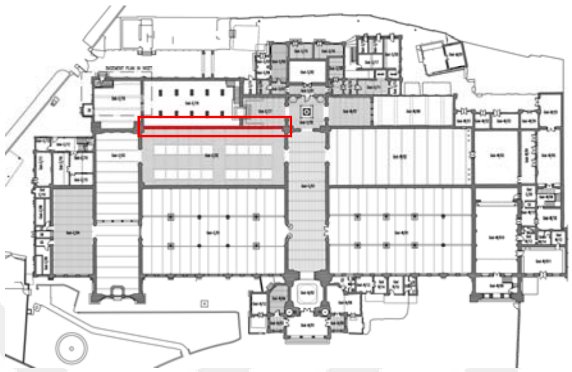

Figure 3.26: Key Plan showing wall Gnd-E/02-S-W

In Stage 2, the S11 results for the selected location exhibits that the nature of the stresses varies with the north (top) face in compression and the south (bottom) face in tension. Similar behavior is observed in the entire wall which indicates out of plane bending (Figure 3.20-d). This can be the result of the roofing system settling and causing the wall to sway towards north. In the subsequent stages the nature of stresses remains the same for the area element, with minute changes in the magnitude of the stresses. However, in case of the entire wall stress reversal is observed in the lower part of the wall in Stage 3, with the north (top) face in tension and the south (bottom) face in compression. This behavior is sustained in Stage 4. The observed behavior can be ascribed to the construction of Spaces Gnd-E/18 and Fst-E/10-14, towards the south of the wall, in Stage 3. The increased gravity load and the addition of slab approximately at mid height of the wall, causes it to sway towards the south.

In case of the S22 results for Stage 2, the wall segment exhibits compression in the north (top) face and tension in the south (bottom) face. Similar behavior is observed in the entire wall which indicates that the wall is bending. This behavior might be due to settling of the roof, which ties the wall at the top and bends it towards north.

The behavior of the wall observed in Stage 4 of the analytical model corresponds with the behavior observed for the actual wall in the documentation stage of the building (Figure 2.68).

Gnd-W/02 South Wall

The critical location in the wall Gnd-W/02-S-W, constructed in Stage 2, is observed near the middle of the wall.

Figure 3.27: Key Plan showing wall Gnd-W/02-S-W

In Stage 2, the S11 results for the selected location exhibits that the nature of the stresses is different; with the north (top) face in tension and the south (bottom) face in compression which indicates out of plane bending (Figure 3.20-d). In Stage 3 the stress values increase, implying more out of plane bending, under increased gravity loads due to the addition of space Gnd-W/08 south of the wall. A further increase in stress is observed in Stage 4 and can be attributed to the construction of a double storey structure south of space Gnd-W/08 which consequently results in the stiffening of the walls Gnd-W/08-E-W and Gnd-W/08-W-W, which are perpendicular to the discussed wall.

In case of the S22 results for all construction stages, the wall segment is in compression with the stress values well below the considered threshold. However, in case of the entire wall the north (top) face is in compression while the south (bottom) face has tension in the top zone and compression in the bottom zone of the wall. This behavior might be due to settling of the roof, which ties the wall at the top and bends it towards north.

During the visual inspection this behavior was not checked on-site and as no section has been cut through this part of the building it is unclear if this behavior reflects the on-site condition.

Gnd-E/03 West Wall

Two critical locations were observed in wall Gnd-E/03-W-W. One of the observed segment is located near the top of the wall close to the junction with wall Gnd-E/01-N-W at the northern end of the wall. The other is located near the top of the wall towards the southern end of the wall.

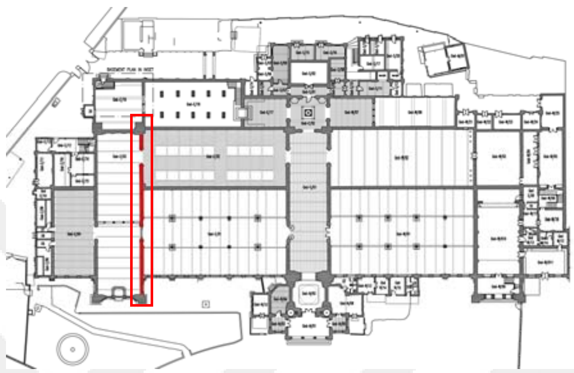

Figure 3.28: Key Plan showing wall Gnd-E/03-W-W

For the area element at the northern end, S11 results for Stage 1 exhibit very high magnitude of stress values. The nature of stresses is different on the opposite faces with the west (top) face exhibiting tension while the east (bottom) face is in compression. This points to out of plane bending with the tilt towards east. With each subsequent stage magnitude of the stresses reduce although the nature of stresses remains the same. Similar behavior is observed in the entire northern part of the wall. The S22 results, of the same area element, for Stage 1 also show that the west (top) face is in tension while the east (bottom) face is in compression, thus depicting out of plane bending (Figure 3.21-c). In Stage 2, magnitude of stress values reduce while the nature of stresses on opposite faces remains the same. However, in Stage 3 a reversal of stresses is observed, with both faces now experiencing compression, this behavior is retained in Stage 4. These results dictate that addition of galleries, such as Gnd-E/02 (south-west) in Stage 2 and Gnd-E/19 (south) and Gnd-E/11-16 (south-east) in Stage 3, around space Gnd-E/03 have been favorable in redistributing and relieving stresses.

For the area element at the southern end, the S11 results for Stage 1 show that the west (top) face is in compression while the east (bottom) face is in tension which indicates out of plane bending with the element swaying towards west. In the subsequent stages the nature of stresses remains the same and though slight variation in magnitude is observed none of the values exceed the threshold. Similar behavior is observed in the entire northern part of the wall as well. The S22 results, for the same area element, for Stage 1 also show that the west (top) face is in compression while the east (bottom) face is in tension which indicates out of plane bending (Figure 3.21-c). For all stages the stress values for tension exceed the threshold; however the values sustain for Stage 1 and 2 but in Stage 3 a sudden increase in tension is observed which is then sustained in Stage 4. This could be attributed to the change in the roofing system of space Gnd-E/03 in Stage 3; the added structural weight could have resulted in increase in tensile stresses. Also the addition of spaces Gnd-E/19 (south) and Gnd-E/11-16 (south-east) in Stage 3, could have contributed to the observed behavior through redistribution of loads.

The behavior of the wall observed, at the southern end, in the analytical model corresponds with the behavior observed for the actual wall in the documentation stage of the building (Figure 2.68). Although it is unclear if the behavior observed at the northern end of the wall reflects the on-site condition; as it was not checked during the visual inspection and no section has been cut through this part of the building.

Gnd-E/03 East Wall

Two critical locations were observed in wall Gnd-E/03-W-W. One of the observed segment is located near the top of the wall close to the junction with wall Gnd-E/04-N-W at the northern end of the wall. The other is located near the top of the wall, above the opening leading to space Gnd-E/04, towards the middle of the wall.

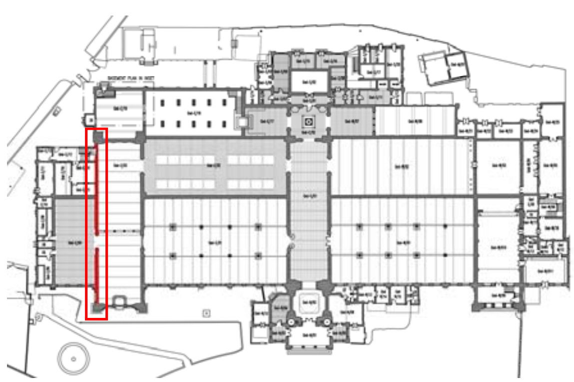

Figure 3.29: Key Plan showing wall Gnd-E/03-E-W

The results for both the area element are very similar. The S11 results, of both area elements, for Stage 1 exhibit compression on the west (top) face while the east (bottom) face is in tension indicating out of plane bending with the tilt in the western direction. In case of the entire wall in Stage 1, the wall from the northern end till the transverse wall Gnd-E/04-S-W exhibits compression on the west (top) face and tension on the east (bottom) face. While in the remaining wall stress reversal is observed with the west (top) face in tension and east (bottom) face in compression. In the subsequent stages for the area element and the entire wall, nature of stresses remain the same while the magnitudes gradually reduce. This could be attributed to the construction of space Gnd-E/02 (south-west) in Stage 2 and spaces Gnd-E/19 (south) and Gnd-E/11-16 (south-east) in Stage 3, which help relieve and redistribute the stresses.

For both area element the S22 results of Stage 1 show that the west (top) face is in compression while the east (bottom) face is in tension depicting out of plane bending (Figure 3.21-c). In the subsequent stages the nature of stresses remains the same while the magnitude gradually reduces. In context of the entire wall, in Stage 1 bending deformations are observed in the top zone which could be caused by the roof of space Gnd-E/03 pulling the wall towards west. While in the mid-section of the wall a reversal of stress is observed which could be due to the roof of space Gnd-E/04, located east of the wall, pulling the wall eastwards. Whereas in the bottom zone the tensile stresses are being eliminated by compression due to the self-weight of the overlying wall matrix. This behavior is sustained in Stage 2 but in Stage 3, an increase in tension is observed in the top zone which could be the result of roof change of space Gnd-E/03 in this stage. The tensile stresses are relieved in the mid-section of the wall which could be due to redistribution of loads due to the addition of spaces Gnd-E/19 (south) and Gnd-E/11-16 (south-east).

The behavior of the wall observed, close to the junction of wall Gnd-E/04 and the discussed wall, in the analytical model corresponds with the behavior observed for the actual wall in the documentation stage of the building (Figure 2.68). Although it is unclear if the behavior observed at the northern end of the wall reflects the on-site condition; as it was not checked during the visual inspection and no section has been cut through this part of the building.

Gnd-W/10 West Wall

The critical location in the wall Gnd-W/01-S-W is observed approximately mid-wall, near the junction with wall Gnd-W/11-S-W.

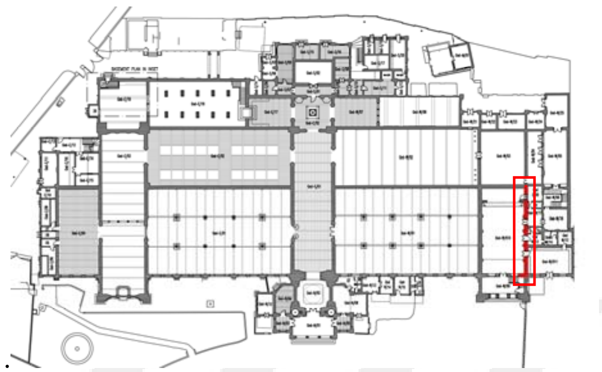

Figure 3.30: Key Plan showing wall Gnd-W/10-W-W

In Stage 1, the S11 results for the selected location exhibits stress reversal, with the west (top) face in tension while the east (bottom) face is in compression. Similar behavior is observed for the entire wall which points to out of plane bending (Figure 3.20-d). For both area element and the entire wall, a reduction in the magnitude of stress is observed in the subsequent stages especially in Stage 3. This change can be ascribed to the addition of a floor slab in space Gnd-W/10, supported through column and beam frames inserted into the discussed wall. Also the addition of spaces on the ground floor at the western end of the wall might have helped relieve the stresses. Furthermore, in Stage 4 a further decrease in stress is observed which could be due to the construction of spaces, with multiple partition walls, over those built in Stage 3. These additions besides resulting in the increased vertical loads also provide lateral stiffening elements which tend to reduce lateral deformations and stresses.

In case of the S22 results for Stage 1, the wall segment exhibits tension on west (top) face while the east (bottom) face is in compression pointing to bending in the vertical plane (Figure 3.21-c). In Stage 2 a reduction in the magnitude of stress is observed but in Stage 3 the stresses increase; this change can be ascribed to the addition of a floor slab in space Gnd-W/10. The tensile stresses breach the threshold in all stages although the stress values decrease in Stage 4. In the context of the entire wall, in Stage 1 bending deformations are observed in the top zone which could be caused by the roof of space Gnd-W/10 pulling the wall towards east. While in the mid-section of the wall a reversal of stress is observed which could be due to the roof of space Gnd-E/26, located west of the wall, pulling the wall westwards. Whereas in the bottom zone the tensile stresses are being eliminated by compression due to the self-weight of the overlying wall matrix. In Stage 2 the stresses are relieved but in Stage 3 the tensile stresses increase in the mid-section of the wall with both faces exhibiting tension. This behavior is sustained in Stage 4 and could be the result of the addition of floor slab in space Gnd-W/10 at this wall height in Stage 3.

During the visual inspection this behavior was not checked on-site and as no section has been cut through this part of the building it is unclear if this behavior reflects the on-site condition.

Gnd-W/05 West Wall

The critical location in the wall Gnd-W/05-W-W, constructed in Stage 3, is observed mid height of the wall near the southern end.

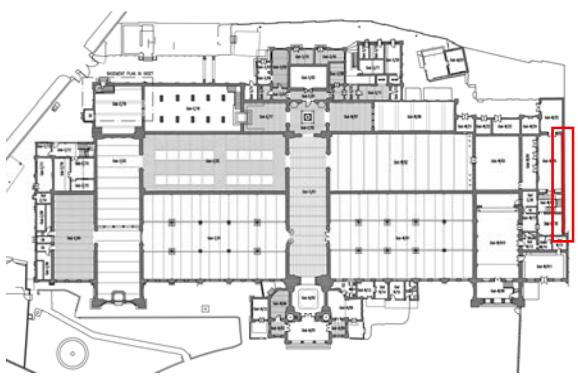

Figure 3.31: Key Plan showing wall Gnd-W/05-W-W

In Stage 3, the S11 results for the selected location exhibits that the nature of the stresses on either face is different; similar behavior is observed in the entire wall as well pointing to out of plane bending with the wall titling in the westward direction (Figure 3.20-d). In Stage 4 for the area element an increase in the magnitude of stresses is observed along with stress reversal, with both faces now in tension. The increase in lateral bending can be the result of construction of space Fst-W/07 over space Gnd-

W/05 in Stage 4; as the wall is an edge wall with a potential to bend laterally under increased load. In case of the entire wall it is observed that the bottom zone (Stage 3 construction) is in tension while the top zone (Stage 4 construction) is in compression pointing to in-plane bending (Figure 3.20-b). This too could be ascribed to the Stage 4 construction of space Fst-W/07 which functions as the reserve storage for the museum.

In case of the S22 results for both stages, the wall segment is in compression with the stress values well below the considered threshold. However, the entire wall exhibits compression on the west (top) face while the east (bottom) face has tension in the top zone and compression in the bottom zone of the wall. This behavior might be due to settling of the roof, which ties the wall at the top and bends it towards west.

During the visual inspection this behavior was not checked on-site and as no section has been cut through this part of the building it is unclear if this behavior reflects the on-site condition.

Conclusion

In the aforementioned results, it is seen that the walls generally exhibit out of plane behavior and in some instances in-plane bending is also observed. This observed behavior is comparable with the on-site behavior of the walls, identified through the documentation of the building. As the model correctly ascertains the problem areas, it can be deemed to be potentially accurate and this provides an important validation for the study.

Furthermore, it is seen that tension stresses for some of the area elements exceed our considered threshold. Although majority of the exceeding tension magnitudes are comparable to the considered limits but as masonry is weak in tension; the tension prone zones should be paid due attention in case of any further alterations, although as per site the building in its current state has redistributed its loads and attained equilibrium.

3.3.4. *Analysis of the Results for Wall Gnd-E/04-N-W*

Most critical of the structural damages are observed in the Northern wall (Gnd-E/04-N-W) of space Gnd-E/04 located in Zone 01 (Section 2.7.3). Two Vertical Cracks (S1), one passing through the central arch and the other passing through the eastern arch, can be seen on the wall (Figure 3.32). The crack passing through the central arch seems to be widening since it was first observed by the author in 2013, while the second crack was seen for the first time in 2017. The wall also shows signs of Lateral Buckling (S6) coupled with Out of Plane behavior (S5) and Differential Settlement (S3). The probable causes of these observed damages were identified as poor local soil conditions and structural alterations.

Figure 3.32: Vertical Cracks (S1)
Through the Central and Eastern Arch of Gnd-E/04-N-W (2017)

To test out the hypotheses, a part model was prepared from the Stage-4 model (current condition), for Space Gnd-E/04 and its adjacent spaces, Gnd-E/06 (East) and Gnd-E/03 (west) (Figure 3.33).

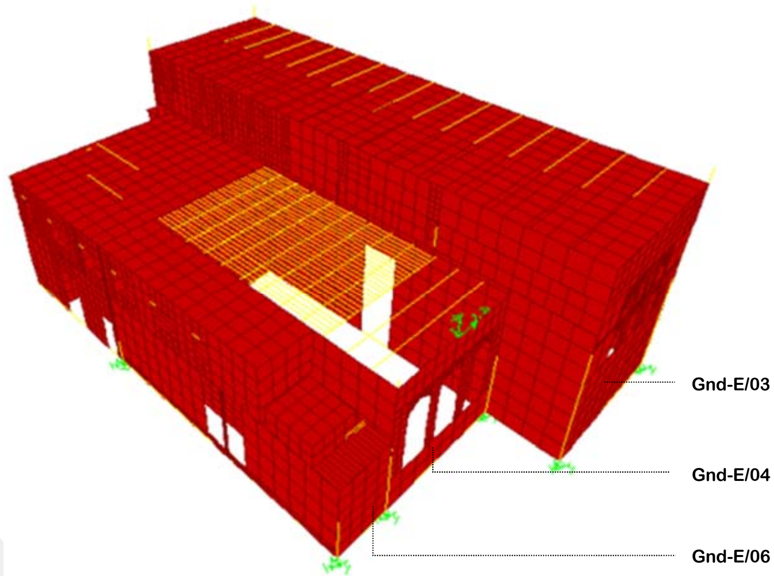

Figure 3.33: Part-Model of Space Gnd-E/04
For testing out probable causes of damage observed in wall Gnd-E/04-N-W

In order to simulate the hypothesis that localized sub-strata performance might be poor, due to rupturing of water pipes in the adjacent space Gnd-E/06, the subgrade values applied in the form of line springs under the walls Gnd-E/04-N-W and Gnd-E/04-E-W were reduced by 30%. The second hypothesis that the structural alteration triggered by the temporary removal of roof structure of space Gnd-E/04, may have caused the wall to lose its top tie action was simulated through the removal of the roof. Furthermore, the hoisting equipment mounted at the top of the wall during the reworking of the roof was simulated through the application of point load in the part model.

The results for maximum principal stresses, under the simulated conditions, show that on the north (exterior) face, the western half of the wall is in tension while the eastern half is in compression. This behavior is reversed on the south (interior) face with the eastern half now in tension while the western half is in compression which points to lateral buckling. Additionally, tension threshold exceeds in the top spandrel above the arch openings (Figure 3.34). The lateral buckling couple coupled with significant tension observed in the top zone could have initiated the crack in the upper part of the wall which would have travelled downward, as the structure is relieved and stresses are redistributed.

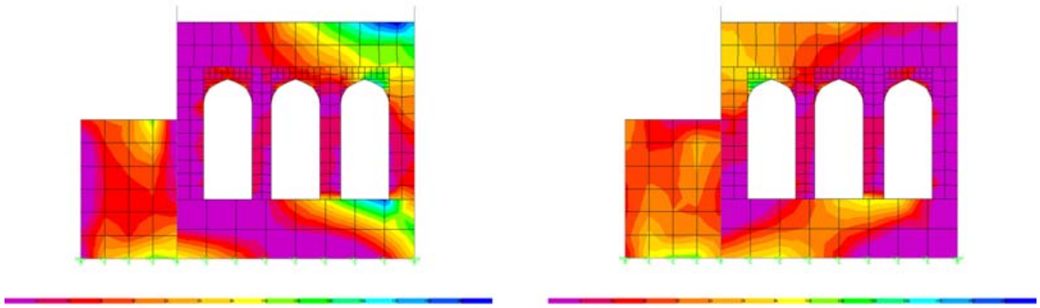

Figure 3.34: Maximum Principal Stresses (kPa) for wall Gnd-E/04-N-W
Left: North (exterior) Face; Right: South (interior) Face

Furthermore, the deformed shape also shows that with worsened local soil conditions the wall exhibits signs of differential settlement; the eastern end of the wall is observed to be lower than the western end.

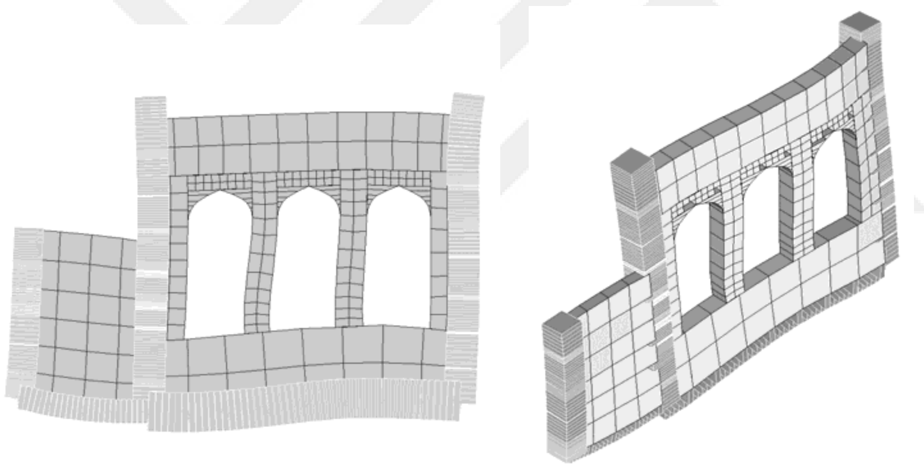

Figure 3.35: Deformed shape of wall Gnd-E/04-N-W
Left: North (exterior) face elevation showing differential settlement
Right: North (exterior) face 3D showing lateral buckling

Hence, the behavior of the wall observed in the analytical model corresponds with the behavior observed for the actual wall in the documentation stage of the building. This suggests that the hypotheses formed are correct and due attention needs to be paid to the local soil condition.

3.3.5. *Column Results Analysis*

The museum building mainly houses two types of columns; the CI columns and the engaged columns built in brick.

The brick columns were evaluated as per Section 2107.3 of the UBC code. It was observed that for all stages of the museum building the brick columns, with utilization ratios of the order 0.2 - 0.3, are satisfactory in performance and hence pose no concern to the structural stability of the building.

The CI columns were also evaluated as per UBC code. It was observed that although the utilization ratio remain under 1.0 for the gravity load combinations but the ratio exceeds 1.0 for seismic load combinations (Figure 3.36).

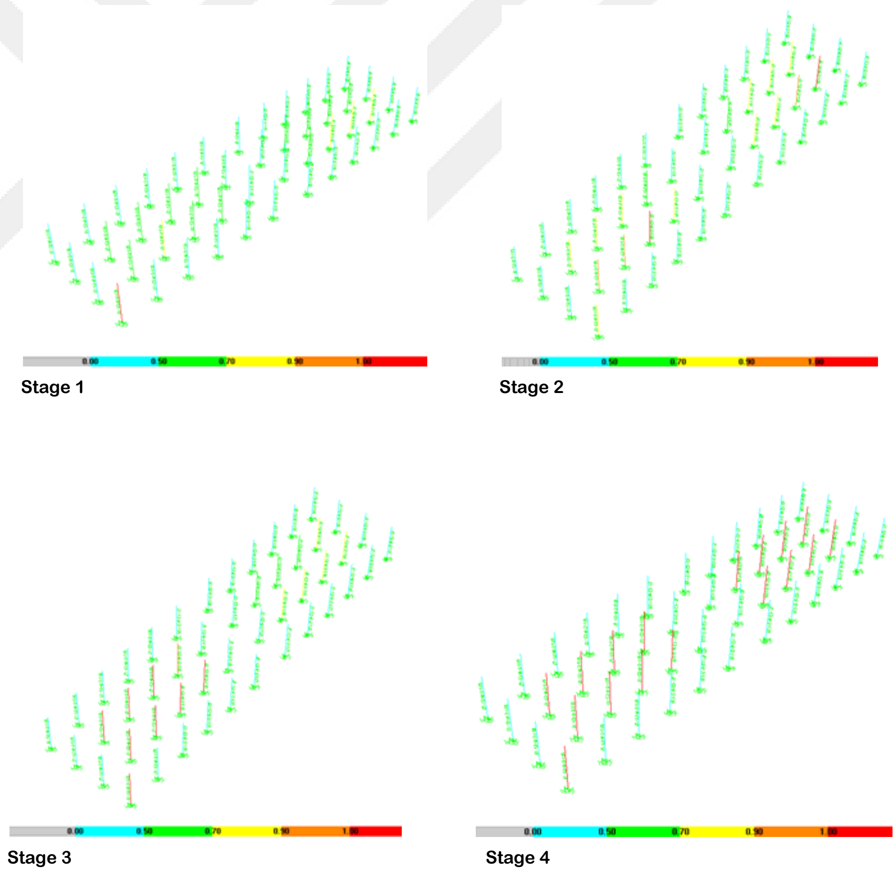

Figure 3.36: Evaluation Results of Cast Iron columns for all four stages.
Stage 1 (Top Left), Stage 2 (Top Right), Stage 3 (Bottom Left) and Stage 4 (Bottom Right)

Although, deformations in the CI columns have also been observed during the documentation stage of the study. But bearing in mind that the material aging and degradation of CI is based on the simplified approach of reduction of MoE of material it cannot be definitively stated whether the problem originates due to inaccuracies of casting or because the material is fatigued. Hence, for any conclusive safety evaluation apropos the structural performance of the CI columns detailed material testing is required.

CHAPTER 4

RECOMMENDATIONS AND DEFINING OF A STRUCTURAL CONSERVATION PROCESS FOR THE LAHORE MUSEUM

This chapter based on the findings of the last two chapters provides the safety evaluation of the building which is then used to define the recommendations and to formulate a proposal for the structural conservation process specific to the Lahore Museum.and it contains three sections.

The first section compares the qualitative and quantitative assessments, presented in the previous chapters, to provide strucutral evaluation of the building. The second section discusses the proposed Structural Conservation Process, which can be part of a holistic restoration project prepared for the Lahore Museum. This process is prepared in conformity with the ISCARSAH Recommendations. It sequentially starts off with a succinct description of the structure of the proposed process within the broader framework of a multi-disciplinary Conservation Process defined by Usman Sami (2017). It next presents the structural conservation process laid out as a flow chart. The flow chart showing the tasks that have been completed within the scope of the thesis as well as the tasks that need to be completed for a comprehensive structural conservation process. It also maps out the flow of information between interrelated studies and tasks. The section ends with full sequential description of all the tasks, envisioned as essential for a complete structural conservation process. The last section presents the two pronged recommendations for the Museum building. It first discusses all the non-invasive forms of interventions recommended as intermediary measures under the Immediate Action label. It then outlines all the recommended pre-conservation studies, required for designing a holistic structural conservation program, under the Further Studies label.

4.1. Evaluation of Strutural Investigation Studies

The main objective of the structural investigation studies was to understand the structural behavior of the Lahore Museum and to assess the building's performance for safety. To this effect historical research, visual observations and documentation of the structural system and its damage and decay patterns (qualitative) as well as the structural analyses of the building through analytical modelling (quantitative) was carried out. The safety evaluation of the building is thus based on reconciliation of both the **qualitative** and **quantitative** approaches.

A comprehensive historical survey was carried out to reconstitute the construction history of the Museum, with special attention paid to the additions, alterations, repair works, failures, damages and structural modifications that lead to the current condition of the building. A detailed visual survey of the building was carried out to develop an understanding of the building and its structural systems and to identify its damage and decay patterns and ongoing environmental effects on the building. As the structural system of the building is exposed no probing was needed in this initial phase. Mapping was prepared to document the construction materials, visible decay and damage especially the crack pattern. Parallel to the visual survey, documentation of the building was carried out using laser scanner to produce a set of measured drawings. The measured drawings and the reconstituted geometries determined through the historical survey were then used to generate the analytical models. These models were used to understand the global structural behavior of the building and to identify the areas of stress and strain in the building especially its main load bearing system i.e. masonry walls.

To determine the seismic performance of the building; seismic loads were applied in the analytical models using two approaches i.e. the equivalent lateral static procedure and response spectrum analysis. It was found that the seismic forces are only 8% to 12% of the structural weight of the building; owing to the fact that the building is primarily composed of thick masonry walls. Additionally, as the building is not a slender structure, larger length of restraining members are available against overturning caused by lateral seismic loads. Besides, the building exhibits low stress values in case of seismic activity; as it lies in a moderate seismic risk zone. Hence, it can be concluded that performance of the building under seismic loading is satisfactory; inherently due to the design and construction of the building itself and its location. Additionally, historical research and visual observations also showed that the building had sustained little or no damage in its service life due to earthquakes that have jolted the city of Lahore in the past.

The Museum building can also be deemed to exhibit a globally stable structural behavior. This evaluation is backed by the analytical models, which show that for none of the stages the masonry structure is overstressed in compression. Despite the thresholds being based on conservative assumptions, for both the material properties and the compressive strength of the masonry; that is taken to correspond to the weakest form of masonry. Additionally, visual observations and documentation of the building also confirm this assessment. As crushing phenomenon, generally associated with overstressed masonry, is not detected in any part of the building and only a few cracks are observed, which are spread all over the building.

Even though the building is globally stable, some localized structural damages are detected in the oldest parts of the building that are also the most culturally significant. The problem areas identified through visual inspection or documentation are corroborated through the analytical models. These models also identified other problem areas in the building that were neither checked during the visual inspection or through documentation. The independent analyses carried out on the reconstituted geometries of the building show the anthropogenic actions, such as architectural additions and alterations, intentional destruction and inadequate maintenance and repairs, are the main cause of the damage incurred by the building. This observation is validated through the qualitative assessment carried out on the building in the light of historical research, visual inspection and documentation. These problems seem not to be critical at the moment but do require further studies.

One location that seems critical is the northern wall of the space Gnd-E/04, which suffers from a multitude of problems. Two vertical are observed on the wall besides a vertical Separation Crack at the junction of the wall and the pier at its eastern end. Besides the wall also shows signs of lateral buckling coupled with out of plane behavior as well as differential settlement. The probable causes of these observed damages were identified, through the qualitative assessment, as poor local soil conditions and structural alterations. These hypotheses were tested, by carrying out linear elastic analysis, on a part model prepared from the current condition of the building. The behavior of the wall in the analytical model was seen to correspond with the observed behavior of the actual wall. Thus suggesting that the hypotheses formed are correct and due attention needs to be paid to the local soil condition.

Additionally, the Museum building is beriddled with material deterioration problems. These problems though not directly responsible for the stresses and strains in the building but can impact the structural safety of the building, by reducing the strength of materials. The principal cause of material damage in the building seems to be the presence of moisture from inadequately contained rainwater. This problem is exacerbated due to poor roof drainage, application of concrete parging to the exterior walls and paving of the surfaces at the base of the exterior walls with concrete and asphalt. Another problem for the brickwork is the continuous reintroduction of salts due to rising damp and rainwater penetration and through the use of Portland cement mortar for carrying out repairs and maintenance works on the building.

4.2. Defining the Structural Conservation Process for the Lahore Museum

The Structural Conservation Process for Lahore Museum has been defined as a sequence of interconnected tasks within the broader framework of a multi-disciplinary Conservation Process (Figure 1.9) prepared by Usman Sami (2017)[31]. The structural conservation process has been particularized and elaborated using the ISCARSAH Recommendations (2003) in conjunction with the guidelines for structural rehabilitation of historic buildings produced by CIB Commission (2010) as its framework. The process, related to the structural aspects, has been elaborated as a flow chart, outlining interrelated studies and activities within the task-group of Architectural Conservation Works (Figure 4.1).

[31] The Conservation Process was prepared by Usman Sami as part of his thesis titled "Understanding the Lahore Museum for the Definition of a Conservation Process" for a Master's degree in Conservation of Cultural Heritage, under the supervision of Prof. Dr. Neriman Şahin Güçhan, Department of Architecture, METU, Ankara, Turkey.

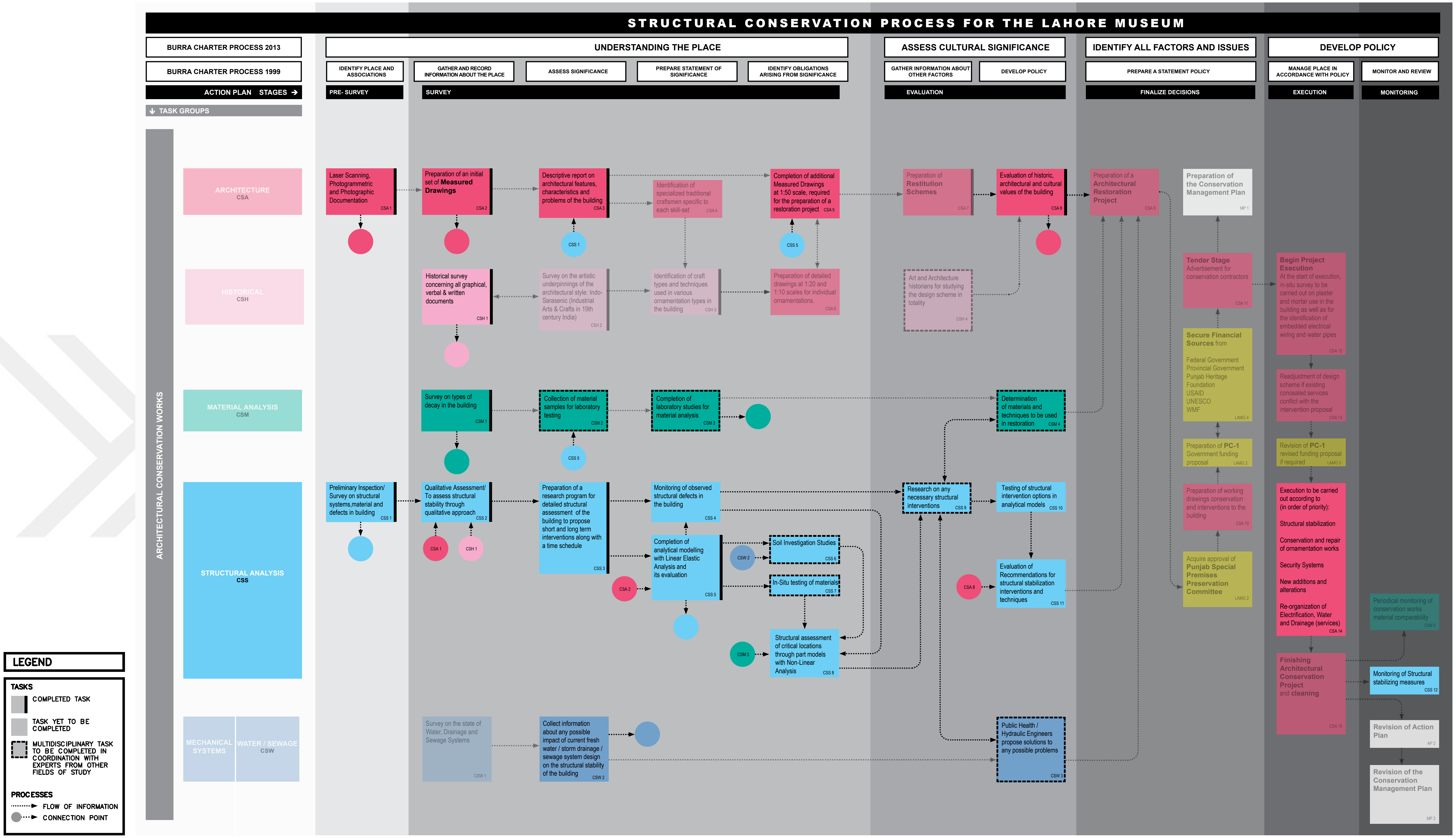

Figure 4.1: Flow Chart – Structural Conservation Process for the Lahore Museum
from the Conservation Process prepared by Usman Sami (2017) - Modified by Author (2018)

Note 1: Sub-groups have been assigned a unique code and each task within the sub-group a number
Each task is represented by a block containing a short description of the task and corresponding task number

Note 2: The parts modified by Author appear darker while others directly taken from the
Conservation Process prepared by Usman Sami have been faded out

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Within this primary task group are sub-groups; each of which has been allocated a unique code and each task in the group a number. The main focus of this study is the sub-group Structural Analysis (CSS). The other sub-groups of interest for this study are Architecture (CSA), Historical (CSH), Material Analysis (CSM) and Water and Sewage (CSW).

The tasks that are listed under the sub-group Structural Analysis (CSS) are discussed in this section and elaborate on the following; what is the nature of the task, why is it necessary, how will it be carried out and who will be responsible for it. The inflow and outflow of information from interrelated studies, needed to minimize redundancy in work, are mentioned only through the use of allocated codes and short description shown in the flow chart.

CSS 1 *Preliminary Inspection/ Survey on Structural Systems, Material and Defects in the building*

This survey was conducted to develop an initial understanding of the building and was carried out through direct visual observations. Signs of visual damage to materials and structural elements were pinpointed and documented. Additionally, the construction materials, structural and roofing system along with structural damages such as cracks, out of plane behavior and other structural irregularities were identified and their mapping was carried out. As the structural and the roofing system of the building is exposed, no probing was required at this stage.

The results of this survey are presented in Sections 2.5 & 2.6, in Figure 2.30 to Figure 2.37 and Figure 2.62 to Figure 2.68. Furthermore, information from this survey was used to write a descriptive report on the current condition of the building (CSA 3), attached to this thesis as APPENDIX B.

CSS 2 *Qualitative Assessment/ To assess structural stability through qualitative approach*

This task was carried out through inductive reasoning and took its cues from the observations in CSS1, the findings of the historical survey (CSH 1) and detailed documentation of the building (CSA 1); to assess the structural stability of the building in a qualitative manner. The observed defects were classified qualitatively, according to their level of importance with regards to the safety of the building and their probable causes were hypothesized at this stage. This qualitative assessment has been presented in Section 2.7 of this thesis.

CSS 3 *Preparation of a research program for detailed structural assessment of the building to propose short and long term interventions along with a time schedule*

The qualitative assessment must reconcile with quantitative assessment, in order to propose structural interventions to the building which are in keeping with the conservation principle of minimum intervention and are reversible and/or re-treatable. To this effect a rigorous research program needs to be established for the collection of quantifiable data that is case-specific to a historic building.

For the Lahore Museum due to its large scale, lack of long term monitoring and absence of any experimental data; the research program is designed to respond to these limitations in a threefold approach. First it proposes setting up of a monitoring schedule for the structural defects observed in CSS 1; to ascertain if there is any continuing de-stabilizing phenomena and to follow its evolution. Next, the building will be modelled with varying levels of refinement and the process will be carried out as two distinct tasks. In the first stage of modelling, the building will be modelled in its entirety on four reconstituted geometries, using basic mechanical properties of materials adopted from literature; and analyzed through simple linear elastic technique. The results from this task will be used to schedule laboratory and in-situ material tests and to carry out investigation of the local soil conditions. In the second stage of modelling, part models of the identified critical zones will be prepared and will be informed by the experimental data gathered through material and soil investigation. At this stage the analysis will be carried out through the use of more complex non-linear constitutive equations. The comparative results of quantitative and qualitative assessment (CSS 2) will be used to develop structural interventions options. These will then be tested and evaluated with the help of the analytical models to ensure minimum intervention to the building and its cultural values; before the most suitable interventions are recommended for implementation which are reversible and allow for re-treatability.

CSS 4 *Monitoring of observed structural defects in the building*

Monitoring the behavior of the building provides invaluable information about any progressive phenomenon that might be affecting the building and hence its safety. It helps in the elaboration of the diagnoses and in the selection of the intervention measures. The monitoring will involve recording the behavior of the observed damages in CSS 1 and those determined through documentation CSA 1 and analytical modelling CSS 5; to determine whether the observed phenomenon are ongoing or have stabilized. The monitoring system will be used to measure parameters such as deformations, cracks, level differences etc. The monitoring schedule for the Museum building is discussed in detail in Section 4.3.2.1.

CSS 5 *Completion of Analytical Modelling with Linear Elastic Analysis and its evaluation*

The process of modelling the entire building, taking into account its history, and analyzing it through linear elastic technique would provide an understanding of the global structural behavior of the building. It will also provide quantitative results regarding the distribution of stresses and deformations in the building.

The process took its cues from the historical survey (CSH 1) to create four models corresponding to the subsequent construction stages experienced by the building. This helps understand the impact of architectural and structural interventions on the current condition of the building. The geometry of the models was created using the set of measured drawings (CSA2). The results obtained were evaluated and tallied against the qualitative assessment (CSS 2) and as the results are deemed comparable therefore the models are considered accurate.

This process helped identify the critical zones in the building in a quantitative manner and should be used to schedule laboratory and in-situ material tests and to carry out investigation of the local soil conditions. This process limits the need of samples otherwise required, for the adequate material characterization of such a large scale building, for laboratory testing (CSM 2). Hence ensuring the preservation of the culturally significant material and in turn the cultural value of the building. The laboratory tests that need to be carried out are discussed in detail in Section 4.3.2.2. This task also pinpoints locations that are in need of monitoring (CSS 4) besides those identified through CSS 1 and CSA 2. Furthermore, it also identifies some additional measured drawings that will be required for the preparation of a restoration project (CSA 5). The results of this task are presented in Section 3.3 and Section 4.1 of this thesis. This task has also been used to develop the recommendations presented in Section 4.3.

CSS 6 *Soil Investigation Studies*

The geo-technical investigations can help identify the cause of various damages, such as differential settlement and cracks, in a building. To guide the investigation of the local soil conditions cues will be taken from CSS 1, CSS 5 and CSW 2. This task will be carried out by geotechnical engineers. The type of tests recommended for the Museum building are discussed in Section 4.3.2.4.

CSS 7 *In-Situ testing of materials*

In situ tests give reliable results for assessment of material properties but determination of the type of tests, locations where the tests should be carried out and interpretation of the data needs careful consideration as well as expertise. The schedule of tests should be based on assessment of the phenomena that needs to be understood. Hence the assessments formed in tasks CSS2 and CSS 5 will guide the type of tests that will be carried out and also determine the location of the tests. This task will be carried out on-site and specialized teams of experts will carry out these tests to ensure reliability of the results. The type of tests recommended for the Museum building are discussed in Section 4.3.2.3.

CSS 8 *Structural Assessment of critical locations through part models with non-linear analysis*

This task should be performed in order to avoid any interventions that can either endanger the safety of the building by being insufficient or affect the cultural value of the building through over strengthening. The part models will be prepared from the models generated in task CSS 5 and use the input data for material and soil characterization from CSM 3, CSS 6 and CSS 7, to run non-linear analysis. The rationale for carrying out this task is discussed in detail in Section 4.3.2.5.

CSS 9 *Research on any necessary structural interventions*

Once the structural problem zones have been isolated through CSS 5 and have been analyzed in-depth through CSS 8, multiple structural intervention options shall be considered. Cost and benefit analysis of each solution will be carried out; cost being the potential loss of fabric due to the proposed intervention and benefit being the effectiveness of the therapy to ensure the safety of the building. This process will be carried out through full coordination with the geotechnical engineers, material scientists and public health engineers.

CSS 10 *Testing of structural intervention options in analytical models*

This task will allow the conservation engineers to experiment with the building in a virtual environment; by studying the impact of every intervention option in a completely non-destructive manner. The analytical models developed in CSS 5 and CSS 8 will be used to test the effectiveness of various structural stabilization options developed in CSS 9.

CSS 11 *Evaluation of Recommendations for structural stabilization interventions and techniques*

In this task, out of the options tested in CSS 10, only those options will be evaluated that will be deemed equally safe and will be subjected to another cost and benefit analysis. The final solutions recommended for implementation will be reversible and re-treatable and will be decided through extensive consultation with the conservation architects to ensure preservation of the cultural values embodied in the building through minimum intervention. All the stabilization intervention solutions brought to the final evaluation shall be documented and the reasoning behind rejecting or accepting a particular therapy recorded.

CSA14 *Prioritized List of the Conservation Works to be executed*

In this task, all the structural stabilization solutions and techniques being executed will be monitored. If the data obtained from monitoring at this stage provides evidence that size of interventions can be reduced then subsequent decisions will be revisited. Revision and/ or readjustment of the design scheme will be considered, through consultation with the key stakeholders.

CSS 12 *Monitoring of Structural Stabilizing Measures*

After the completion of the architectural conservation project (CSA 15), long term monitoring schedule will be set up to periodically check the effectiveness of the structural stabilizing measures used in the building. Monitoring of the building at this stage will also help identify any problems that may arise from any of the interventions made to building, during the course of the conservation works. Additionally, to test out the efficacy of any future works to be carried out on the Museum building, the results obtained from monitoring will be used to recalibrate and refine the analytical models

4.3. Recommendations

Recommendations for structural rehabilitation of a historic building must coalesce technical knowledge with the cultural values embodied in the building, to reach the best decisions vis-à-vis structural interventions. These interventions to be successful must be based on the principles recommended in the Venice Charter (1964) i.e. guarantee of structural stability, respect for cultural value of the building, minimum intervention, reversibility and integration on the whole building. Additionally, the ISCARSAH (2003) principles of adopting the medical analogy, reconciliation of the qualitative and quantitative to reach a diagnosis and that therapy must address the cause and not the symptom; must also be used as guides when recommending structural interventions.

In keeping with the approach presented above, the recommendations for the Museum building are designed to be two pronged. The *Immediate Actions*, recommend non-invasive forms of interventions as intermediary measures while *Further Studies* propose those pre-conservation studies that need to be carried out in order to develop a better informed, holistic structural conservation program.

4.3.1. *Immediate Actions*

This section enumerates some interim measures that need to be taken to safeguard the building till better informed structural solutions can be developed; in light of the evidence established through further studies. This scientific yet empathetic approach will allow for the development of a structural conservation program that adheres to the principles set forth by the modern approaches to conservation.

Restriction of Use

Restriction of use is being recommended for two parts of the building that have been identified, through the course of this study, to be in need of immediate attention.

Pre and Proto Historic Gallery and adjacent Public Toilets in Eastern Part of the Building

Most critical of the structural damages are observed in the northern wall of the Pre and Proto Historic Gallery (Gnd-E/04-N-W) - Block B. The wall besides having two vertical cracks, one through the central arch and a second through the eastern arch, is showing signs of lateral buckling, differential settlement and is out of plane. The probable causes of these observed damages could be the worsening of the local soil conditions due to possible water leakage from the adjacent public toilets (Gnd-E/05 - E/08) - Block A, and structural alterations to the roof of the gallery.

Therefore, it is proposed that the public toilets adjacent to space Gnd-E/04 (Pre and Proto Historic Gallery) should immediately be closed off to public and the water supply to these toilets shut down. In-situ and laboratory tests should be performed on soil by geotechnical engineers to determine the local soil conditions. Additionally, the cracks and differential settlement of the wall should be monitored to ascertain if the phenomenon are on going or have stabilized, before any remedial measures are prescribed.

Reserve Godowns and Storage Spaces in Western Part of the Building

The roofs of the storage spaces (Gnd-W/13, W/15-W/17) - Block H and reserve godowns (Gnd-W/04-W/05 & Gnd-W/19-W/20) - Block R on the ground floor are sagging while the partition walls of these spaces exhibit out of plane behavior. The probable cause of these damages is the alteration in the building constitution, through the addition of the first floor in both Block H and Block R to house reserve godowns and a further second floor in Block R for library storage. This has led to a substantial increase in gravity loads and as the slabs and partition walls on the ground floor were not designed to take this load we observe the aforementioned structural damages. This phenomena is further aggravated due to the presence of structural discontinuities in this part of the building.

Therefore it is proposed that the upper floors in this part of the building no longer be used to store heavy objects. Alternatively, if the demolition of this part is considered as per the recommendations made by Usman Sami (2017, p. 386) then the impact of such a change on the global behavior of the building should be studied as reduction of loads can also cause damage to the building which has attained equilibrium. This task should be carried out using the analytical model, developed as part of this thesis, which has been calibrated using the material characterization data from laboratory and in-situ material tests. If the ensuing results show that such a scheme can cause further damage to the building and no alternative space can be found for the storage of the reserves then design of a secondary support sytem should be considered. Furthermore, the objects which are currently haphazardly strewn in these space should be placed systematically to ensure equal load distribution.

Limitations on Future Works

Through the course of this study, it has been firmly established that anthropogenic actions are the main cause of damages that afflict the building in its current condition. Therefore, limitation on the scope of future works is being proposed till a holistic Conservation Management Plan (CMP) is not put into action. Preventive maintenance, such as re-pointing necessitated by loss of mortar or replacing of worn out water proofing, should continue. Maintenance work of such nature minimizes further damage and deterioration of the heritage, keeping at bay the need for more intrusive interventions. In an event where structural elements are to be intervened upon, prior to the setting up of a CMP, conservation engineers should be consulted. The effects of any proposed schemes should be determined on a holistic level prior to implementation, through the use of analytical models. To develop and maintain a repository of structural interventions all actions should be documented in a report.

Measures to Control Moisture in Brick Masonry

The degradation of brick masonry is inextricably linked to its constituent materials. The presence of moisture in masonry coupled with temperature variations and existence of salts, causes weakness in masonry which can adversely impact the structural safety of the building. Through the course of this study, it is evident that the Museum building faces rainwater drainage problems which is introducing moisture and salts into the building, through phenomenon such as rising damp and rain water penetration. Hence there exists a need to carry out a detailed investigation as to the drainage system of the Lahore Museum, which has been incrementally installed in an arbitrary fashion, and the sources of moisture in the building. Public Health Engineers should be tasked to document the current condition of the drainage system and to probe parts of the building fabric which show signs of dampness for plumbing and sewage leaks. This information is crucial to the structural safety of the building as such leaks can affects the bearing capacity of the soil. Till such an extensive study is not carried out preventative measures need to be taken to minimize further damage and decay.

Therefore, in order to control rainwater penetration, it is recommended that water proof coating on the flat roofs which is worn out and peeling should be repaired or alternatively replaced by a rubber membrane. Furthermore, the corrugated steel or iron roofing on the skylights should be repaired or replaced and sufficient overlaps provided at the joints to curtail water ingress into the building.

Additionally, in Lahore Museum the rainwater directly discharging onto the ground, at the base of the exterior walls, is a major cause of rising damp in the building. Therefore, in order to control this problem it is recommended that the slopes of the paved areas immediately adjacent to the building should be maintained to channel water away from the building. Also if feasible the material of the paved areas which is currently concrete should be replaced with more pervious material, which would allow the rainwater discharge to be absorbed into the soil. Moreover, in the last few decades concrete parging has been applied to the exterior walls, which has driven dampness up the walls. Its removal should be considered in light of the cultural significance of the building and is the purview of conservation architects.

4.3.2. *Further Studies*

This section enumerates the pre-conservation studies that need to be carried out to collect data that is crucial to developing structural solutions which are in sync with the principles proposed in the modern conservation studies. These structural measures will assist in proposing a holistic structural conservation program which is key to carrying out a successful architectural restoration project.

4.3.2.1. Monitoring Works

Monitoring of the building, carried over a period of time, can yield invaluable information when progressive non-stabilizing phenomena are suspected. It is important to understand if the observed deformations are “active” or “static” to determine the course of action.

Monitoring system in Lahore Museum should be set up to record changes in cracks, level differences and out of plumbness that have been detected during the course of this study. Monitoring schedule can also be set up to observe moisture penetration into the building and temperature variations.

Monitoring the Cracks

Vertical and diagonal cracks have been observed spread all over the building with the highest concentration in the northern part of the building. Due to lack of monitoring, no data is available to determine whether these cracks are “active” or “static”.

The vertical cracks observed in the northern wall of Pre and Proto Historic Gallery (Gnd-E/04-N-W) can be monitored either by using the displacement tell-tales or through fissurometers attached to data loggers which transmit the record to computers in real time (Croci, 1998, p. 74). Of the two the former is cheaper to install but less accurate than the later. Therefore, both methods should be subjected to cost-benefit analysis before a method is decided upon, where cost is measured as the potential loss of cultural value and benefit as the knowledge gained.

For the remaining cracks plastic tell-tales can be used to measure movement across the cracks in horizontal as well as vertical direction. The tell-tales can measure movement with an accuracy of ± 1 mm, which can be increased to ± 0.1 mm by measuring distance between the monitoring spigots with a Vernier caliper.

Monitoring the Out of Plumbness of Walls

The out of plumbness of the walls can be monitored by two different methods and the decision to choose one over the other must be subject to a cost-benefit analysis.

Plumb-bobs can be used to check the verticality of the walls. To increase accuracy the plumb-bobs should be furnished with vanes and suspended in buckets of water to reduce oscillations. Micro-meters should be used to take measurements between the plumb wire and metal studs permanently fixed to masonry. This method is labour intensive when multiple points need to be checked though cheaper in prime cost (Beckmann & Bowles, 2004, p. 55).

Alternatively, dual axis digital inclinometer with MEMS tilt sensors can be used to observe the tilt or out of plumbness of the walls. They can be fixed directly onto the structural member and periodic readings. They can be easily automated with data loggers and can be read remotely. Although the initial set up cost of this method is high but of the two methods it is more accurate and requires little manual labour. It is also less intrusive in a building which is in use and open to public.

Measuring the Differential Settlement

Differential settlement can be monitored by mounting studs on opposite ends of the walls and the distance between them can be periodically measured. Alternatively, inclinometers or titlmeters can be used. The selection of the method used should be subjected to a cost-benefit analysis.

Additionally, periodic measurements should be taken to determine the amount of moisture penetrating into the building and percentage of water in the construction materials through the hygrometers and moisture meters respectively. Furthermore, strain gauges can be used to measure the stresses in the materials.

4.3.2.2. Laboratory Tests

Laboratory tests should be carried out by material scientists to define the physico-mechanical, mechanical, physical and compositional properties of the construction materials and to identify the strength and durability of the materials along with the probable causes of deterioration. This data will provide material parameters required by conservation engineers to carry out finite element modeling and particularly to execute non-linear analysis on the masonry structural elements.

The samples from the Museum building should be taken from areas which show signs of various material deterioration types and from zones that exhibit structural problems, identified through qualitative and quantitative assessment, to carry out the laboratory tests.

Laboratory Tests for Physical Properties

To assess physical properties of materials, tests such as density and porosity test, and water vapour permeability test should be performed, in the laboratory, on the samples taken from the Museum building.

Bulk Density and Porosity Test is useful for identifying material performance and can also be used to check the effectiveness of a treatment aimed at improving the performance of the material. The porosity of the material affects its performance as a more porous material is more water and vapor permeable. The relationship of density and porosity of the material is reciprocal; as one increases the other decreases.

Water Vapor Permeability Test helps determine the resistance of the material to moisture penetration and is useful for understanding material deterioration problems in historic buildings due to dampness. A low water vapor permeability means that material is breathable while a higher value points to the imperviousness of the material. To carry out this test samples should have two parallel faces and a diameter of at least 1.5cm.

Laboratory Tests for Mechanical Properties

The mechanical properties of materials should be determined using Point Load, Indirect Tension Test, Uni-Axial Compression, and Ultrasonic Pulse Velocity (UPV) tests. These laboratory tests should be carried out and assessed by material scientists.

Point Load Test is used to determine the strength index for strength classification of rigid materials. It can also be used to predict other correlated strength parameters such as material anisotropy and its uniaxial tensile and compressive strengths (Zacoeb & Ishibashi, 2009, p. 46). Depending on the shape and size of the samples available three configurations of the point load test can be used. *Diametric Test* should be used when length/ diameter ratio is greater than 1.0 while *Axial Test* should be used for samples with length/diameter ratio of 0.3-1.0. *Block and Irregular Lump Test* should be used for block or irregular lump samples, of size 35-50 mm and with depth/width ratio between 0.3-1.0; preferably close to 1.0 (Bieniawski, 1974, p. 2).

Indirect Tension (Brazillian) Test can be used to determine the uniaxial tensile strength of brick and brick masonry samples (Beckmann & Bowles, 2004, p. 97). It should be noted that this test gives a little higher strength value compared to the direct tests but is far more practical (Teomete, 2004, p. 11).

Uni-Axial Compression Test is used to measure the uniaxial compressive strength of a material, using samples with regular geometry, for strength classification and characterization (Zacoeb & Ishibashi, 2009, p. 46). By using strain gauges and linear variable differential transformers, modulus of elasticity and Poisson's ratio of the materials can also be determined through this test (Teomete, 2004, p. 11).

Ultrasonic Pulse Velocity (*UPV)* is a non-destructive test that can be performed in-situ or in the laboratory. It is used for the detection of visible and non-visible defects (cracks, detachments, voids etc) and to determine material soundness (CIB Commission, 2010, p. 17). It is also possible to estimate the compressive strength of the material as well as the elastic constants like MoE and Poisson's ratio (Özerkan & Yaman, 2007, p. 1). According to various scientific studies, higher UPV values mean higher compressive strength and MoE values.

Laboratory Tests for Chemical Properties

The chemical properties of the materials should be assessed through the use of tests such as X-Ray diffraction (XRD), Cross Section Analysis by Optical Microscopy, FTIR Analysis and Spot Salt Test.

X-Ray diffraction (XRD) Analysis should be used for the characterization and identification of crystalline components present in composite materials. In material characterization science, X-ray powder diffraction is the most prevalent technique. It is a two phased analysis technique; the first phase is qualitative and allows for the separation and identification of the various crystalline components present in the composite material. The second phase is quantitative and is used to determine the approximate weights of each constituent component in the composite material being analyzed (Cullity, 1978, pp. 397, 398, 407 & 408).

Cross Section Analysis by Optical Microscopy should be used for analyzing the physical, chemical and the micro-grain structure of the material and can be used to examine defects, contaminants, cracks etc. to determine the cause of degradation and decay. In this procedure the material cross-section prepared in the laboratory is studied with a stereo-binocular microscope under reflected light.

Fourier Transform Infrared Spectroscopy (FTIR) Analysis is used for the characterization and identification of constituent compound present in composite material sample and to determine the cause of degradation and decay. Each compound produces a unique IR spectrum that relates to its chemical composition. A large number of FTIR spectra on a surface can be collected through the imaging equipment to produce distribution map of identified compounds. One of the main reasons for choosing this microdestructive analysis technique is because it requires tiny samples (1 to 2 mg) (Urland & Borrelli, 1999, p. 11).

Spot Salt Analysis is used to indicate the type of salt present in the sample. Although it is a qualitative test, as it does not provide information about the quantity of salts, it assists in developing an understanding for the types of deterioration and their causes (Borrelli, 1999, p. 15; Teutonico, 1988, p. 58). The most common salts found in masonry are the carbonates, sulphates, chlorides, phosphates, nitrates and nitrites; the presence of each is determined by carrying out a separate test (Borrelli, 1999, p. 16; Teutonico, 1988, p. 63).

4.3.2.3. In-Situ Tests

In-situ tests should be executed and the data assessed by specialized teams of experts to ensure reliability of results. Non-destructive Tests (NDT) are the preferred choice for historic buildings; if these do not yield sufficient data then Minor Destructive Tests (MDT) should be considered. Only as a last recourse should the destructive tests be considered and their necessity deliberated upon and subjected to a cost-benefit analysis. As per ISCARSAH Recommendations (2003) and CIB Guidelines (2010) different test methods should be concurrently used and the results compared to ensure the accuracy of the results. In light of these recommendations multliple tests methods are being recommended to be carried out simultaneously at the Lahore Museum.

In-Situ Tests for Masonry

Quantitative InfraRed Thermography (QIRT) is and NDT test should be used to identify material anomalies, surface and subsurface defects and to detect moisture in porous materials. It can also help understand the causes of decay besides determining effectiveness of repair techniques (Akevren, 2010, p. 20).

UPV is an NDT test that should be used to detect flaws in masonry and to determine material soundness besides estimating it’s the compressive strength as well as the elastic constants (CIB Commission, 2010, p. 17; Özerkan & Yaman, 2007, p. 1). The test can be carried out in two ways; direct transmission mode where transit time readings are taken mutually perpendicular to each other or the indirect transmission mode where transit time readings are taken parallel to the surface. As direct transmission mode gives more accurate results it should be used wherever it is possible to do so. It should be noted that the values of elastic constants can be determined through this test but they are generally higher as compared to the destructive tests (Teomete, 2004, p. 8).

Surface Penetrating Radar (SPR) Technique is an NDT technique that is used to characterize multi-wythe walls. Therefore, it should be used in the Museum building which has multi-wythe walls, to identify internal anamolies in the masonry. It can detect metal ties inside the masonry as well as zones with the moisture and high salt content. It can also be used to determine the effectiveness of repair techniques (CIB Commission, 2010, p. 18; Maierhofer & Wöstmann, 1998, p. 261).

The three tests mentioned below should only be considered to be used if the aforementioned tests do not yield sufficient data.

Endoscope Analysis is an MDT method. Endoscope which is a fibre optic viewing device incorporates an internal light and an inspection camera which makes it very effective in observing and recording identified anomalies and internal wall components around the holes drilled into the walls. They also come with graduated scale in the viewfinder which can assist in identification and sizing of objects. Endoscopes are preferred over boroscopes because of their flexibility and smaller diameters although they can be used as an alternate to one another (CIB Commission, 2010, p. 17).

Flat Jack Test is an MDT technique that helps determine the stress-strain relationship of masonry as well as its strength, current stress levels and modulus of elasticity (CIB Commission, 2010, p. 17; Croci, 1998, p. 71). This technique can also be use to obtain the resistance of masonry in compression under increased applied loads. For thicker walls a dialometer can be used as an alternate to flat jack (CIB Commission, 2010, p. 18).

Drilling Energy Test is another MDT technique that can be used to assess the compressive strength of masonry by measuring the power consumption required to drill a standard diameter hole in masonry elements. It must be noted that the results must be calibrated by comparison with other approaches (CIB Commission, 2010, p. 18).

In-Situ Test for Cast Iron (CI)

Leeb Rebound Hardness Test (LRHT) is an NDT compression test used to determine the hardness of the material and also the volume and configuration of the graphite. The tensile strength of CI, which is highly dependent on the amount of graphite, can therefore be estimated through hardness values using established empirical relationships. The yield strength and the fatigue behavior of the material can also be indirectly determined through this test. In this method the energy in the impact body is measured and compared, before and after the force is applied. This provides results in form of Leeb Rebound Hardness Unit (HL) using the following equation:

$$\text{HL} = \frac{\text{velocity rebound}}{\text{velocity impact}} \times 1000$$

Greater rebound velocities result in higher hardness values which consequently represents the hardness of material as the impact body rebounds faster from harder material samples than the softer ones (Krichko & Valente, 2018, pp. 19-20).

UPV is also an NDT test that can be used for the detection of imperfections and voids in CI. As the load carrying capacity of CI is dependent on the presence and extent of voids and imperfections, this technique is useful in understanding the behavior of the CI columns (Beckmann & Bowles, 2004, p. 77). The measurements should be taken for multilple columns, at the top, mid-height and base of each column at 120° spacing around the circumference. The ultrasonics can be calibrated using results from the drilling test (Beckmann & Bowles, 2004, p. 211).

Drilling Test is an MDT test that can be used to establish the cross sectional area of the CI columns and for the detection of eccentricity. This method can also provide insight into the internal conditions of the columns such as presence of blowholes, layers of corrosion etc. To determine the cross sectional area of the hollow CI columns, three evenly spaced holes should be drilled about the centre of the column at slightly varying heights, to avoid weakening of the element. Circumference of the column should be measured at each level in order to calculate the diameter of the column at each drilling location. A straight wire should then be inserted into each holes till it touches the opposite wall of the column. The length of the inserted wire should be subtracted from the diameter, to determine the wall thickness at each location. This information can then be used to calculate the cross sectional area. This procedure should be repeated for multiple columns. The eccentricity can be determined by comparing the wall thickness at each location with the mean wall thickness of each column (Krichko & Valente, 2018, pp. 16-17).

In-Situ Tests for Timber

To assess the soundness of timber members and for the detection of visible and invisible cracks, voids, increase in porosity etc., *UPV* testing combined with *QIRT* should be carried out.

4.3.2.4. Geo-technical Studies

To fully understand the local soil conditions laboratory and in-situ soil tests, presented below, should be carried out by geotechnical engineers. They can be used to define the state of stress under loading, load carrying capacity and for determining the agents causing damage to the structure.

Cone Penetrometer Test is an in-situ test that should be used to quantitatively determine the approximate soil strength. As the test is conducted without soil removal it gives a relatively accurate reflection of the underground conditions. *Hand-Auger Test* that is also an in-situ test that should be used to qualitatively determine the nature of the soil as well as the relative strength of the penetrated strata. *Speedy Moisture Test* is another in-situ test that can be used to determine the moisture content of the soil (Beckmann & Bowles, 2004, pp. 283-285). An additional in-situ test that can be carried out is the *Vane Shear Test*, to determine the shear strength of the soil (Beckmann & Bowles, 2004).

Trial Pits not only allow for the observation of the soil but also enables inspection of the foundations. Two or maximum three trial pits, with a plan area of 2 to 3 m^2, should be excavated by hand; till the bottom level of the foundation. One of the trial pits should be located where no problem related to soil settlement is observed. Soil samples should be collected from the soil strata at the side of the pit as well as the bottom of the pit for further in-situ and laboratory tests to determine soil type and moisture content. The samples can also be used to carry out contaminant analysis in the laboratory (Beckmann & Bowles, 2004, p. 282).

If the information gathered from the above mentioned tests is considered to be insufficient then *Core Drilling* or *Hand Operated Core Samplers* should be used to collect undisturbed soil samples. These samples should then be tested in the laboratory for accurate determination of the geotechnical properties of soil such as permeability, compressibility and strength (Beckmann & Bowles, 2004, p. 286). Additionally, *Piezometers* should be used to measure the level of ground water table (Croci, 1998, p. 77).

4.3.2.5. Part Models and Non-Linear Analysis

Masonry is a non-linear entity with its tension behavior not symmetrical to its behavior in compression. The linear FEM approach does not cater for the redistribution or the actual cutoff for tensile stresses beyond the tension limit of masonry. Notwithstanding, this approach has been successfully used in the characterization of structural behavior of large masonry structures with complex geometries. Even so, results of this approach should not be used to conclude on the strength and structural safety of masonry structures. Roca et al. (2010), and others propose that linear elastic analysis should always be performed for acquiring prilimnary information about stress distribution and deformational behavior of the structure. Henceforth, the information should be used to construct detailed part models of critical zones, which should be studied with more complex analyses techniques (Roca et al., 2010, p. 311).

Non-linear analysis is the most accurate technique for analyzing masonry structures, as it allows behavior of the structure to be analyzed even after some local elements have breached elastic limit till complete failure. Therefore, a non-linear analysis should be performed, to determine the true behavior of masonry structures such as their deformational behavior, failure mechanism and to understand the structural problems related to material degradation. A pre-requite to successfully carrying out this technique is the availability of detailed mechanical properties, pertaining to inelastic behavior of the materials, which can only be obtained through different in-situ and laboratory mechanical tests. It must also be noted, that the current computer technology puts limitations on the application of this technique to large scale buildings; on account of the intensive computational time and storage space required to carry out such a task.

In light of the discussion presented above recommendation is being made to evaluate the critical zones (Section 2.7.3, Section 3.3.3 & 3.3.4), identified through the course of this study, with non-linear analysis using part models after the acquisition of the detailed mechanical properties. Any structural stabilization solutions should be proposed based on the results of this study. In order to ensure that no intervention is made to the building that can endanger its safety by being insufficient nor affect the cultural value of the building through over strengthening.

4.3.2.6. Conservation Management Plan

This study shows that historically anthropogenic actions have been the main cause of damage to the building and its safety. Therefore, it is recommended that a Conservation Management Plan needs to be urgently put in place to ensure that in future sound decisions can be made about the conservation and management of the Museum building.

CHAPTER 5

CONCLUSIONS

This thesis for structural assessment of Lahore Museum adopted the methodology prescribed by the ISCARSAH Recommendations (2003) as frame work to define a structural conservation process and to develop recommendations. For the Museum building its case history was gathered through a comprehensive historical research, documentation of the building and on-site surveys. The structural assessment was based on integration of qualitative and quantitative approaches to reach a safety evaluation for the Museum building. The building was qualitatively assessed by juxtaposing the data gathered through historical research, documentation and on-site surveys of the building while quantitative assessment was based on structural modelling, that took into account historical dimension of the building, and its analyses.

As a result of the two set of diagnostic studies carried out as part of this thesis, it can be safely concluded that performance of the Museum building under seismic loading is satisfactory. The building shows little or no sign of distress due to seismic activity and this is inherently due to its design and construction technique as well as its location. The analyses also show that global structural behavior of the building is stable as none of the masonry elements is overstressed in compression despite the thresholds being based on conservative assumptions for both material properties as well as compressive strength of masonry.

Additionally, the study was successful in identifying localized zones that suffer from structural damage, incidentally all these zones are situated in the oldest and most culturally significant part of the building. This finding would have been alarming if the analysis had been conducted only on the current condition of the building and could have resulted in imprecise diagnosis. But by carrying out stage wise analyses on four reconstituted geometries it was possible to identify the affect of additions and alterations on the structural behavior of the building. The results of each stage when studied sequentially, conclusively showed that most of the problems originate from earlier additions and alterations carried out on the building. The building in its current state, having redistributed the loads and by attaining equilibrium, has stood the test of time. Hence, these problems are not a source of alarm at the present time. This study thereby reaffirms that historical background is a key consideration when structural vulnerability of a historic structure is being assessed. By including the history of the building it is possible to detect the origin of the structural problems and can help avoid implementation of strengthening solutions that can be harmful for the heritage. Having said that long-term damage processes, such as creep under constant stress, can induce significant, cumulative damage in masonry as was observed in case of the sudden collapse of Civic Tower of Pavia and Noto Cathedral in Italy. Hence, it is imperative that the zones identified as being afflicted with structural problems in the Museum building, be subjected to long term monitoring and in-depth studies, as recommended in the course of this thesis.

Furthermore, the studies show that all the interventions in the past i.e. the additions, alterations or repairs, have lacked a holistic approach and considered only the need or the part while ignoring the whole. Also, based on the assessment of both set of studies it can be conclusively said that most if not all of the structural problems afflicting the Museum building germinate from anthropogenic actions. To this effect a recommendation has been made in this thesis for the formulation of a Conservation Management Plan to ensure that future interventions to the building are more sympathetic and holistic in nature.

The most critical of the problem zones, the northern wall of the Pre and Proto Historic Gallery, identified through the qualitative assessment was studied by what can loosely be termed as “reverse engineering” method. The hypotheses set out by inductive reasoning as to the probable causes of damage were simulated in the analytical model. The results of this analysis confirmed the hypotheses to be true as the simulated behavior of the wall was found comparable with the observed behavior of the actual wall. Worsening of local soil conditions, due to probable leakage in the sewage and/or water supply of the public toilets adjacent to the wall, was determined to be the major cause of the incurred damage. Based on this finding intermediary action to close down the toilet to public and shutting off water supply to them is proposed besides recommending soil investigation studies and long term monitoring.

One of the limitation for this study was posed by the scale of the building and lack of experimental data for material characterization. This meant that the study could only be conducted using linear elastic analysis, which is a conservative technique used to form preliminary assessments in case of masonry structures. If no stress threshold is breached when analysis is carried out using this technique then the building can be considered safe and no further analyses is required. For the Museum building although tensile stress threshold is breached in some locations non-linear analysis could not be carried out as inelastic properties of materials were unavailable. If this sophisticated analysis technique was carried out using incorrect material and mechanical characterization it would give ineffective results which can lead to strengthening proposals that are harmful for the heritage. Additionally, for large structures it is intensive both in terms of time and computational efforts. Therefore, non-linear analysis technique has been recommended to study only those parts of the building that have been identified as having structural problems after the acquisition of the detailed mechanical properties through laboratory and in-situ tests. Material characterization of masonry is difficult due to the heterogeneous and anisotropic nature of its constituent materials. It is particularly the case for brick masonry, as mechanical properties of bricks can be different even if they are from the same kiln. Hence, for comprehensive material characterization large number of samples would be required for laboratory tests, which can have adverse effect on the structural safety and/or cultural value of the building. Therefore, it is recommended that in-situ NDT tests should be given preference.

The thesis proposes some non-invasive interventions as intermediary actions, keeping safety of people as well as the heritage in mind, till better informed structural solutions can be developed. A restrain has been shown in this thesis towards proposing strengthening solutions as a few pre-conservation studies i.e. monitoring and material characterization, through laboratory and in-situ tests, have still not been carried out. Any proposal based on incomplete information can result in over strengthening of the structure that will violate the “minimum intervention” principle and can cause needless loss of original fabric and a subsequent loss of cultural value embodied in the Museum building.

The comprehensive Structural Conservation Process proposed as part of this thesis is envisioned as a plug-in, into a holistic restoration project prepared for the Lahore Museum. This process, particularized through the ISCARSAH principles, elaborates an essential task-group in a multi-disciplinary Conservation Process proposed by Usman Sami (2017). Although, a clear direction has been laid out in this process but there are some pre-conservation studies that need to be carried out before it can be used in the preparation of an architectural conservation project.

The Author wishes that the analytical models developed for this study and recalibrated with material data, proposed to be acquired through laboratory and in-situ tests, can be used as a resource by the Museum Authorities. The updated models can be used to test out the impact of any future works planned for the Lahore Museum, in a virtual environment and in a non-destructive manner, to ensure a holistic approach and minimum intervention to the building. Additionally, this study conducted methodologically, using the ISCARSAH Recommendations as its framework, to assess the structural safety of a historic masonry building is the first of its kind to be carried out for a historic masonry building located in Pakistan. It is therefore hoped that the methodology adopted in this study can act as a precedent for future structural appraisals carried out on historically significant masonry buildings, found in abundance, in Pakistan. This approach would ensure that the buildings are dealt with, in an empathetic manner and the interventions to these buildings will be in keeping with the modern approaches to conservation.

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A. HISTORY OF ADDITIONS AND ALTERATIONS

Year(s)	Type	Stage	Definition	Source of Information	Relia bility
1888–1889	Design	Building Plans Prepared.	Mayo School of Art prepared plans for the New Museum.	(Revenue and Agricultural Department, 1889)	High
1889–1890	Primary Construction	Foundation Stone Laid.	By Prince Albert Victor.	(Revenue and Agricultural Department, 1890)	High
1892–1893	Primary Construction	Building practically complete.	Building not yet occupied.	(Revenue and Agricultural Department, 1893)	High
	Ornamentation	Central Gallery back wall decorated in color (paint).	The treatment was to serve as a sample for general decoration of the building. (Additional treatment of this type did not take place).		
	Ornamentation	Plasterwork ornamentation prepared	Designs, models, molds and casts have been prepared but not yet fixed in place.		
	Function	Stupa assembled in-situ.			
	Primary Construction	Coin safes are built into the wall of the office block.			
	Primary Construction	Gallery built and seats fixed in Lecture Hall.	Presently, the Auditorium		

Year(s)	Type	Stage	Definition	Source of Information	Relia bility
1893–1894	Ornamentation	Molded plasterwork installed.	On the doorways between the galleries.	(Revenue and Agricultural Department, 1894)	High
	Ornamentation	Decoration on the south wall of the Central Gallery.	Painted ornamentation complete.		
	Problem	Roof leaking.	The Executive Engineer stated that the expansion and contraction of the roof is too great and leakage is inevitable. They will try to rectify by October.		High
1894–1895	Problem	Roof leaking.	Problem not resolved by the PWD.	(Revenue and Agricultural Department, 1895b)	High
1895–1896	Repair	Roof leak fixed.	Problem resolved.	(Revenue and Agricultural Department, 1896)	High
1896–1897	Problem	Roofs leak.	Roofs leak periodically during heavy showers.	(Revenue and Agricultural Department, 1897)	High
1897–1898	Repair	Roof leak fixed.	Roof leaks fixed by the PWD	(Revenue and Agricultural Department, 1898)	High
	Repair	Half burnt brick exterior walls repaired.	Exterior walls built of half-baked bricks in some placed have been repaired and pointed with cement.		
1899–1900	Problem	Windows leak.	Large windows leak considerably.	(Revenue and Agricultural Department, 1900)	High

Year(s)	Type	Stage	Definition	Source of Information	Relia bility
	Problem	Zink gutters leak.	The zinc gutters wear out and have to be renewed frequently.		
	Repair	Roof overhaul.	Plans made for annual overhaul of roofing prior to the monsoons.		
	Problem	Mosaic floor wearing out.	Original materials used for the floor pavement were not good. The floor is under constant repair while parts of it wear out constantly.		
1900–1901	Repair	Mosaic floor repaired.		(Revenue and Agricultural Department, 1901)	High
	Problem	Roof leak.	Roofs leaking again. Contents of two cases damaged due to leakage from the gutters.		
1901-1902	Problem	Roof leak.	Roof leaks have gotten worse flooding two rooms during the monsoon. Suggestion made to make alternative roof drainage plans instead of using the leaky gutters.	(Revenue and Agricultural Department, 1902)	High
1902-1903	Problem	Roof leak.	New plans for replacing the gutters submitted for sanction.	(Revenue and Agricultural Department, 1903)	High
1903–1904	Problem	Roof leak.	New system of gutters still not watertight.	(Revenue and Agricultural Department, 1904)	High

Year(s)	Type	Stage	Definition	Source of Information	Relia bility
	Alteration	Mosaic floor to be replaced.	The deteriorating mosaic floor is to be replaced by a marble design.		
	Addition	Fountain to be built in front of the entrance.			
1904–1905	Alteration	Roof of the entrance and sculpture gallery and the verandas replaced	Roofs were removed completely and replaced	(Revenue and Agricultural Department, 1905)	
	Problem	Attempts made to improve the state of roof leakage	During winter rains, the gutters leaked at 13 different places.		
	Alteration	Mosaic floor replaced.	With marble.		
1905–1906	Alteration	Replacement of brickwork arches in the portico.	The brickwork flat arches in the portico have been replaced by a marble veranda.	(Revenue and Agricultural Department, 1906)	High
	Alteration	Replacement of terracotta grills flanking the porch.	Terracotta grills flanking the porch on either side have been replaced by 4 specially designed sand-stone *jalis*		
	Alteration	Replacement of window sashes.	All window sashes have been replaced and built to the original design which had not been executed and replaced with an alternative during the original construction.		
	Addition	Two cloak rooms added.	To either side of the entrance portico.		

Year(s)	Type	Stage	Definition	Source of Information	Relia bility
	Problem	Roof leaks.	Some galleries were flooded and several articles irretrievably damaged. Suggestion made to scientifically study roofing system in its totality.		
1906–1907	Alteration	Marble porch completed.	The design prepared at the MSA and carried out in Jodhpur white marble.	(Revenue and Agricultural Department, 1907)	
	Problem	Roof leak.	As much as usual. Small repairs carried out by PWD in a perfunctory manner. Not much attention paid to the building.		
1907–1908	Problem	Replaced roof leak.	Total replacement of the roof made no difference as the new roofs leaked the same amount as the old ones.	(Lahore Museum, 1908)	High
1908–1909	Alteration	Roofing to be replaced.	By corrugated metal sheets.	(Lahore Museum, 1909)	High
1909–1916	Addition	New gallery and administrative spaces added.	The new gallery has been built along with office, library and printing room along with a workshop for *mistreees* at the rear of the building.	(Central Museum, 1914, 1915, 1916; Lahore Museum, 1910, 1911, 1912, 1913)	High
	Repair	Picture gallery wall repaired.	The wall was opened up and rebuilt.		

Year(s)	Type	Stage	Definition	Source of Information	Relia bility
1916–1917	Ornamentation	Plasterwork	Completed on all but one doorway.	(Central Museum, 1917)	High
1918–1919	Problem	New roof leaking.	Roof of the newly constructed parts of the building leak.	(Central Museum, 1919)	High
	Repair	Picture Gallery walls re-plastered	The walls of the picture gallery were re-plastered with Portland cement.		
	Function	New gallery to be used as the Arts and Crafts depot.	The gallery was to be fitted with a permanent display of Punjab Industries and Arts and Crafts.		
1920–1921	Alteration	Central Gallery roof replaced	The arched portion of the roof [sic] has been replaced by a new wooden roof covered in malthoid sheets.	(Central Museum, 1921)	High
1921–1922	Function	Arts and Crafts depot shifted to the Lecture Hall	Leaving the New Gallery vacant.	(Central Museum, 1922)	High
	Repair	Sculpture gallery skylights repaired.	The skylights were repaired to increase the amount of light entering the gallery and prevent pigeons coming through.		
	Alteration	New doorway opened in the western gallery.	A new doorway was opened by the PWD between the lecture hall and the western gallery to connect the main museum with the arts and crafts depot.		

Year(s)	Type	Stage	Definition	Source of Information	Relia bility
1923–1924	Repair	New gallery roof was remodeled.	The roof has improved but there is still some leakage.	(Central Museum, 1923)	High
	Problem	All other gallery roofs leak.	Exhibits are damaged during every rain shower.		
1924–1925	Repair	Entire roofing was improved [sic].	General improvements were made to the entire roof of the building by the PWD.	(Central Museum, 1925)	High
	Alteration	Iron crossbars added to skylights in Tibetan Gallery.	Iron crossbars were added to skylights to increase security.		
	Alteration	Large window opened up Tibetan gallery.	Window opened up in the south wall of the Tibetan gallery to increase light.		
1925–1926	Problem	Sculpture gallery roof leak.		(Central Museum, 1926)	High
1926–1927	Function	New eastern gallery to be used as Sculpture Gallery.	The roof leaks have been fixed and the gallery is to be fitted with display cases.	(Central Museum, 1927)	High
	Problem / Repair	Dampness in the wall in the textile section damaged objects.	The display cases were repaired and refitted a few inches removed from the wall.		
1927–1928	Problem	Rising damp in walls of all galleries during rainy season.		(Central Museum, 1928)	High
1928–1929	Addition	New western gallery, new Coin Room, Godown, and 2 bathrooms built.	New gallery opposite the New Sculpture Gallery to be used for Painting displays.	(Central Museum, 1928, 1929)	High

Year(s)	Type	Stage	Definition	Source of Information	Relia bility
	Function	New central platform built in the middle of the Gandhara gallery	The sculpture gallery is now called the Gandhara gallery as most of the sculptural exhibits are Gandharan.		
	Problem	Curator's room roof leaked.	Room flooded and books damaged.		
	Problem	Textile gallery roof leaked.	Carpets and Silks damaged.		
1936–1937	Repairs	Minor leakages repaired by the PWD.		(Central Museum, 1937)	High
1937–1938	Alteration	New cement floors laid.	in Agricultural Forestry and Raw product Gallery, Indian Antiquities and Prehistoric Gallery and the Central Asian and Further Indian Objects Gallery.	(Central Museum, 1938)	High
1941–1942	Alteration	New conglomerated cement floor laid in the left wing of the Applied Arts Gallery.		(Central Museum, 1942)	High
	Alteration	Walls of the Tibetan Gallery and the former Arts and Crafts Depot re-plastered.			

B. DESCRIPTION OF SPACES

In the Museum accessing all the spaces in a sequential order is not possible as only a few spaces connect multiple spaces in the building. Most spaces when accessed by passing through a sequence of spaces are dead ends. The coding/ labeling of spaces on each floor and in different parts of the building are based on the sequence of their accessibility (See Section 1.3 and Figure 2.23). The description of spaces are thus more or less grouped based on the same logic of accessibility.

The description of spaces begins with the *Ground Floor* that is subdivided into the *Northern and Central*, *Eastern*, *Western* and *Southern* Parts. Each sub section then sequentially describes the spaces, according their circulation/ access, in that part of the floor and then through the serial number. One after the other the spaces in *Basement*, *First Floor*, *Second Floor* and *Third Floor* are discussed as per the building Parts. A systematic approach is used to describe each space and sequentially starts off with its Space Code, current use and the year of construction. Next, the dimensions of the space are presented as its width (east-west dimension) and depth (north-south dimension), followed by the height of the soffit of the ceiling from the plinth level. The floor level is only mentioned if it is above or below the plinth level. This is followed by the description of architectural features of each wall. Thereafter, the ceiling of the space visible from the underside is described. Where applicable the dimensions and/or location of the beams is also presented. In case of domes the details of the dome profile both interior and exterior is described. The space description ends with the information regarding the type of surface degradation and/or structural problem observed in the space.

Photographs accompany the description of each space to show its spatial quality and any visible material or structural problem. The photographs within the text are kept at a minimum but a sequenced and coded image library has been attached with this thesis on CD (APPENDIX E).

Ground Floor – Building Interior

This section deals with the description of spaces which are located on the ground floor and are accessible from within the building.

The Visitor interacts with the Museum by moving through the following sequences of spaces. They enter the building through space Gnd-N/01 which lead to Gnd-N/02 which guides them to the central gallery space Gnd-C/01. From this gallery space they can access gallery spaces Gnd-E/01 & 02 to the east, which lead to galleries Gnd-E/03 & 04 and end in the toilets for the public Gnd-E/05 – 08 or they can move to the west, to gallery spaces Gnd-W/01 and Gnd-W/02 & 03. Alternatively they can move south to space Gnd-C/02 which further offers two options gallery spaces Gnd-E/17 – 19 towards the east and Gnd-W/07 & 08 to the west. From space Gnd-E/18, gallery spaces Fst-E/10 – 15 on the first floor can be accessed.

The Reserves (Gnd-W/04 – 06) are accessible only through gallery (Gnd-W/03). The entrance to the Reserves is restricted to the Museum Administration.

Northern & Central Part – The Staging Area

Gnd-N/01

This space built in 1893 functions as the *Entrance Portico*. It is 8.8m (28ft. 10in.) in width and is 3.98m (13ft.) in depth; the soffit of the ceiling is +5.3m (17ft. 5in) above plinth level.

The space is accessed from its northern side which is colonnaded. It has three openings formed by two solid white columns in the middle and halved columns on the side. The columns carry solid marble lintels which are supported through stepped marble brackets (Figure 2.26). On its eastern and western walls are arched doorways leading to spaces Gnd-N/03 and Gnd-N/05 respectively. On the southern wall there are three openings. The central opening is the main entrance of the museum and leads to space Gnd-N/02. The two side openings are arched and fitted with doors which open onto the spiral staircases (Gnd-N/10 & 11). Directly above these doors are arched ventilators fitted with terracotta *jalis.* The roofing system of the space cannot be observed as it has carved wooden ceiling.

Figure B.1: Gnd-N/01 – Entrance Portico (2017)
Looking south the image shows the main entrance door to the Museum and the carved wooden ceiling. Also the walls built in exposed bricks can be observed.

The walls built in exposed brick have been repointed in cement mortar. Cement has been used to even out the surface of the bricks as well. The paint and the cement is flaking in numerous places to expose powdering brick.

Figure B.2: Gnd-N/01 – Entrance Portico (2017)
Flaking of red tinted cement layer and powdering of brick

Gnd-N/02

This space built in 1893 functions as the *Entrance Vestibule* and is the most ornamented space in the whole Museum. The space which is 5.78m (19ft.) by 5.78m (19ft.), is entered through a double layered four panel wooden door in the northern wall. The door is fitted in a flat arch opening which is supported with masonry brackets. The remaining three walls all have identical flat lintel doorways supported on brackets and ornamented with plasterwork. The doorways in the eastern and the western wall are blind and fitted with ornamental fireplaces while the doorway in the southern wall is open and space Gnd-C/01 is accessed through it. All walls excluding the doorways are fitted with a wooden dado. In the south-east and south-west corners, glazed tiles from a 17^{th} Century tomb have been fixed onto the walls with cement mortar and framed into the dado.


Figure B.3: Entrance Vestibule (2017)
Looking up (left) Looking South East (right)

The ceiling of the space is formed through cantilevers extending from all the walls and supported by three pairs of brackets on each side. A square opening is formed in the middle of the ceiling which visually connects the space to chambers Fst-N/06 and Thd-N/05 located directly above. The soffit of the ceiling is at +5.58m (18ft. 3in.) above the plinth.

Discoloration of paint due to dampness can be seen above the dado level on both the eastern and the western wall. Additionally the paint has swelled and is flaking off at various places. The dampness is also affecting the glazed tiles used in the dado as efflorescence is seen where the glazing of the tiles has flaked off.

Figure B.4: Gnd-N/02 – Entrance Vestibule – Deterioration (2016)
From left to right: Flaking of paint and detachment of molded Plaster of Paris; Flaking of paint on the Eastern Wall; and Flaking of paint and efflorescence on glazed tiles on Southern Wall.

Gnd-C/01

The space built in 1893 functions as the *Miniature Gallery,* additionally it acts as the central hallway of the Museum. It is 8m x 29.4m (26ft. 3in. x 96ft. 6in.) with the soffit of the ceiling at +12.43m (40ft. 9in.) above the plinth.

The space is entered through a flat lintel doorway in the northern wall. The doorway is part of the ornamentation in Plaster of Paris framed within a large arch, covering almost the entire northern wall. Above the doorway is a balcony supported on three pairs of brackets. The access to the balcony is through three archways above which are three openings fitted with terracotta *jalis*. The eastern wall has two large ornamented flat lintel doorways supported on brackets. The doorway at the northern end of the wall, has a decorative arch fitted with a Plaster of Paris peacock motif above it and leads onto space Gnd-E/01 while the doorway at the southern end of the wall leads onto space Gnd-E/02. Along the top of the wall there are eighteen arches of which ten have been fitted with ventilators while eight of them are blind. The southern wall has a corbelled bracketed doorway which opens onto space Gnd-C/02. Above the doorway in raised plasterwork is an arch, outlining the stylized and mirrored calligraphy in Arabic. The arch is surrounded by rectangular frame the same width as the doorway, in raised plasterwork. The doorway and the raised plasterwork ornamentation is framed within a large arch, covering almost the entire wall. The spandrels and thin vertical bands along the sides of the arch are decorated with glazed tiles.

Figure B.5: Gnd-C/01 – Miniature Painting Gallery (2017)
Looking North (left) Looking South (Right)

The two large doorways on the western wall are mirrors of those seen on the eastern wall. The doorway at the northern end of the wall onto space Gnd-W/01 while the doorway at the southern end of the wall leads onto space Gnd-W/02.The eastern wall also has eighteen arches along the top out of which of which ten have been fitted with ventilators while eight of them are blind. An ornamented plasterwork cornice runs along the top of all the walls.

The roofing system consists of I-Beams, running along the shorter span of the space in the E-W axis, supporting wooden battens and boarding. There is a metal frame suspended from ceiling. The roof has a central rectangular opening for a skylight which has been boarded up and can only be observed from the outside. The skylight measuring 3.5m x 28.72m (11.5 ft. x 94.25 ft.) has a double pitch and is built with a wooden frame fitted with glazing.

Swelling of plaster is observed midway up the eastern and the western wall. Discoloration of paint is also observed on the cornice of the western and the northern wall. There are drip marks near the ventilators on the southern end of the western wall. The marble floor is uneven and the marble has cracked in multiple points.

Figure B.6: Gnd-C/01 – Miniature Painting Gallery – Deterioration (2017)
Swelling of Plaster on the Eastern Wall (left) Marble floor pattern cracked (right)

Gnd-C/02

The space built in 1916 and modified in 1969, functions as the *Jain Gallery (I).* It is 7.88m x 1.93m (25ft. 10in. x 6ft. 4in.) with the soffit of the ceiling at +7.57m (24ft. 10in.) above the plinth.

The space is accessed through an ornamented corbelled bracketed doorway, in the northern wall. There is a doorway in the western wall leading to space Gnd-W/07. The southern wall in its middle has a large wooden door that opens onto space Gnd-C/03. The doorway in the eastern wall leads onto space Gnd-E/17. All the walls have a 2m (6ft. 6in.) high wooden paneled dado.

Figure B.7: Gnd-C/02 – Jain Gallery (I) (2016)
Looking South

The roofing system consists of I-Beams, running in the E-W axis, supporting wooden battens and boarding. The roof has a central square opening for a skylight which has been boarded up and can only be observed from the outside. The skylight measuring 2.5m x 2.5m (8 ft. 3in. x 8ft. 3in.) is built with a wooden frame which is fitted with glazing.

No visible signs of deterioration are observed in the space.

Eastern Part – Galleries & Services

Gnd-E/01

This space built in 1893 functions as the *Islamic Art Gallery*. The space is 30.48m (100ft.) wide and 18.28m (60ft.) deep; the soffit of the ceiling is +7.46m (24ft. 6in.) above the plinth level.

The space is accessed through a large doorway on its western wall. The doorway is fitted with plasterwork ornamentation which features a flat lintel supported on brackets at +4.5m (14ft. 9in.) above plinth, over which is a decorative arch 1.52m (6ft.) high, fitted with a Plaster of Paris peacock motif. The northern wall has nine arched windows which have been closed off with calligraphic paintings done on chipboard. Above these windows are sixteen arched ventilators. The eastern wall also has a doorway leading to the space Gnd-E/03. The doorway is similar in design and ornamentation as the one seen in the western wall. The southern wall has no architectural features of any importance.

Figure B.8: Gnd-E/01 – Islamic Arts Gallery (2017)
Looking East

The roofing system comprises of fourteen saw tooth trusses built with railway girders running in the N-S axis. The trusses on the periphery of the space are supported by the walls while in the middle of the space they rest on two compound girders running in the E-W direction, which in turn are supported by CI columns. There are twenty four CI columns which divide the space in five bays (N-S axis) and three aisles (E-W axis). Sixteen of the columns are embedded into the walls while only eight are seen in two row of four column each in the middle of the room.

Figure B.9: Gnd-E/01 – Islamic Arts Gallery – Structural Components (2016)
Saw Tooth Trusses built with railway girders (left) Cast Iron Columns supporting compound girders which in turn support the trusses (right)

Discoloration of paint due to dampness is observed on the upper portion of the western wall as well as the lower half of the northern wall. The calligraphic paintings fitted into the windows on the northern wall are also being damaged due to dampness. A crack is also observed on the floor, in the northern aisle of the space running in the East-West direction.

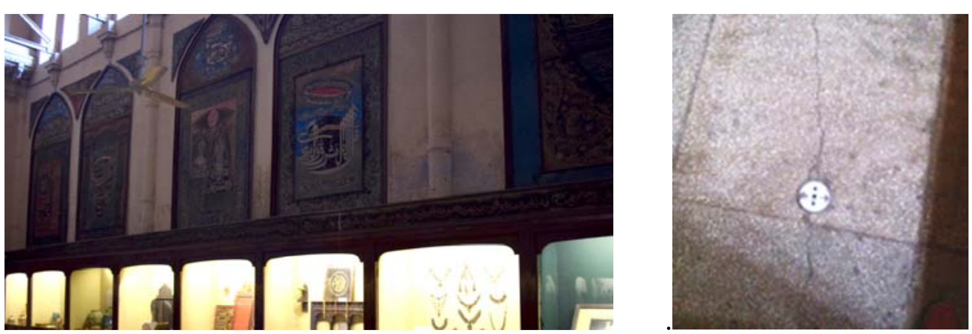

Figure B.10: Gnd-E/01 – Islamic Arts Gallery – Deterioration (2015)
Discoloration of paint due to dampness on the Northern wall (left) Crack observed on the floor (right)

Gnd-E/02

This space was built in 1916 and functions as the *Gandhara Gallery*. The space is 30.5m x 12.1m (100ft. x 39ft. 9in.) and the soffit of the ceiling is at +7.25m (23ft. 9in.) above plinth.

The space is accessed through an ornamented plasterwork doorway in the western wall. The northern and the southern walls of the space have no architectural features of importance. There is a doorway in the eastern wall which leads to space Gnd-E/03 and is similar in design and ornamentation to the doorway in the western wall.

Figure B.11: Gnd-E/02 – Gandhara Gallery (2015)
Looking West

The roofing system consists of I-Beams, running along the shorter span of the space in the N-S axis, supporting wooden battens and boarding. The roof has four rectangular skylights running in the E-W axis and resting on brick masonry. The skylights are in two rows of two and have pitched roofs that slope towards south and are fitted with glazing on the other three sides. Efflorescence is observed on the bricks masonry supporting the skylights.

Figure B.12: Gnd-E/02 – Gandhara Gallery – Deterioration (2016)
Efflorescence on brick masonry supporting skylight

Gnd-E/03

This space built in 1893 functions as the *Hindu and Buddhist Gallery*. The room is 9.07m x 34.2m (29ft. 9in. x 112ft. 3in.) and has the soffit of the ceiling at +12.36m (40ft. 6in.) above plinth level.

Figure B.13: Gnd –E/03 – Hindu and Buddhist Gallery (2016)
Looking South (left) Looking North (right)

The room is accessed through two doorways located on the western wall. Both doorways are fitted with plasterwork ornamentation featuring a flat lintel supported on brackets. The doorway on the northern end of the wall additionally has a decorative arch fitted with a peacock motif in Plaster of Paris, over the flat lintel. Along the top of the wall are twenty one arch openings, out of which ten are fitted with ventilators while the others are blind. The northern wall has a large blind arch while on northern end of the eastern wall is a doorway fitted with plasterwork ornamentation featuring a flat lintel supported on brackets over which is a decorative arch fitted with a peacock motif in Plaster of Paris. Also along the top of the eastern wall are twenty one arch openings, out of which seventeen are fitted with ventilators while the others are blind. The southern wall is a large arch vertically divided in three sections. The bottom and the middle section are blind but in the top section there are two triangular arches that are fitted with glazing. The room has an ornamented Plaster of Paris cornice running along all the walls of the space. The roof is an RC slab supported on I-Beams running along the shorter span, in the E-W axis.

There is swelling of plaster on both eastern and western walls at mid-level. Also paint discoloration due to dampness is observed in the roof.

Figure B.14: Gnd-E/03 – Hindu and Buddhist Gallery (2017)
Plaster swelling on Eastern wall (left) Discoloration due to dampness on roof (right)

Gnd-E/04

The space built in 1893 functions as the *Pre and Proto Historic Gallery*. The room is 8.53m x 18.3m (28ft. x 60ft.) with the soffit of the ceiling at +4.64m (15ft. 3in.) above plinth.

Figure B.15: Gnd-E/04 – Pre and Proto Historic Gallery (2016)
Looking South East; Discoloration and flaking of paint can be observed on the eastern wall

The space is entered through an ornamented plasterwork doorway in the western wall. On the northern wall are three arched windows. The eastern wall in the middle is fitted with a wooden screen behind which is space Gnd-E/09. On either side of the screen are doors which lead onto spaces Gnd-E/05 and Gnd-E/07. On the upper level of the wall besides ten identical rectangular recessions there is a blind arch at the southern end. There is a blind arch in the upper level of the southern wall. The roofing system consists of I-Beams, running along the shorter span of the space in the E-W axis, supporting wooden battens and boarding.

Discoloration and flaking of paint due to dampness along with efflorescence is observed in the eastern as well as the northern wall. On the northern wall vertical cracks are also observed passing through the central as well as the eastern window.

Figure B.16: Gnd-E/04 – Pre and Proto Historic Gallery – Deterioration (2016)
Discoloration and flaking of paint near the ceiling on the Eastern wall (left) Vertical crack passing through the central window on the Northern wall (right)

Gnd-E/05 & Gnd-E/06

Both spaces are part of the *Men's Toilets.* The space built in 1893 was previously part of the eastern verandah and was modified in 1965. Space Gnd-E/05 which measures 3.05m x 1.52 m (10ft. x 5ft.) functions as the *Corridor* while Gnd-E/06 is used as *Toilet* space and measures 3.05m x 5.88m (10ft. x 19ft. 3in.). The soffit of the ceiling for both spaces is at +4.64m (15ft. 3in.) above the plinth.

The access to space Gnd-E/05 is through a door in its western wall. There is no architectural feature of importance on its southern wall while on its eastern wall is a window over which is a ventilator. The door in the northern wall leads onto space

Gnd-E/06. The space Gnd-E/06 has three toilet stalls built in its north eastern corner. It has one exhaust fan in the middle of its northern wall and two exhaust fans on its eastern wall. Its western wall is blank while its southern wall has the door through which the space is accessed. The roof in both the spaces is an RC slab.

Figure B.17: Gnd-E/05 (left) & Gnd-E/06 (right) – Men's Toilet (2015)

Slight out of plane behavior is observed in the northern wall of Space Gnd-E/05. Also discoloration of paint due to dampness is observed on the ceiling of both the spaces.

Figure B.18: Gnd-E/05 – Men's Toilet – Deterioration (2015)
Discoloration of paint due to dampness on the ceiling

Gnd-E/07 & Gnd-E/08

Both spaces are part of the *Ladies Toilets.* The space built in 1893 was previously part of the eastern verandah and was modified in 1965. Space Gnd-E/07 which measures 3.05m x 0.91 m (10ft. x 3ft.) functions as the *Corridor* while Gnd-E/08 is used as

Toilet space and measures 3.05m x 5.5m (10ft. x 18ft.). The soffit of the ceiling for both spaces is at +4.64m (15ft. 3in.) above the plinth.

The access to space Gnd-E/07 is through a door in its western wall. There is no architectural feature of importance on its northern wall while on its eastern wall is a window over which is a ventilator. The door in the southern wall leads onto space Gnd-E/08. The space Gnd-E/08 has five toilet stalls built along its eastern wall. The space has two horizontal ventilators in its eastern wall. The southern and western walls are blank while the northern wall has the door through which the space is accessed. The roof in both the spaces is an RC slab.

Figure B.19: Gnd-E/07 (left) & Gnd-E/08 (right) – Ladies Toilets (2015)

Slight out of plane behavior is observed in the northern wall of Space Gnd-E/07 while in space Gnd-E/08 flaking of paint due to dampness is observed in the upper part of its western wall.

Gnd-E/17

This space built in 1916 functions as *Jain Gallery.* It is 9.06m x 6.05m (29ft. 9in. x 19ft. 10in.) with the soffit of the ceiling at +7.62m (25ft.) above plinth.

The space is accessed through a doorway on its western wall. On the other three walls a carved wooden balcony has been fixed. Under the balcony on the eastern wall there is a doorway the lead onto space Gnd-E/18. The floor in the doorway is lowered by 30.5cm (12in.) through a double stepped square trough in white marble. All the walls have a wooden dado. The roofing system consists of I-Beams, running along the shorter span of the space in the N-S axis, supporting wooden battens and boarding.

Figure B.20: Gnd-E/17 – Jain Gallery (II) (2017)
Looking East

Swelling of plaster is observed on the south wall while paint is flaking at the upper level of the western wall.

Figure B.21: Gnd-E/17 – Jain Gallery (II) – Deterioration (2016)
Swelling of plaster on the South wall while flaking of paint on the Western wall

Gnd-E/18

This space built in 1972 functions as *Armory Gallery*. It is 20.53m x 9.67m (67ft. 3in x 31ft. 9in.) with the soffit of the ceiling at +4m (13ft. 2in.) above plinth level.

The room is accessed through a doorway in the western wall. The northern as well as the southern wall are fitted with floor to ceiling display units. The eastern wall clad in black marble has two arched doorway leading to space Gnd-E/19. In the middle of the space there are ten pairs of circular RC columns, in two rows of five pair each. There is a staircase in the south west corner leading onto space Fst-E/10. The space has an RC slab roof. There are no visible signs of deterioration in this space.

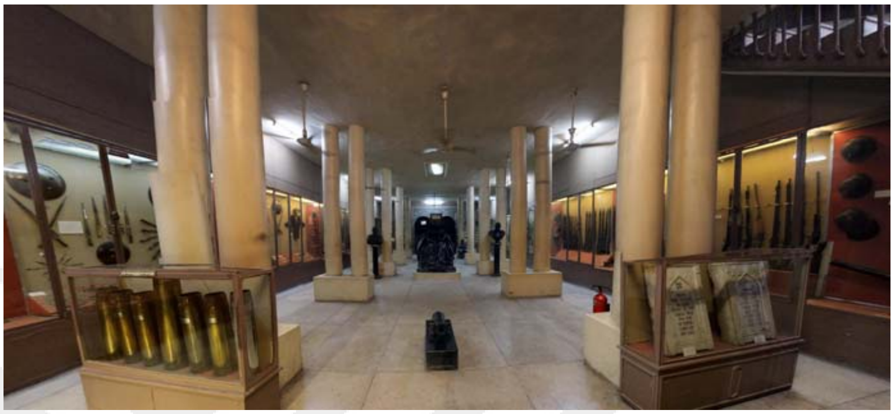

Figure B.22: Gnd-E/18 – Armory Gallery (2016)
Looking East

Gnd-E/19

This space built in 1972 is currently used as a *Reserve Store* for the Museum's painting collection. The room is 10m x 10.24m (32ft. 9in. x 33ft. 6in.) with the soffit of the ceiling at +4.2m (13ft. 9in.) above plinth.

Figure B.23: Gnd-E/19 – Reserve Store (2016)
Looking East

The space is accessed through two arched doorways in its western wall. The northern wall is entirely covered with floor to ceiling display cases. Nearly half of the southern wall is fitted with similar display cases and at the eastern end the wall traces of a blocked doorway can be seen. There is a wooden screen fitted into an opening on the eastern wall behind which is space Gnd-E/20. The roof is an RC slab supported by three RC beams running in the E-W axis. No sign of deterioration are observed in this space.

Western Part – Galleries & Reserves

Gnd-W/01

This space built in 1893 functions as the *General Gallery*. The room is a mirrored space of Gnd-E/01 which has been described in detail in above (Section 2.1.7.2).

Figure B.24: Gnd-W/01 – General Gallery (2017)
Looking West

Flaking as well as discoloration of paint due to dampness is observed on the lower half of the northern wall in this space. Drip marks flowing down from the ceiling observed on the Southern wall show the lack of water tightness.

Figure B.25: Gnd-W/01 – General Gallery (2016)
Flaking of paint and discoloration due to dampness on the Northern wall (left) Drip marks flowing down from the ceiling on the Southern Wall (right)

Gnd-W/02

This space built in 1929 functions as the *Contemporary Painting Gallery*. It is 30.5m x 12.11m (100ft. x 39ft. 9in.) with the soffit of the ceiling at + 7.1m (23ft. 3in.) above the plinth.

Figure B.26: Gnd-W/02 – Contemporary Painting Gallery (2017)
Looking West

The space is accessed through an ornamented plasterwork doorway in the eastern wall. The southern wall at its western end has a wooden screen fitted into an opening, behind which is space Gnd-W/21. There is a carved wooden doorway in the western wall which leads to space Gnd-W/03. The northern wall has no architectural features of importance. The roof is an RC slab supported on I-Beams running along the shorter span, in the N-S axis. A chunk of concrete has detached from the roof exposing the steel rebars near the southern wall.

Figure B.27: Gnd-W/02 – Contemporary Painting Gallery (2016)
Detached chunk of concrete near the Southern wall

Gnd-W/03

The space functions as the *Manuscript Gallery*. It was temporarily being used as a store at the time of the survey and was returned to its regular function in late 2017. It was built in the year 1893 and was modified in 1965. The space is 9.35m x 11.5m (30ft. 8in. x 37ft. 9in.) with the soffit of the ceiling at + 7.9m (26ft.) above the plinth.

The space is accessed through a carved wooden door set in the eastern wall. There are two circular openings of 0.45m (1ft. 6in.) dia., for ventilation at +6.25m (20ft. 6in.) above the plinth in the southern wall. There is a door on the western wall which opens onto space Gnd-W/04. There are no architectural features of importance on the northern wall. The space has an RC slab roof.

Figure B.28: Gnd-W/03 – Manuscript Gallery (2015)
Looking South-West

No visible signs of deterioration are observed in this space.

Gnd-W/04

The space functions as *Reserves Storage* for the Museum. The space was previously part of the western verandah which was built in the year 1893 and modified in 1965. It is 3m x 11.35m (9ft. 10in. x 37ft. 3in.) with the soffit of the ceiling at +4.4m (14ft. 6in.) above the plinth.

The space is accessed through a door set in an in-filled archway in the eastern wall; south of the door on the same wall are traces of another in-filled archway. On the southern wall traces of a blocked doorway can be seen. There are three doors set in arched openings on the western wall that lead onto space Gnd-W/05. The doors are set below the spring line of the arches; the arches above are fitted with terracotta *jalis.* A fourth archway in the wall has brick masonry infill. The northern wall has no architectural features of significance. The space has an RC slab roof.

Figure B.29: Gnd-W/04 – Reserves Storage (2015)
Looking South (left) Looking North (right)

Sagging of roof and out of plane behavior of the northern wall is observed. Also the southern and the eastern walls have been re-plastered with cement mortar. Flaking of paint is observed on the northern and the western walls.

Gnd-W/05

The space functions as *Reserves Storage* for the Museum. The room was built in 1969 in the open space between the Museum and NCA. It is 4.98m x 11.64m (16ft. 4in. x 38ft. 3in.) with the soffit of the ceiling at +4.5m (14ft. 9in.) above the plinth.

The space can be accessed through any of the three doors set into archways, in the eastern wall. The doors are set below the spring line of the arches; the arches above are fitted with terracotta *jalis.* A fourth archway at the northern end of the wall has been in-filled with brick masonry. On the southern wall is steel door opening onto space Gnd-W/25; above the door is an arched ventilator fitted with a concrete *jali*. There are four equally spaced arched ventilators on the western wall. On the northern wall there is a door that leads onto space Gnd-W/06. The space has an RC slab roof supported on three RC beams running along the shorter span in the E-W axis.

Figure B.30: Gnd-W/05 – Reserves Storage (2015)
Looking East (left) Looking West (right)

Slight sagging of roof is observed. Also the western wall has been re-plastered and the terracotta *jalis* fixed in the arches on the eastern wall are powdering in some places. Additionally Flaking of paint is also seen on the eastern wall.

Gnd-W/06

The space functions as the *Stairwell* connecting the ground floor Reserves Storage spaces with those located on the first floor. The room was built in 1969 in the open space between the Museum and NCA. It is 5m x 3.8m (16ft. 5in. x 12ft. 6in.) with the soffit of the ceiling at +9.64m (31ft. 8in.) above the plinth.

Figure B.31: Gnd-W/06 – Stairwell for Reserves Storage spaces (2015)
Looking South-West

The space is accessed through a door on the southern wall. On the eastern wall there are traces of an archway in-filled with brick masonry. The northern wall has a door at its eastern end, which opens onto space Gnd-W/18. There is a ventilator high on the western wall.

The staircase rising through the space starts from the northern wall turns and runs along the western and then the southern wall before transitioning into space Fst-W/06, at +4.9m (16ft.) above the plinth level. The staircase is 1.25m (4ft. 1in.) and the riser for each step at an average is 18.7cm (7.4in.). The space has an RC slab roof. No visible signs of deterioration are observed in this space.

Gnd-W/07

The space functions as the *Swat Gallery (I).* It was built in the year 1916 and was modified in 1969. It is 9.3m x 6m with the soffit of the ceiling at +7.67m above the plinth.

Figure B.32: Gnd-W/07 Swat Gallery (I) (2016)
Looking West

The space is accessed through a doorway on its eastern wall. There are two ventilators along the top of the southern wall. On the western wall is a large archway framing three arches fitted with *jalis* at the upper level and three horseshoe arches that lead onto space Gnd-W/08, at the lower level. The northern wall has no architectural features of importance. The roofing system consists of I-Beams, running along the N-S axis, supporting wooden battens and boarding. No visible signs of deterioration are observed in this space.

Gnd-W/08

This space built in 1969 functions as the *Swat Gallery (II).* It is 17m x 6.24m (55ft. 9in. x 20ft. 6in.) with the soffit of the ceiling at +7m (23ft.) above the plinth.

Figure B.33: Gnd-W/08 – Swat Gallery (II) (2016)
Looking East

The space is accessed through any of the three horseshoe arches built in the western wall. Along the top of the southern wall there are two ventilators and two exhaust fans. The northern and the western walls do not have architectural features of importance. The roof is an RC slab supported on 28.5cm (11in.) wide RC beams with a drop of 38cm (15in.), running along the shorter span in the N-S axis.

Figure B.34: Gnd-W/08 – Swat Gallery (II) – Deterioration (2016)
Discoloration due to dampness on the ceiling around the electric points (left) Flaking of paint on the Southern wall close to the ceiling

Drip marks and discoloration is observed around every electric point on the ceiling which suggests lack of water tightness around the electric conduits. Flaking of paint due to dampness is also observed on the southern wall and the ceiling.

Ground Floor – Spaces Accessed Externally

This section deals with the description of spaces, on the ground floor, which are part of the museum but are only accessible from outside the building. Most of the spaces in this section are restricted to the Administration only and are not part of the visitors' experience. The spaces accessible to the public include a Curio Shop (Gnd-N/12), a Bookshop (Gnd-N/15), Public Toilets (Gnd-N/16 – 18) and the Auditorium (Gnd-W/10) for special events.

Northern Part – Public Relations, Security Offices & Commercial Areas

Gnd-N/03

This space is used as the *Security Office* was built in 1893 and measures 2.95m x 2.95m (9ft. 8in. x 9ft. 8in.), the soffit of the ceiling is at +5.79m (19ft.) above plinth level. The walls have been plastered up to +2.5m (8ft. 3in.) above plinth, the remaining height of the walls is painted exposed brick masonry.

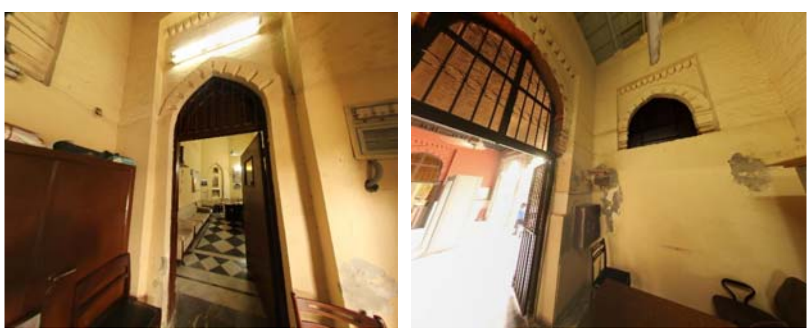

Figure B.35: Gnd-N/03 – Security Office (2016)
Looking South (left) Looking North-West (right)

The space is entered through an arched doorway in its western wall. On the northern and the eastern walls are arches with sandstone *jalis*. Only part of these arches is visible from the inside as they have been blocked up to +2.5m (8ft. 3in.) above plinth, with brick curtain wall laid in cement mortar. The southern wall has an arched door which leads to space Gnd-N/04. The room has flat wooden roof supported on I-Beams laid in the N-S axis. The paint in the room is flaking on all walls except the western wall.

Gnd-N/04

This space functions as the *Office* for the Chief Security Officer and was built in the year 1906. The room measures 3.9m x 6m (12ft. 9in. x 19ft. 9in.) with the soffit of the ceiling at +5.6m (18ft. 3in.) above the plinth level.

Figure B.36: Gnd-N/04 – Office of Chief Security Officer (2015)
Looking South (left) Looking North-West (right)

The space is entered through the arched door in its northern walls. The eastern wall has traces of an arched opening that has been blocked off; towards the southern end the wall is chamfered at 45° angle. The chamfered portion of the wall has an arched window opening which has been boarded off with plywood sheet. The western wall of the room is staggered and can be read as two distinct sections. The northern section of the wall has an arched opening fitted with terracotta *jali* below which is a built-in fireplace with the same terrazzo finish as the dado. The southern section of the wall is adorned with a decorative flat archway with masonry brackets. The walls have terrazzo till dado height above which they have cement plaster that has been painted.

The roof was modified in 1965 and has brick tiles supported on T-iron strips resting on I-Beams laid in the E-W direction. There is discoloration and flaking of paint on both the northern and the western walls due to dampness.

Figure B.37: Gnd-N/04 – Office of Chief Security Officer – Deterioration (2015)
Flaking of paint on the Western wall (left) Flaking of paint and discoloration Northern wall (right)

Gnd-N/05

This space functions as an *Office* for the Assistant to the Public Relations Officer. The room is a mirrored space of Gnd-N/03 which has been described in detail above. The space shows no signs of deterioration as it has been recently painted.

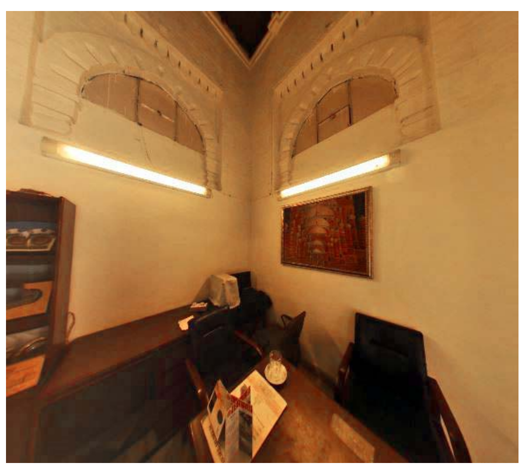

Figure B.38: Gnd-N/05 – Office for Assistant to Public Relations Officer (2015)
Looking North-West

Gnd-N/06

This space built in 1906 and modified in 1965 functions as an *Office* for the Public Relations Officer. The space is irregular in shape as it was formed by combining two separate spaces. The eastern part of the space is 3.9m x 6m (12ft. 9in. x 19ft. 9in.) while the western part is 2.74m x 4.35m (9ft. x 14ft. 3in.). The whole space has suspended false ceiling, the soffit of the ceiling in the eastern part is at +5.11m (16ft. 9in.) above plinth while in the western part it is lower at +3.5m (11ft. 6in.) above plinth.

The northern wall is in two sections and the space is accessed through an arched door located in eastern section of this wall. The western section of the wall staggers 35cm (13.5in.) northwards and has an arched door in its middle. The eastern wall of the space is again in two sections. The northern section of the wall has an arched opening fitted with a terracotta *jali*. The southern section, which is set back from the northern section by 75cm (29.5in.) towards the west, has a decorative flat archway with masonry brackets. The southern wall is also split into two sections the eastern section is set back from the western section by 1.9m towards south. These two sections of the wall are connected through a 45° chamfered wall. In the middle of the chamfered wall is an arched door which open onto space Gnd-N/07. The western wall of the room is straight and has three arched window openings.

Figure B.39: Office for the Public Relations Officer (2015)
Looking North (left) Looking South (right)

As the room had been recently painted the only deterioration observed was discoloration and flaking of paint on the south western corner of the space due to dampness (Figure B.39).

Gnd-N/07

The space functions as a *Kitchenette* for the Office of the Public Relations Officer. The space has an irregular shape and was built in 1969 by roofing the empty space between Gnd-N/06 and Gnd-W/01, and was modified in the 2000s. The largest dimensions of the space are 3.58m (11ft. 9in.) in width and 3.28m (10ft. 9in.) in depth with the soffit of the ceiling at +1.83m (6ft.) above plinth.

The space is entered through an arched door built in the chamfered section of the staggered northern wall of the space. The eastern and southern walls of the space are blank while there are two doors on the western wall that lead to Gnd-N/08 & 09.

Figure B.40: Gnd-N/07 – Kitchenette (2015)
Looking South

The space has a RC roof which due to dampness shows discoloration and the paint is also flaking in some patches (Figure B.40 & Figure B.41).

Gnd-N/08 & Gnd-N/09

These spaces are mirrored spaces that function as *Toilet Stalls.* Each space is 1.33m (4ft. 4in.) x1.52m (5ft.) and has the soffit of the ceiling at +1.83m (6ft.) above plinth level.

The spaces are entered through doors located on their eastern walls. There are no architectural features of importance on the remaining three walls.

Figure B.41: Gnd-N/08 & Gnd-N/09 – Toilet Stalls (2015)
Looking West

These spaces also have an RC roof which due to dampness shows discoloration and the paint is also flaking in some patches.

Gnd-N/10 & Gnd-N/11

These spaces built in 1893 are mirrored spaces that are spiral *Stairwells.* Currently space Gnd-N/10 is being used as an electrical duct and is inaccessible while space Gnd-N/11 is accessible and retains the function of the stairwell.

Figure B.42: Gnd-N/11 – North Western Stairwell (2016)
Powdering of brick and mortar on the central column and the periphery wall (left) Steps supported on brickwork arches (center) Crack towards the North, halfway to the first floor (right)

The spaces are accessed through doors located on the southern wall of space Gnd-N/01 (Entrance Portico). Space Gnd-N/10 is built within the north-eastern pier while Gnd-N/11 is built within the north-western pier of the Gnd-N/02 (Entrance Vestibule). The staircases start from the plinth level and rise throughout the height of the building making their first landing onto Fst-N/03 (First Floor Terrace) while the second landing is at roof level from where space Thd-N/05 can be accessed. The diameter of the stair shafts is 1.47m (4ft. 9in.) and each step has a riser of 25.8cm (10in.). The steps are supported on brickwork arches which in turn are supported by a 21.5cm (8.5in.) central column and the periphery walls. The steps as well as the walls of the shafts are finished in exposed brickwork with lime mortar pointing.

The spaces are in general state of disrepair. The bricks and the lime mortar pointing have powdered and cracks are observed in Gnd-N/11 (Figure B.42).

Gnd-N/12

This space built in 1965 functions as the *Curio Shop*. The space is 3.28m x 4.42m (10ft. 9in.x14ft. 6in.) and the soffit of the ceiling is at +2.14m (7ft.) above the plinth level.

The space is accessed through a door in the northern wall. There are three arched window openings in the eastern wall while the southern and the western wall are blank. The space has an RC slab roof.

Figure B.43: Gnd-N/12 – Curio Shop (2015)
Interior looking East (left) Exterior looking South (right)

The paint is flaking due to dampness at the upper edges of the walls and the connecting ceiling edges (Figure B.43).

Gnd-N/13

This space is used as *Office* for the security staff. The space was built in 1969 and has been modified twice, first in 1978 and later in the 2000s. The space is 3.52m x 3.44m (11ft. 6in. x 11ft. 3in.); its floor is at -29cm (11.5in.) below plinth and the soffit of the ceiling is +1.68m (5ft. 6in.) above plinth.

The space is accessed through a door in its northern wall and the southern end of the room is defined by the northern wall of Gnd-W/02. The eastern and the southern walls are blank while there is a door in the middle of the western wall that opens onto space Gnd-N/14. The space has an RC slab roof.

Figure B.44: Gnd-N/13 – Office for Security Staff (2016)
Looking South (Left) Looking South- East close to the top end of the wall near the ceiling (right)

It is observed that paint as well as plaster is flaking due to dampness on the western and the southern wall as well as the ceiling (Figure B.44).

Gnd-N/14

This space was built in 1985 and functions as the *Ticketing Booth.* The space is 2.73m x 3.51m (9ft. x 11ft. 6in.); its floor is at -29cm (11.5in.) below plinth and the soffit of the ceiling is +1.68m (5ft. 6in.) above plinth.

The space is entered through a door on its eastern wall and the southern end of the room is defined by the northern wall of Gnd-W/02. There is a ticketing window in the northern wall while the other two walls are blank. The roof has pre-cast RC girders lying in the E-W axis and supporting pre-cast RC slabs.

Figure B.45: Gnd-N/14 – Ticketing Booth – Deterioration (2016)
Discoloration of paint on the western wall and the ceiling (left) Concrete chunk fallen off near the southern wall (right)

Flaking and discoloration of paint due to dampness is observed on the southern and western wall. On the ceiling not only is the paint flaking and discoloration is seen but concrete has fallen off in large chunks exposing the steel rebars in a couple of places due to dampness (Figure B.45).

Gnd-N/15

This space was built in 1985 and functions as the *Book Shop.* The space is 3.12m x 3.73m (10ft. 3in. x 12ft. 3in.); its floor is at -29cm (11.5in.) below plinth and the soffit of the ceiling is +1.68m (5ft. 6in.) above plinth.

The space is accessed through a door fixed into the glazed shop window which covers the entire northern end of the space while the southern end of the room is defined by the northern wall of Gnd-W/02. All the other walls of the space are stacked from floor to ceiling with bookshelves and could not be observed. The space has an RC slab roof.

The condition of the walls could not be observed due to the floor length book shelves but the paint on the roof is flaking in various locations due to dampness.

Gnd-N/16, Gnd-N/17 & Gnd-N/18

All three spaces built in 1985 are part of the *Public Toilets*. Space Gnd-N/16 which measures 0.85m x 3.84m (2ft. 9in x 12ft. 7in.) functions as the *Corridor* while spaces Gnd-N/17 and Gnd-N/18 which are used as *Toilet Stalls* are mirrored spaces and measure 1.38m x 1.75m (4ft. 6in. x 5ft. 9in.) each. The access to the Public Toilets is from the door in the northern wall of space Gnd-N/16 while spaces Gnd-N/17 and Gnd-N/18 are accessed via doors in the western wall of space Gnd-N/16. The floor of all three spaces at -29cm (11.5in.) below plinth and the soffit of the ceiling is +1.68m (5ft. 6in.) above plinth. None of the rooms have any architectural features of importance. All three spaces have an RC slab roof.

The paint on the roof is flaking in various locations due to dampness and the southern wall of Space Gnd-N/16 has discoloration of paint due to dampness.

Eastern Part – Services & Conservation Laboratory

Gnd-E/09

This space functions as the *Ventilation Extractor*. The space previously part of the eastern verandah was built in 1893 and was modified in 1965. It is 3.05m x 1.37m (10ft. x 4ft. 6in.) with the soffit of the ceiling at +4.64m (15ft. 3in.) above the plinth.

The eastern wall has an iron grille and a steel door which are opened for servicing the extractor. The northern and southern walls are blank while the western wall has a wooden screen. The roof is an RC slab. The condition of the space could not be observed.

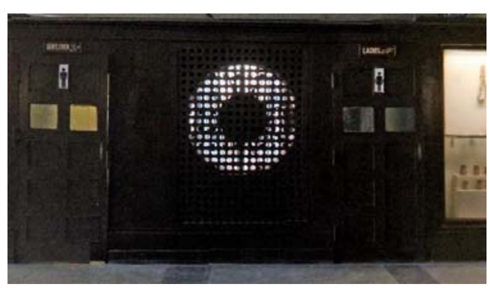

Figure B.46: Gnd-E/09 – Ventilation Extractor (2016)
Steel door - the eastern wall of the space (left); Wooden screen - the western wall of the space (right)

Gnd-E/10

This space functions as *Toilet* for the staff. The space previously part of the eastern verandah was built in 1893 and was modified in 1965. It is 3.05m x 2.23m (10ft. x 7ft. 3in.) with the soffit of the ceiling at +4.64m (15ft. 3in.) above the plinth.

Figure B.47: Gnd-E/10 – Toilet for staff (2016)
Looking West

The space is accessed through the door in the eastern wall. All other walls of the space have no architectural features of importance. The roof is an RC slab. Paint is flaking off on all the walls and where the paint has completely fallen off there are visible signs of dampness.

Gnd-E/11

This space functions as *Rest Room* for the staff. The space previously part of the eastern verandah was built in 1893 and was modified in 1965. It is 3.13m x 7.16m (10ft. 3in. x 23ft. 6in.) with the soffit of the ceiling at +4.64m (15ft. 3in.) above the plinth.

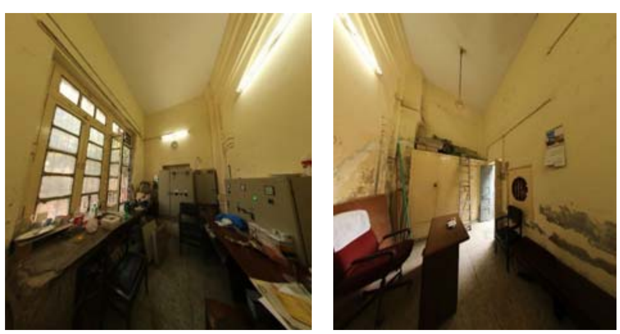

Figure B.48: Gnd-E/11 – Restroom for staff (2016)
Looking South (left) Looking North (right)

The space is accessed through the door in the eastern wall. There is a window in the southern part of the eastern wall. The northern and southern walls are blank while there are two blind arches in the western wall. The space has an RC slab roof.

Flaking of paint due to dampness is observed in the lower part of the eastern and the western walls. There are visible signs of dampness where paint has completely fallen off (Figure B.48).

Gnd-E/12

This space built in 1978 is used as a *Verandah/ Stair Hall* for the Conservation Laboratory. The space is 9.22m x 2.6m (30ft. 3in. x 8ft. 6in.) with the soffit of the ceiling at + 4.6m (15ft. 1in.) above the plinth.

The space is accessed through an iron grille door fitted in the eastern part of an opening in the southern wall. The western part of the opening is fitted with a fixed iron grille. The eastern wall of the space has a door that leads onto space Gnd-E/13. The northern wall has three arch openings. The central arch is fitted with a door opening onto space Gnd-E/14 while those on either side are fitted with windows. At the western end of the space is the staircase that leads to Fst-E/01. The roof is an RC slab with a drop beam in the N-S axis (Figure B.49).

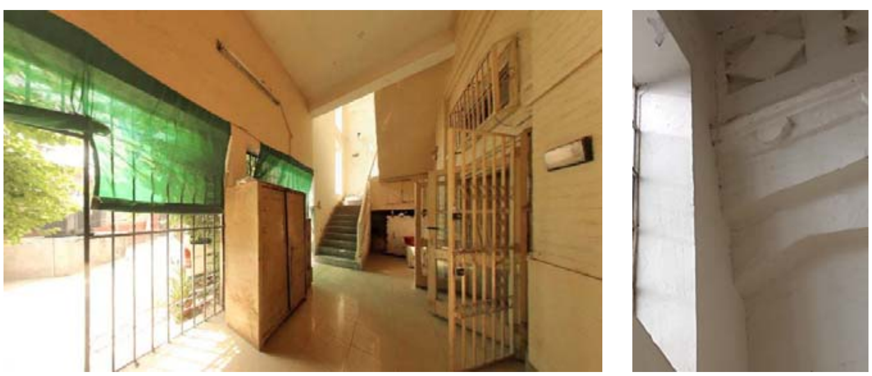

Figure B.49: Gnd-E/12 – Verandah/ Stair hall for Conservation Laboratory (2015)
Looking West (left) Separation Crack (right)

A separation crack is observed between the southern and the western wall of the space (Figure B.49).

Gnd-E/13

This space built in 1978 functions as a *Toilet*. The space is 2.97m x 2.76m (9ft. 9in. x 9ft.) with the soffit of the ceiling at +4.6m (15ft. 1in.) above plinth.

Figure B.50: Gnd-E/13 – Toilet (2015)
Looking South-East

The space is entered through a door in the western wall. On the southern wall is a ventilator while there is an exhaust fan on the eastern wall. Traces of the end of the eastern verandah can be seen on the northern wall. The space has an RC slab roof.

Swelling of plaster is observed on all the walls above the dado height.

Gnd-E/14

This space built in 1929 and modified in 1965, functions as *Office* for the Chief Conservator. It is 4.92m x 4.18m (16ft. x 13ft. 9in.) with the soffit of the ceiling at +4.6m (15ft. 1in.) above plinth.

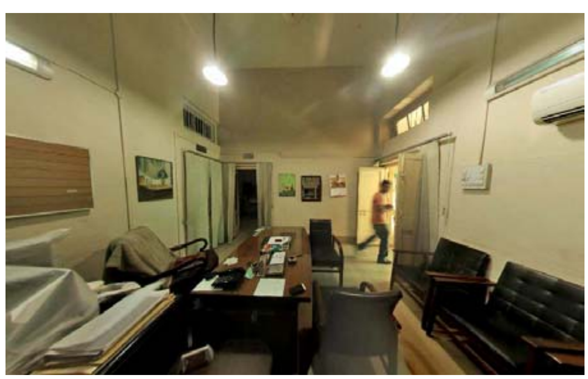

Figure B.51: Gnd-E/14 – Office for the Chief Conservator (2015)
Looking East

The space is accessed through a door in the southern wall; west of the door is a window. The eastern wall has a door that opens onto space Gnd-E/16. The door in the northern wall opens onto space Gnd-E/15; above the door is a horizontal ventilator. The western wall is without any significant architectural features. The RC roof is supported by I-beams running in the N-S axis.

Flaking of paint is observed in the upper part of the western wall.

Gnd-E/15

This space built in 1929 and modified in 1965, functions as *Storage Room* for conservation materials and equipment. It is 4.92m x 2.47m (16ft. x 8ft. 2in.) with the soffit of the ceiling at +4.6m (15ft. 1in.) above plinth.

The space is accessed through a door in its southern wall; above which is a horizontal ventilator. The eastern and the northern walls have built-in concrete shelves at three levels. The western wall is without any significant architectural features. The RC roof is supported by I-beams running in the N-S axis.

Figure B.52: Gnd-E/15 – Storage Room for Conservation Laboratory (2015)
Looking East

Flaking of paint is observed in the upper part of the western wall.

Gnd-E/16

This space built in 1929 and modified in 1965, functions as *Conservation Laboratory*. It is 3.37m x 6.88m (11ft. x 22ft. 6in.) with the soffit of the ceiling at +4.6m (15ft. 1in.) above plinth.

Figure B.53: Gnd-E/16 – Conservation Laboratory (2015)
Looking South

The space is accessed through the door in the western wall. The northern and eastern walls are blank while there is a window in the southern wall. The RC roof is supported by I-beams running in the N-S axis.

Flaking of paint is observed on the eastern and northern walls while visible signs of dampness are seen where the paint has completely fallen off.

Gnd-E/20

This space functions as the *Ventilation Extractor*. It is 1.94m x 2.45m (6ft. 4in. x 8ft.) with the floor -0.13m (5in.) below plinth level and with the soffit of the ceiling at +2.83m (9ft. 3in.) above plinth.

The eastern wall has an iron grille and a steel door which are opened for servicing the extractor. The northern and southern walls are blank while the western wall has a wooden screen. The space has an RC slab roof.

Flaking of paint is observed in lower part of all the walls.

Gnd-E/21

This space built in 1972 functions as a *Stair Hall* for the stairs leading to space Bas-E/01 in the basement. It is 3.83m x 1.36m (12ft. 6in. x 4ft. 6in.). Its floor is at -0.15m (6in.) below the plinth while the soffit of the ceiling is at +3.56m (11ft. 8in.) above the plinth.

Figure B.54: Gnd-E/21 – Stair Hall providing access to Basement (2015)
Looking East

The space is accessed through the door in its southern wall. The eastern wall has no significant architectural features while traces of a blocked door can be seen on the northern wall. The stairs descends towards the western wall which is devoid of architectural features of importance. The space has an RC roof.

The space shows no visible signs of deterioration.

Southern Part – Administrative Offices

Gnd-C/03

The space built in 1916 and modified in 1969, functions as the *Corridor* that connects the administrative areas with the display areas. It is 7.88m x 1.93m (25ft. 10in. x 6ft. 4in.) with the soffit of the ceiling at +7.57m (24ft. 10in.) above the plinth.

The space is accessed through a wooden door set in the northern wall. On the eastern wall there is a door that leads onto space Gnd-S/02. The door on the southern wall opens onto space Gnd-S/01. There are three ventilators in the upper section of the wall.

The western wall has a door, above which is a ventilator. The roofing system consists of wooden battens running in the N-S axis over which lie the wooden boarding.

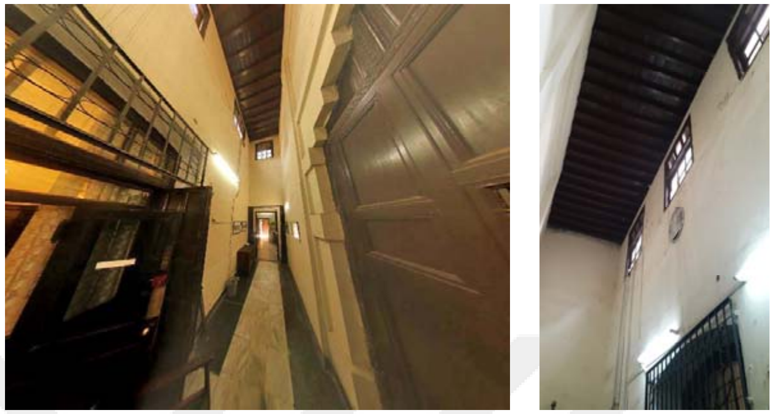

Figure B.55: Gnd-C/03 – Corridor connecting administrative areas to display areas (2015)
Looking West (left) Looking East (Right)

Drip marks flowing down the ventilators are observed on both the southern and the eastern walls (Figure B.55).

Gnd-S/01

This space built in 1929 functions as the *Coin Room*. The room is 7.87m x 4.6m (25ft. 9in. x 15ft.) with the soffit of the false ceiling at +3.65m (12ft.) above plinth.

Figure B.56: Gnd-S/01 – Coin Room (2013)
Looking East (left) Looking North-West (right)

The space is accessed through the door in the northern wall; two safe have been built into the paneling west of the door. Two more safes are built into the paneling on the eastern wall along with a built in writing desk. On the southern wall there is a built in writing desk similar to the one on the eastern wall, two windows and two built-in safe. The western wall also has two built-in safe besides the built-in seating. All walls have carved wooden paneling up to 2m (6ft. 6in.) height above which the walls have painted cement plaster. The roofing system cannot be observed due to the false ceiling.

The space shows no visible signs of deterioration.

Gnd-S/02

This space functions as a *Kitchenette* for the Director's Office. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. The space is 3.12m x 2.35m (10ft. 3in. x 7ft. 9in.) with the soffit of the ceiling at +4.72m (15ft. 6in.) above the plinth.

The space is accessed from the door in the southern wall. The eastern wall has a door set into an in-filled archway leading onto space Gnd-S/03. The northern wall is without any significant architectural features while the door in the western wall leads onto space Gnd-C/03. The roofing system consists of I-Beams, running along the E-W axis, supporting wooden battens and boarding.

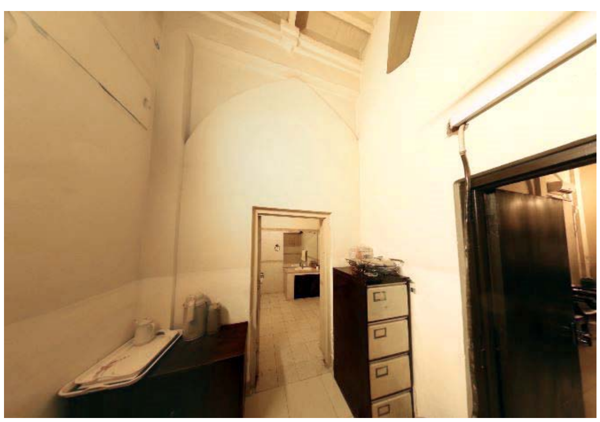

Figure B.57: Gnd-S/02 – Kitchenette for Director's Office (2015)
Looking East

The space shows no visible signs of deterioration.

Gnd-S/03

This space functions as a *Toilet* for the Director's Office. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. It is 2.54m x 3m (8ft. 4in. x 9ft. 10in.) with the soffit of the ceiling at +4.72m (15ft. 6in.) above the plinth.

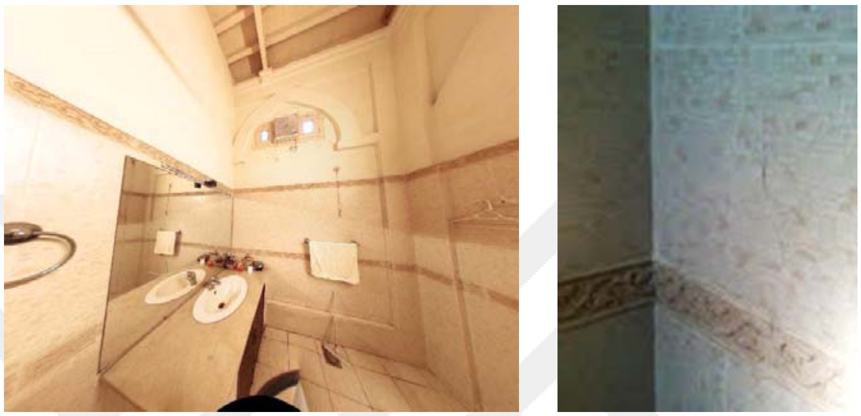

Figure B.58: Gnd-S/03 – Toilet for Director's Office (2015)
Looking South (left) Diagonal crack on the Northern wall (right)

The space is accessed through a door set into an in-filled archway in the western wall. Traces of an archway can be seen in the upper portion of the southern wall. The northern and the southern walls are without any significant architectural features. The roofing system consists of I-Beams, running along the N-S axis, supporting wooden battens and boarding.

Minor diagonal cracks are observed in the tiles at the western end of the northern wall (Figure B.58).

Gnd-S/04

This space functions as the *Office* for the Director of the Museum. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. It is 3.2m x 8.1m (10ft. 6in x 26ft. 6in.) with the soffit of the ceiling at +4.72m (15ft. 6in.) above the plinth.

The space is accessed through doorway set into an in-filled archway in the eastern wall. At the southern end of the eastern wall a window has been fitted into another in-filled archway while traces of a closed off archway are seen in the middle of the wall. The southern wall also has a window set in the middle of an in-filled archway. The western wall at its southern end has a bookshelf built flush with the wall. The door in the northern wall leads onto space Gnd-S/02 which internally connects the director's office to other administrative areas as well as the display areas. The roofing system consists of I-Beams, running along the E-W axis, supporting wooden battens and boarding.

Figure B.59: Gnd-S/04 – Office for Director of the Museum (2015)
Looking South (left) Flaking of Paint on the eastern wall (right)

Flaking of paint is observed over the doorway in the eastern wall (Figure B.59).

Gnd-S/05

The space built in 1978 functions as the *Waiting Area* for the Director's Office. It is 2.75m x 2.26m (9ft. x 7ft. 5in.) with the soffit of the ceiling at +2.86m (9ft. 5in.) above the plinth level.

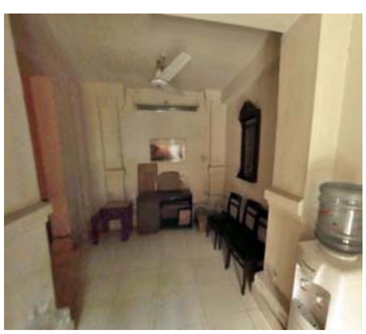

Figure B.60: Gnd-S/05 – Waiting Area for Director's Office (2015)
Looking North (left) Flaking of paint on the Northern wall (right)

The space is accessed through an opening in the southern wall. The western wall has a doorway set into an in-filled archway leading onto space Gnd-S/04. The northern wall has traces of a closed off archway while the eastern wall is without any significant architectural features. The space has an RC slab roof. Flaking of paint is observed on the lower half of the northern wall (Figure B.60).

Gnd-S/06

The space built in 1978 functions as the *Lobby* for the Director's Office. It is 2.75m x 1.9m (9ft. x 6ft. 3in.) with the soffit of the ceiling at +2.86m (9ft. 5in.) above the plinth level.

The space is accessed through a door in the southern wall. The eastern wall features a window while there is an opening leading onto space Gnd-S/05 in the northern wall. The western wall does not have any significant architectural features. The space has an RC slab roof. No visible signs of deterioration are observed in this space.

Figure B.61: Gnd-S/06 – Lobby for the Director's Office (2015)

Gnd-S/07

This space functions as a *Lobby* between administrative offices. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. It is 2.95m x 3m (9ft. 8in x 9ft. 10in.) with the soffit of the ceiling at +4.72m (15ft. 6in.) above the plinth.

The space is accessed through a door set into an in-filled archway in its western wall. On its southern wall is a door leading onto space Gnd-S/08 while the door in the eastern wall opens onto space Gnd-C/03. The northern wall does not have any significant architectural features. The roofing system consists of I-Beams, running along the E-W axis, supporting wooden battens and boarding.

No visible signs of deterioration are observed in this space.

Gnd-S/08

This space functions as an *Office*. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. It is 3m x 4.5m (9ft. 10in. x 14ft. 9in.) with the soffit of the ceiling at +4.72m (15ft. 6in.) above the plinth.

The space is accessed through a door in the northern wall. The western wall has two windows while there are no architectural features of importance on the southern and the eastern wall. The roofing system consists of I-Beams, running along the E-W axis, supporting wooden battens and boarding. The condition of the space could not be observed.

Gnd-S/09

This space functions as a *Verandah*. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. It is 2.72m x 3m (8ft. 11in. x 9ft. 10in.) with the soffit of the ceiling at +4.72m (15ft. 6in.) above the plinth.

Figure B.62: Gnd-S/09 – Verandah (2016)
Looking East

The space is accessed from the southern end through an open archway. The eastern wall has a door that leads onto space Gnd-S/07. There are no architectural features of importance on the northern wall. The western wall has a door that opens onto space Gnd-S/10. The roofing system consists of I-Beams, running along the N-S axis, supporting wooden battens and boarding. No visible signs of deterioration are observed in this space.

Gnd-S/10

This space functions as an *Office*. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. It is 6.56m x 3m (21ft. 6in. x 9ft. 10in.) with the soffit of the ceiling at +4.72m (15ft. 6in.) above the plinth.

The space is accessed through a door set into an in-filled archway in its eastern wall. There are no architectural features of significance on the northern wall. There is a door in the western wall that opens onto space Gnd-S/12. The southern wall at its western end has an opening leading onto space Gnd-S/11; east of the opening on the same wall is a window. The roofing system consists of I-Beams, running along the N-S axis, supporting wooden battens and boarding. Discoloration and flaking of paint due to dampness is observed on the western wall.

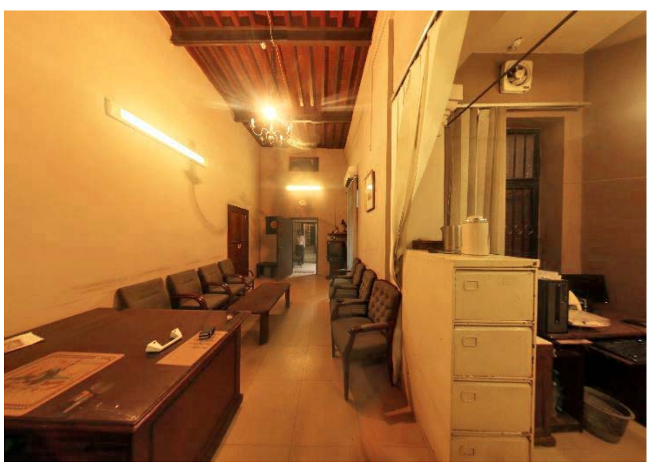

Figure B.63: Gnd-S/10 – Office (2015)
Looking East

Gnd-S/11

This space built in 1978 functions as a *Sub Office*. It is 2.23m x 1.85m (7ft. 3in. x 6ft.) with the soffit of the ceiling at +4.6m (15ft. 1in.) above the plinth level.

The space is accessed through an opening in its northern wall. On the eastern wall is a glass door which can be used as external entrance to the space but is permanently locked. The southern and the western wall have no architectural features of significance. The space has an RC slab roof.

No visible signs of deterioration are observed in this space.

Gnd-S/12

This space built in 1978 is used as a *Toilet*. It is 2m x 3.17m (6ft. 6in. x 10ft. 5in.) with the soffit of the ceiling at +2.8m (9ft. 3in.) above the plinth.

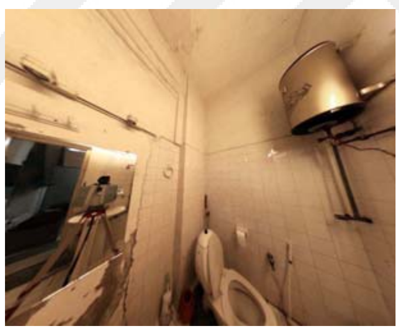

Figure B.64: Gnd-S/12 – Toilet (2015)
Looking North-West

Flaking of paint due to dampness is observed on the ceiling. The space has partial re-plastering on the western wall.

Gnd-S/13

The space functions as the *Electric Control Room*. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. It is 2.75m x 3.1m (9ft. x 10ft. 2in.) with the soffit of the ceiling at +4.72m (15ft. 6in.) above the plinth.

The space is accessed through an arched door set in the middle of an in-filled archway in the southern wall; above the door is an exhaust fan. A hole has been punctured through the masonry wall, at the same height as the exhaust fan, at the western end of the wall to carry the electric wires into the space. The eastern wall has an in-filled archway, holes have been punctured at the northern end of the wall, above the spring line of the arch, to carry electric wires into the space. On the northern wall the opening for an exhaust fan is being used as an electric duct. The western wall has no architectural features of significance. The space has an RC slab roof.

Figure B.65: Gnd-S/13 – Electric Control Room (2016)
Looking North (left) Flaking of paint observed on the Southern wall and on the ceiling (center)
Looking North-East flaking of paint observed on the Eastern wall as well as detachment of concrete from ceiling (right)

Chunks of concrete have detached from the ceiling in three places, exposing steel rebars. Flaking of paint due to dampness is observed on the southern wall, the eastern wall as well as the ceiling (Figure B.65).

Gnd-S/14

The space is used as an *Office*. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. It is 5m x 3m (16ft. 5in. x 9ft. 10in.) with the soffit of the ceiling at +4.72m (15ft. 6in.) above the plinth.

The space is accessed through a door set in an in-filled archway in the southern wall; west of the door in the same wall is a window set in the middle of an in-filled archway. Traces of a blocked off window are seen on the northern wall. The eastern and western walls have no architectural features of importance. The roofing system consists of I-

Beams, running along the N-S axis, supporting wooden battens and boarding. No visible signs of deterioration are observed in this space.

Figure B.66: Gnd-S/14 – Office (2015)
Looking West

Gnd-S/15

The space is used as an *Office*. The space previously part of the southern verandah was built by the year 1929 and was modified in 1965. The space is 6.1m (20ft.) in width, its depth at the eastern end is 3.1m (10ft. 2in.) while at the western end it is 2.45m (8ft.) deep. The soffit of the ceiling is at +4.72m (15ft. 6in.) above the plinth.

Figure B.67: Gnd-S/15 – Office (2015)
Looking East (left) Looking West (right)

The space is accessed through a door set in an in-filled archway in the southern wall; west of the door in the same wall is a window set in the middle of an in-filled archway. There is a boarded up window set in the middle an in-filled archway on the western wall. The northern wall is in two sections; its eastern section is set forward from the western section by 65cm (25.5in.) in the northward direction. The eastern section of the wall has traces of a blocked off window while the western section has an in-filled archway. There are no architectural features of importance on the eastern wall. The roofing system consists of I-Beams, supporting wooden battens and boarding. The I-Beam in the eastern section of the room run in N-S axis while in the western section the I-Beams are placed in the E-W axis. No visible signs of deterioration are observed in this space.

Gnd-S/16

This space built in 1978 functions as the *Server Room* for the internal computer network of the Museum. It is 5.2m x 3m (17ft. x 9ft. 10in.) with the soffit of the ceiling at +3.6m (11ft. 9in.) above the plinth.

Figure B.68: Gnd-S/16 – Server Room (2015)
Looking North-East (left) Looking West (right)

The space is accessed through a door in the eastern wall. There is a window at the western end of the northern wall. There are no architectural features of importance on the western and southern walls. The roof is an RC slab supported by a 30.5cm (12in.) wide RC beam with a 53cm (21in.) drop running in the N-S axis.

No visible signs of deterioration are observed in this space.

Gnd-S/17

This space built in 1978 functions as an *Office*. It is 2m x 3m (6ft. 6in. x 9ft. 10in.) with the soffit of the ceiling at +3.6m (11ft. 9in.) above the plinth.

The space is accessed through a door in the southern wall; above the door is a boarded up ventilator. There are no architectural features of importance on the remaining three walls. The space has an RC slab roof. No visible signs of deterioration are observed in this space.

Gnd-S/18

This space built in 1978 functions as an *Office*. It is 2.95m x 3m (9ft. 8in. x 9ft. 10in.) with the soffit of the ceiling at +3.6m (11ft. 9in.) above the plinth.

The space is accessed through a door in the southern wall; above the door is a boarded up ventilator. There are no architectural features of importance on the remaining three walls. The roof is an RC slab supported by a 30.5cm (12in.) wide RC beam with a 53cm (21in.) drop running in the N-S axis. No visible signs of deterioration are observed in this space.

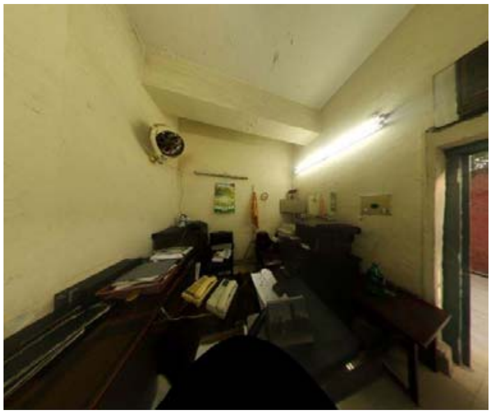

Figure B.69: Gnd-S/18 – Office (2015)
Looking East

Gnd-S/19

This space built in 1978 functions as an *Office*. It is 3.27m x 6.32m (10ft. 9in. x 20ft. 9in.) with the soffit of the ceiling at +3.6m (11ft. 9in.) above the plinth.

Figure B.70: Gnd-S/19 – Office (2015)
Looking South (left) Detachment of concrete from ceiling at the Southern end of the room (right)

The space is accessed through a door in the southern wall; above the door is a boarded up ventilator. There is a window on the western wall. On the northern wall is the door that leads onto space Gnd-S/20. There are no architectural features of importance on the eastern wall. The roof is an RC slab supported by a 30.5cm (12in.) wide RC beam with a 53cm (21in.) drop running in the N-S axis.

A large chunk of concrete has detached from the ceiling exposing the steel rebars.

Gnd-S/20

This space built in 1978 is used as a *Toilet*. It is 2.4m x 1.85m (7ft. 10in. x 6ft.) with the soffit of the ceiling at +3.6m (11ft. 9in.) above the plinth.

The space is accessed through a door in the southern wall. There is a window in the western wall. The northern and the eastern wall have no architectural features of importance. The space has an RC slab roof.

No visible signs of deterioration are observed in this space.

Gnd-W/21

This space built in 1893 functions as the *Ventilation Extractor*. The space could not be accessed for measurements during the survey, thus the measurements are approximate. The space is 3.8m x 3.27m (12ft. 6in. x 10ft. 9in.) with the soffit of the ceiling approximately at +4.4m (14ft. 6in.) above the plinth.

The space is accessed through a door on the southern wall; above the door is a ventilator. The northern wall has a wooden screen that can be observed from space Gnd-W/02. The eastern and western walls are without any architectural features of importance. The space has an RC slab roof. The condition of the space could not be observed.

Gnd-W/22

The space built in 1893 is used as a *Store*. The space could not be accessed for measurements during the survey, thus the measurements are approximate. The space is 3.21m x 3.18m (10ft. 6in. x 10ft. 5in.) with the soffit of the ceiling approximately at +7.9m (26ft.) above the plinth.

The space is accessed through a door on the southern wall; above the door is a ventilator. There are no architectural features of importance on the remaining three walls. The space has an RC slab roof. The condition of the space could not be observed.

Gnd-W/23

The space built in 1893 is used as a *Store*. The space could not be accessed for measurements during the survey, thus the measurements are approximate. The space is 5.76m x 3.18m (18ft. 11in. x 10ft. 5in.) with the soffit of the ceiling approximately at +7.9m (26ft.) above the plinth.

The space is accessed through a door on the southern wall; above the door is a ventilator. There are no architectural features of importance on the remaining three walls. The space has an RC slab roof. The condition of the space could not be observed.

Gnd-W/24

The space built in 1893 is used as a *Store*. The space could not be accessed for measurements during the survey, thus the measurements are approximate. The space is 3.71m x 3.67m (12ft. 2in. x 12ft.) with the soffit of the ceiling approximately at +4.4m (14ft. 6in.) above the plinth.

The space is accessed through a door on the southern wall; above the door is a ventilator. There are no architectural features of importance on the remaining three walls. The space has an RC slab roof. The condition of the space could not be observed.

Gnd-W/25

The space functions as the *Store*. The room was built in 1969 in the open space between the Museum and NCA. The space could not be accessed for measurements during the survey, thus the measurements are approximate. The space is 4.46m x 6.84m (14ft. 8in. x 22ft. 5in.) with the soffit of the ceiling approximately at +4.4m (14ft. 6in.) above the plinth.

The space is accessed through a door in the northern wall, above the door is a ventilator fixed into a concrete *jali*. The space can also be accessed from the door on the eastern wall, above the door is a ventilator. The southern and the western wall have no architectural features of importance. The space has an RC slab roof. The condition of the space could not be observed.

Western Part – Auditorium, Library & Stores

Gnd-W/09

This space built in 1893 and modified in 1969 functions as the *Entrance Lobby* to the Auditorium & the Museum Library. The space is 9m x 3.4m (29ft. 6in. x 11ft. 2in.) and has the soffit of the ceiling at +4m (13ft. 2in.) above the plinth.

The space is accessed from its northern side which is colonnaded. It has three openings formed by two brick masonry columns in the middle and halved columns on the side. The columns carry the flat masonry arches which are supported through stepped sandstone brackets. There are no architectural feature of importance on the eastern wall while the southern wall has two windows and a door. The door opens onto space

Gnd-W/10. Towards the western end of the south wall a staircase leading to the first and second floor rises up. It turns and runs along the western wall before turning and rising along the northern wall. The space under the stairs, on the western wall has been closed off to be used for storage with a brick masonry, and can be accessed through a door. The space has an RC slab roof.

Parts of brick have detached from the columns between the northern openings.

Figure B.71: Gnd-W/09 – Entrance Lobby to the Auditorium and Library (2015)
Looking South at the colonnaded entrance from outside (left) Looking West from inside (right)

Efflorescence is observed on the northern brick columns also cement repointing has detached from the brick surfaces.

Figure B.72: Gnd-W/09 – Entrance Lobby to the Auditorium and Library – Deteriorations (2016)
Efflorescence as well as a powdering and detachment of bricks

Gnd-W/10

This space built in 1893 and modified in 1969 functions as the *Auditorium.* The space was built in 1893 and modified in 1969. It is 9m x 18.25m (29ft. 6in. x 59ft. 10in.) with the soffit of the suspended false ceiling at + 6.7m (22ft.) above the plinth.

The space is accessed through a door in its northern wall; on either side of the door there is a window. The eastern wall has five 45.5cm (18in.) wide pilasters, clad in wooden paneling and set forward from the wall by 20cm (8in.). The wall has 1m (3ft. 3in.) high wooden paneled dado in between the pilasters. The detailing on the western wall is the same as the eastern wall. Additionally there are four doors on the wall. There is a stage at the southern end of the space. The stage is +0.84m (2ft. 9in.) above the plinth and is accessed by steps on either side of the stage. The stage set forward from the southern wall is 3.89m (12ft. 9 in.) in depth. The roofing system of the space could not be observed due to the suspended false ceiling.

Figure B.73: Gnd-W/10 – Auditorium (2016)
Looking South (left) Looking North (right)

No visible signs of deterioration are observed in this space.

Gnd-W/11

This space built in 1893 functions as a *Conference Room*. It is 9.37m x 5.55m (30ft. 9in. x 18ft. 3in.) with the soffit of the ceiling at +6m (18ft. 9in.) above the plinth.

The space is accessed through a door built into book shelving cabinet in the eastern wall. On the southern wall there is a door built into the book shelving cabinet at the western end of the room that opens onto Gnd-W/12. At the eastern end of the wall there is another opening in the cabinets but the doorway has been blocked off. The western wall has the same cabinets as seen on the eastern and the southern wall. On the northern wall there are three arched doors that open onto the NCA parking lot. They have iron grilles on the building exterior that are permanently locked. The roof is an RC slab supported on two 28.5cm (11in.) wide RC beams with a drop of 38cm (15in.), running along the shorter span in the N-S axis.

Flaking of paint due to dampness is observed at the upper parts of the southern wall. Close to the southern wall a chunk of concrete has also detached from the ceiling exposing the steel rebars.

Figure B.74: Gnd-W/11 – Conference Room (2015)
Looking East (left) Flaking of paint on the southern wall & detachment of concrete (right)

Gnd-W/12

The space is used as a *Toilet* for the Conference Room. The space was previously part of the western verandah which was built in the year 1893 and modified in 1965. The space could not be accessed for measurements during the survey, thus the measurements are approximate. The space is 2.95m x 2.83m (9ft. 8in. x 9ft. 3in.) with the soffit of the ceiling at +4.4m (14ft. 6in.) above the plinth.

The space is accessed through a door in its northern wall. There are no architectural features of importance on the three remaining walls. The space has an RC slab roof.

Efflorescence and flaking of paint is observed on the eastern wall and the south east corner of the ceiling. Also in the middle of the ceiling discoloration of paint due to dampness is observed (Figure B.75).

 

Figure B.75: Gnd-W/11 – Toilet for the Conference Room (2015)
Looking North-East (left) Flaking of paint and efflorescence on eastern wall as well as discoloration on the ceiling due to dampness (right)

Gnd-W/13

This space functions as a *Vestibule* to the Toilets for the Auditorium. The space was previously part of the western verandah which was built in the year 1893 and modified in 1965. It is 3m x 2.33m (9ft. 10in. x 7ft. 8in.) with the soffit of the ceiling at +4.4m (14ft. 6in.) above the plinth.

The space is accessed through a door in the eastern wall. The southern wall has a door that leads to space Gnd-W/15. On the western wall there is a door that opens onto space Gnd-W/14. There are no architectural features of importance on the northern wall. The space has an RC slab roof. No visible signs of deterioration are observed in this space.

Figure B.76: Gnd-W/13 – Vestibule to the Auditorium Toilets (2015)
Looking South-East

Gnd-W/14

This space functions as the *Men's Toilets* for the Auditorium. The space was previously part of the western verandah which was built in the year 1893 and modified in 1965. It is 2.73m x 2.9m (9ft. x 9ft. 6in.) with the soffit of the ceiling at +4.4m (14ft. 6in.) above the plinth.

The space is accessed through a door in the eastern wall. On the southern wall there is an exhaust fan fitted into a pre-existing window above a blocked archway. There are no architectural features of any importance on the western or the northern walls. In the south west corner of the space is a toilet cubicle accessible through a door on its northern side. The space has an RC slab roof. Flaking of paint due to dampness is observed on the southern wall and parts of the ceiling.

Figure B.77: Gnd-W/14 – Men's Toilet for Auditorium (2015)
Looking West

Gnd-W/15 & Gnd-W/16

Both spaces are part of the *Ladies Toilets* for the auditorium. The space built in 1893 was previously part of the western verandah and was modified in 1965. Space Gnd-W/15 which measures 1.32m x 1.21m (4ft. 4in. x 4ft.) functions as the *Vestibule* while Gnd-W/16 is used as *Toilet* space and measures 1.43m x 1.17m (4ft. 8in. x 3ft. 10in.). The soffit of the ceiling for both spaces is at +4.4m (14ft. 6in.) above the plinth.

The access to space Gnd-W/15 is through a door in its northern wall. There is no architectural feature of importance on its eastern wall while on the southern wall there is a block off doorway. The door in the western wall leads onto space Gnd-W/16.

There are no architectural features of importance on any of the walls of space Gnd-W/16. Both the spaces have an RC slab roof. No visible signs of deterioration are observed in either of the spaces.

Figure B.78: Gnd-W/15 (left) & Gnd-W/16 (right) - Ladies Toilets for the Auditorium (2015)

Gnd-W/17

This space is used as a *Store*. The space built in 1893 was previously part of the western verandah and was modified in 1965. It is 3m x 3.6m (9ft. 10in. x 11ft. 10in.) with the soffit of the ceiling at +4.4m (14ft. 6in.) above the plinth.

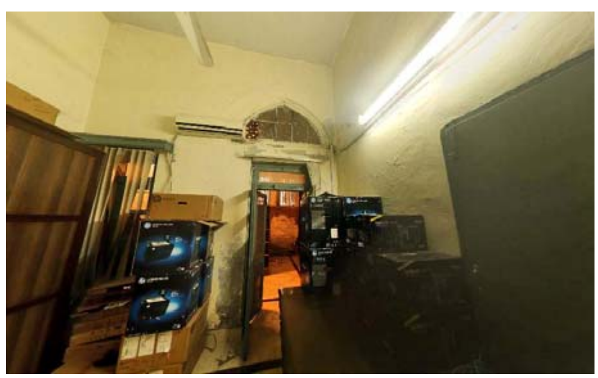

Figure B.79: Gnd-W/17 – Store (2015)
Looking West

The space is entered through the door in the eastern wall. On the northern wall there is a boarded up doorway. There is a door that opens onto space Gnd-W/18 in the western wall. The door in southern wall leads onto space Gnd-W/19. The space has an RC slab roof.

Sagging of roof is detected along with the out of plane behavior of the northern wall. Also flaking of paint due to dampness can be seen on both the eastern and the western wall.

Gnd-W/18

This space is used as a *Store*. The room was built in 1969 in the open space between the Museum and NCA. The space is 5m x 4.26m (16ft. 5in. x 14ft.) with the soffit of the ceiling at +4.67m (15ft. 4in.) above the plinth. Its floor is -14.3cm (5.6in.) below the plinth.

The space is accessed through a door set into an in-filled archway on the eastern wall; south of the door there are traces of another archway in-filled with brick masonry. There is a door on the southern wall that leads onto space Gnd-W/06. The western wall has two windows in the upper half. On the northern wall there are two archways that have been in-filled with brick masonry till the spring line of the arch; the arches above are fitted with terracotta *jalis*. An exhaust fan has been fitted into each of the *jalis*. The space has an RC slab roof.

Figure B.80: Gnd-W/18 – Store (2015)
Looking West

The paint has powdered and flaked off both from the northern and the western wall. At the north-western corner of the space there is a storm drainage downpipe. The water from the pipe empties onto the floor from where it flows into the floor drain located in the corner.

Gnd-W/19

This space is used as a *Toilet*. The space built in 1893 was previously part of the western verandah and was modified in 1965. It is 3m x 1.2m (9ft. 10in. x 3ft. 11in.) with the soffit of the ceiling at +4.4m (14ft. 6in.) above the plinth.

The space can be accessed either through a door in the northern wall or the southern wall. Part of an archway in-filled with the brick masonry can be seen on the western wall while the eastern wall has no architectural features of importance. The space has an RC slab roof.

Figure B.81: Gnd-W/19 – Toilet (2015)
Looking West (left) Looking East (right)

Sagging of roof is detected along with the Out of Plane behavior of the northern wall. Also powdering and flaking off paint due to dampness can be seen on the eastern wall. Additionally some efflorescence can also be observed where the paint has completely fallen off.

Gnd-W/20

This space is used as the *Backstage Area* for the Auditorium. The space built in 1893 was previously part of the western verandah and was modified in 1965. It is 3m x 3.22m (9ft. 10in. x 10ft. 6in.) with the soffit of the ceiling at +4.4m (14ft. 6in.) above the plinth.

The space is accessed through a door in its eastern wall. On the northern wall there is a door that leads onto space Gnd-W/19. The western wall has traces of an archway in-filled with brick masonry. There are no architectural features of importance on the southern wall. The room has an RC slab roof.

Figure B.82: Gnd-W/20 – Backstage Area for Auditorium (2015)
Looking East (left) Looking West (right)

Sagging of roof is observed along with out of plane behavior of the northern wall. There is also flaking and powdering of paint due to dampness on the eastern wall.

Basement

The only room in the basement is for Administration use only and is accessed from the building exterior through stairs leading down from space Gnd-E/21.

Eastern Part – Security & Surveillance Room

Bas-E/01

The space built in 1972 functions as the *Surveillance Room*. It is 9.96m x 5.68m (32ft. 8in. x 18ft. 8in.) with the floor at -3.31m (10ft. 10in.) below the plinth and the soffit of the ceiling at +0.54m (1ft. 9in.) above the plinth.

The space is accessed from the stair hall through a door in the southern wall. At the eastern end of the wall there is a door that leads to the storage space under the stairs while at the western end there is a ventilator that is currently being used as an electric duct. There are no architectural features of any importance on the remaining three walls. The roof is an RC slab supported on two 34cm (13in.) wide RC beams with

32cm (12in.) drop from the soffit running along the shorter span in the N-S axis. No visible signs of deterioration are observed in the space.

Figure B.83: Bas-E/01 – Surveillance Room (2015)
Looking North East

First Floor

This section provides descriptions of spaces in all the sections of the first floor located in different parts of the building and reachable only through their own dedicated vertical circulation. Most of the spaces described in this section are restricted to Administration only. The spaces open to the visitor are the south eastern galleries Fst-E/10 – 15, accessed through the stair ascending from space Gnd-E/18 and the Auditorium Gallery (Fst-W/03) in the west accessed via the stairs coming up from space Gnd-W/09.

Northern Part – The Staging Area

Fst-N/01 & Fst-N/02

Both the spaces built in 1893 are spiral *Stairwells*. Fst-N/01 and Fst-N/02 are continuation spaces for Gnd-N/11 & Gnd-N/10 respectively, which have been described in detail above (Section 2.7.2.1).

Figure B.84: Fst-N/01 – Western Stairwell (2015)
Looking North-East

Fst-N/03

This is an open air space technically part of roof for space Gnd-N/0, is used as a *Terrace*. It is included in the list of spaces as it is essential for the vertical circulation of the Northern Section of the Museum and spaces Fst-N/04, Fst-N/05 and Fst-N/06 can only be accessed through this space. It is 9m x 4.72m (29ft. 6in. x 15ft. 6in.) and the floor is +5.7m (18ft. 9in.) above the plinth.

Figure B.85: Fst-N/03 – Terrace (2015)
Looking East

The space is accessed through the door leading from space Fst-N/01, in the southern wall. East of the door on the same wall is an arch, vertically divided into two sections. The upper section is horizontally divided into three sections and each section is fitted with terracotta *jalis* while the lower section is divided into three arch openings. The middle arch is fitted with a door leading onto space Fst-N/06 while the arches on either side have floor length windows. Further east of the arch is a door which leads onto space Fst-N/02. On the western side there are three corbelled brick openings leading onto space Fst-N/04. The eastern side has identical openings leading onto space Fst-N/05. The bounding surface on the northern side is a solid marble parapet which is 80cm (31.5in.) high in the middle and 36.5cm (14in.) on either sides. Microbiological growth is observed on the floor of the terrace.

Figure B.86: Fst-N/03 – Terrace – Deterioration (2015)
Microbiological growth on the floor

Fst-N/04 & Fst-N/05

These spaces built in 1893 are mirrored spaces that are the *Turrets*. The spaces measure 3.16m x 3.16m (10ft. 4in. x 10ft. 4in.) each. The center of the intrados of the flat dome is at +9.44m (31ft.) above the plinth. The dome rests on four corner columns which are interspersed with two columns on all four sides, hence forming three openings each side.

The space Fst-N/04 is accessed through three corbelled brick openings in the eastern side while space Fst-N/05 is accessed through identical openings in its western side. Towards the north the three corbelled openings of both spaces have sandstone balustrades which are fitted with terracotta *jalis*. On the western side of space Fst-N/04 the corbelled openings also have the sandstone balustrade which is fitted with terracotta *jalis*. Similar treatment is seen on the eastern side of the space Fst-N/05. On the southern side both spaces have recessed impressions of the corbelled openings but these are in-filled with brick masonry. The roofing system for both spaces comprises of a double dome in brick masonry. From inside the chamber a flat dome is seen while from the exterior the upper dome with a four-cross centered profile is seen. The cavity between the two domes is inaccessible.

Figure B.87: Fst-N/04 (left) & Fst-N/05 (right) – Western & Eastern Turret respectively (2015)
Looking North in the image on the left; Looking South in the image on the right

In space Fst-N/04 electric conduits have been installed by carving grooves in the walls which have been grouted with cement. Some of the brick tiles used on the floor are starting to powder and disintegrate. While in space Fst-N/05 the bricks around the edge of the inner dome as well some brick tiles on the floor are starting to powder and disintegrate.

Fst-N/06

The space is the *Balcony* on the first floor. The space is 7m x 7m (23ft. x 23ft.) with a truncated square opening in the middle, forming a 1.25m (4ft.) wide balcony on all four sides, visually connecting the space with Gnd-N/02 (Entrance Vestibule) directly below. The ceiling of the space is marked at +11.28m (37ft.) by a corbelled projection extending 0.99m (3ft. 3in.) from the wall. An octagonal opening is formed in the middle of the ceiling which visually connects the space to chamber Thd-N/05 located directly above.

The space is accessed through an arched doorway that is flanked on either side by floor length arched windows in the northern wall; above the door and the windows are three openings fitted with terracotta *jalis.* This arrangement is framed by a shouldered flat arch. On the eastern and western wall an identical arrangement is seen but all the openings are in-filled with brick masonry. The southern side has three archways that are open and lead onto space Fst-N/07; above the archways are three openings fitted with terracotta *jalis.* On top of each corner is a corbelled pendentives finished in ornamental plasterwork. The transition from the four walls of the chamber into an octagon at the upper level is achieved by means of these pendentives.

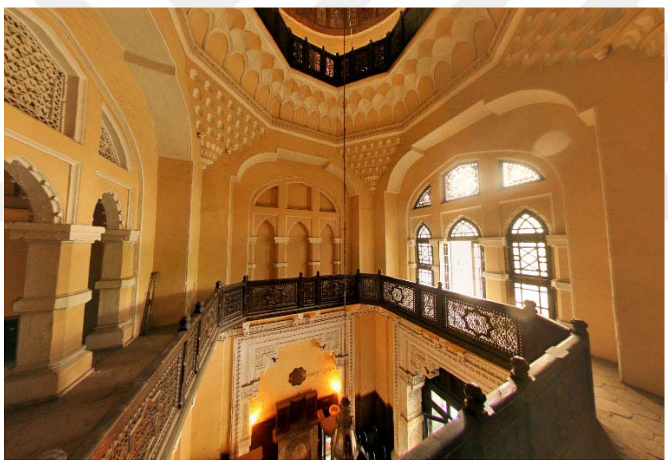

Figure B.88: Fst-N/06 – Balcony above the Entrance Vestibule (2015)
Looking East (left) Looking West (right)

No visible signs of deterioration are observed in the space.

Fst-N/07

This is the *Balcony* that was built in 1893 as part of the ornamentation of the northern wall of Gnd-C/01. It faces south and looks below onto space Miniature Gallery (Gnd-C/01). The space is 3.65m x 1.45m (12ft. x 4'-9") with its floor at +5.8m (19ft.) above the plinth.

The space is accessed from three archways leading from space Fst-N/06 on its northern side. There are three openings, one above each of the archways fitted with a terracotta *jali*. The space is bounded by carved wooden balustrade on the remaining three sides. No visible signs of deterioration are observed in the space.

Figure B.89: Fst-N/07 – Balcony (2016)
Looking North from the Miniature Gallery (left) Close-up view showing details of the carved wooden balustrade (right)

Eastern Part – Galleries & Conservation Laboratory

Fst-E/01

This space built in 1978 is used as a *Verandah/ Stair Hall* for the Conservation Laboratory. The space is 9.22m x 2.6m (30ft. 3in. x 8ft. 6in.) with the floor at +4.95m (16ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth.

Figure B.90: Fst-E/01 – Verandah/ Stair Hall for Conservation Laboratory (2015)
Looking East

The space is accessed through a staircase that rises up from space Gnd-E/12 on the ground floor, at the western side of the space. At the western end of the southern wall there is a window; east of the window on the same wall there are two windows fitted with iron grilles. The eastern wall has a door leading onto space Fst-E/02. There is a door leading onto space Fst-E/03, at the eastern end of the northern wall; west of the door on the same wall there are two windows. The space has an RC slab roof.

Drip marks and discoloration of paint is observed around every electric point on the ceiling. Flaking of paint is also observed on the southern wall.

Fst-E/02

The space built in 1978 functions as an *Office*. The space is 2.74m x 2.7m (9ft. x 8ft. 10in.), with the floor at +4.95m (16ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth.

The space is accessed through a door in the western wall. On the southern wall there is a window. The eastern wall also has a window while the northern wall has no architectural features of importance. The space has an RC slab roof.

Figure B.91: Fst-E/02 – Office (2016)
Looking East (left) Looking South (right)

Flaking and discoloration of paint due to dampness is observed on ceiling as well as the eastern and the southern walls.

Fst-E/03

The space built in 1978 is used as the main *Conservation Workshop*. It is 8.66m x 6.9m (28ft. 5in. x 22ft. 8in.) with the floor at +4.95m (16ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth.

Figure B.92: Fst-E/03 – Conservation Workshop (2015)
Looking West

The space is accessed through a door on the eastern end of the southern wall; west of the door on the same wall there are two windows. There are no architectural features of importance on the western and the northern walls. The eastern wall at southern end has a door which opens onto space Fst-E/04 while the northern end is open and leads onto space Fst-E/05. The space has an RC slab roof.

Drip marks and discoloration of paint is observed around every electric point on the ceiling. Discoloration of paint is also observed on the northern and the southern walls.

Fst-E/04

The space built in 1978 is used as the *Photography Room* for the Conservation Workshop. It is 3.3m x 3.4m (10ft. 10in. x 11ft. 2in.) with the floor at +4.95m (16ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth. The space is accessed through a door in the western wall. There are no architectural features of importance on the northern and the southern wall. On the eastern wall there is a window.

Figure B.93: Fst-E/04 – Photography Room for Conservation Workshop (2015)
Looking East

Drip marks and discoloration of paint is observed around every electric point on the ceiling. Flaking of paint due to dampness is observed on the eastern wall.

Fst-E/05

The space built in 1978 functions as a *Transition Space* and is an extension of the Conservation Workshop (Fst-E/03). It is 3.58m x 3.23m (11ft. 9in. x 10ft. 7in.) with the floor at +4.95m (16ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth.

Figure B.94: Transition Space – Extension of Conservation Workshop (2015)
Looking North-East

The space is accessed from its western side. On the northern wall there is a door that leads onto space Fst-E/06. The eastern wall has a window under which is a built-in concrete shelf. There are no architectural features of importance on the southern wall. The space has an RC slab roof. Drip marks and discoloration of paint is observed around every electric point on the ceiling. Discoloration of paint is also observed on the northern and the eastern walls.

Fst-E/06

This space built in 1978 is an auxiliary *Conservation Workshop*. It is 3m x 3m (9ft. 10in. x 9ft. 10in.) with the floor at +4.95m (16ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth.

The space is accessed through the door in the southern wall. There is a window in the eastern wall. The northern wall constructed with plywood panels fixed onto a wooden frame has a door leading onto space Fst-E/07. There are no architectural features of importance on the western wall. The space has an RC slab roof. Drip marks and discoloration of paint is observed around every electric point on the ceiling. Flaking of paint due to dampness is also observed on the eastern wall.

Figure B.95: Fst-E06 – Conservation Workshop (2015)
Looking North

Fst-E/07

This space built in 1978 is an auxiliary *Conservation Workshop*. It is 3.8m x 3m (12ft. 6in. x 9ft. 10in.) with the floor at +4.95m (16ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth.

Figure B.96: Fst-E/07 – Conservation Workshop (2015)
Looking North

The space is accessed through the door in the southern wall. There is a window in the eastern wall. The northern wall has a door leading onto space Fst-E/08. There are no architectural features of importance on the western wall. The space has an RC slab roof.

Drip marks and discoloration of paint is observed around every electric point on the ceiling. Discoloration of paint continues onto the northern and eastern walls. Slight flaking of paint is observed on the western wall.

Fst-E/08

This space built in 1978 is an auxiliary *Conservation Workshop*. It is 2.77m x 3m (9ft. x 9ft. 10in.) with the floor at +4.95m (16ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth.

The space is accessed through the door in the southern wall. There is a window in the eastern wall. The northern wall has a door leading onto space Fst-E/09. There are no architectural features of importance on the western wall. The space has an RC slab roof. Drip marks and discoloration of paint is observed around every electric point on the ceiling. Discoloration of paint continues onto the northern wall. Slight flaking of paint is observed on the eastern wall while the western wall has recently been re-plastered with cement mortar.

Figure B.97: Fst-E/08 – Conservation Workshop (2015)
Looking North

Fst-E/09

This space built in 1978 is used as *Storage Room* for the Conservation Workshop. It is 2.77m x 3m (9ft. x 9ft. 10in.) with the floor at +4.95m (16ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth.

Figure B.98: Fst-E/09 – Storage Room for Conservation Workshop (2015)
Looking North

The space is accessed through the door in the southern wall. An exhaust fan has been fitted in the northern wall. There are no architectural features of importance on the eastern and the western walls. The space has an RC slab roof. Flaking of paint due to dampness is observed on the eastern, western and the northern walls.

Fst-E/10 to Fst-E/14

All these spaces are essentially a single rectangular space built in 1974 and are being used as the *Pakistan Freedom Movement Gallery I*. This space is divided by the use of two brick masonry walls running in the E-W axis. The floor of all the spaces is at +4.36m (14ft. 3in.) above the plinth level while the soffit of the ceiling for spaces Fst-E/10, Fst-E/11, Fst-E/12 & Fst-E/14 is at +7.45m (24ft. 5in.) above the plinth and the soffit of the ceiling for space Fst-E/13 is at +9.39m (30ft. 9in.) above the plinth.

Space **Fst-E/10** measuring 12.7m x 2.7m (41ft. 8in. x 8ft. 10in.) is accessed through a staircase that rises up from space Gnd-E/18 on the ground floor, at the western side of the space. Adjacent to the stairs at the western end is an opening that leads onto space Fst-E/11. There is a window on the western wall above the staircase. On the southern wall there is an iron grille door leading onto the Auxiliary block. The doorway on the eastern wall leads onto space Fst-E/14. There are no architectural features of importance on the northern wall.

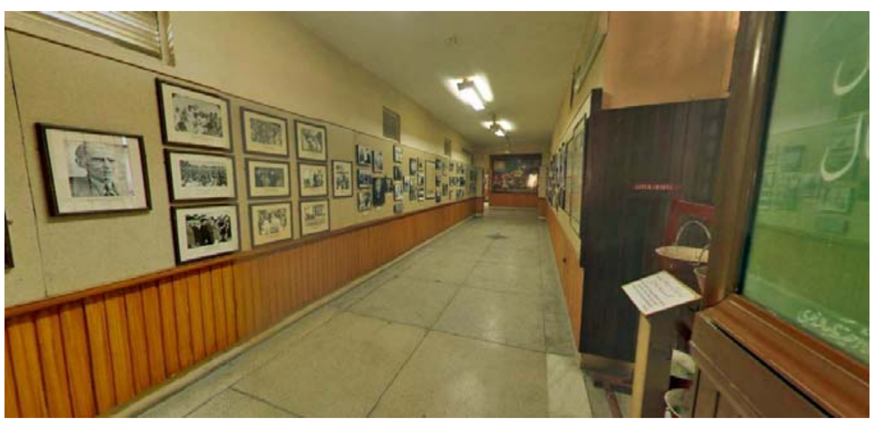

Figure B.99: Fst-E/10 – Freedom Movement Gallery (I) (2015)
Looking East

Space **Fst-E/11** measuring 3.45m x 8.2m (11ft. 4in. x 26ft. 11in.) is accessed through an opening in the eastern wall. North of the opening there are two more openings on the same wall that lead onto spaces Fst-E/12 & Fst-E/13. There are no architectural features of any importance on the northern wall. The western wall is completely obscured by deep display cases. On the southern side there is a floor to ceiling iron grille, separating the space from the staircase.

Figure B.100: Fst-E/11 – Freedom Movement Gallery (I) (2015)
Looking North

Space **Fst-E/12** measuring 12.7m x 2.7m (41ft. 8in. x 8ft. 10in.) can be accessed from a doorway at the western end from space Fst-E/11 or the doorway at the eastern end from space Fst-E/14. There are no architectural features of any importance on the northern and the southern walls.

Figure B.101: Fst-E/12 – Freedom Movement Gallery (I) (2015)
Looking East

Space **Fst-E/13** measuring 12.7m x 3.43m (41ft. 8in. x 11ft.) can be accessed from a doorway at the western end from space Fst-E/11 or the doorway at the eastern end from space Fst-E/14; above each doorway there is a ventilator. There are four ventilators each on top of the northern and the southern walls.

Figure B.102: Fst-E/13 – Freedom Movement Gallery (I) (2015)
Looking East

Space **Fst-E/14** measuring 3.45m x 9.7m (11ft. 4in. x 31ft. 10in.) can be accessed through any of the three doorways in the western wall from spaces Fst-E/10, Fst-E/12 & Fst-E/13. There are two doorways in the eastern wall leading onto space Fst-E/15. There are no architectural features of importance on the northern and the southern walls.

Figure B.103: Fst-E/14 – Freedom Movement Gallery (I) (2015)
Looking North

All the spaces have an RS slab roof. No visible signs of deterioration are observed in spaces Fst-E/10, Fst-E/11, Fst-E/12 & Fst-E/14. In space Fst-E/13 drip marks are observed flowing from the ventilators on the northern and the southern walls. Slight flaking of paint due to dampness is observed on the ceiling of the space as well.

Figure B.104: Fst-E/13 – Freedom Movement Gallery – Deterioration (2015)
Drip marks on the northern wall

Fst-E/15

This space built in 1978 is used as *Pakistan Freedom Movement Gallery II*. It measures 9.8m x 10m (32ft. 2in. x 32ft. 10in.) with the floor at +4.36m (14ft. 3in.) above the plinth and the soffit of the ceiling at + 8m (26ft. 3in.) above the plinth.

Figure B.105: Fst-E/15 – Freedom Movement Gallery (II) (2015)
Looking West

The space is accessed through either of the two doorways in the western wall. The southern wall has a window in the middle. High on the wall on either side of the window are two circular openings of 0.5m (1ft. 8in.) dia. each. On the eastern wall there are two ventilators. There are no architectural features of any importance on the northern wall. The space has an RC slab roof.

Drip marks and discoloration of paint is observed around every electric point on the ceiling. Slight flaking of paint and drip marks under the ventilators are observed on the eastern wall.

Figure B.106: Fst-E/15 – Freedom Movement Gallery (II) – Deterioration (2016)
Flaking of paint and drip marks on the Eastern wall (left)
Drip marks and discoloration of paint on the ceiling (right)

Southern Part – Administrative Offices

Fst-S/01

The space built in 1978 is used as an *Office* for the clerical staff. It is 6.86m x 6.3m (22ft. 6in. x 20ft. 8in.) with the floor at +3.83m (12ft. 7in.) above the plinth and the soffit of the ceiling at + 7.53m (24ft. 8in.) above the plinth.

Figure B.107: Fst-S/01 – Office for Clerical Staff (2015)
Looking North (left) Looking West (right)

The space is accessed through a door in the eastern wall. The southern wall has three windows with ventilators above each. There are no architectural features of importance on the western wall. On the northern wall there are two doors. The door at the western end opens onto space Fst-S/03 while the door at the eastern end leads to space Fst-S/02. The space has an RC slab roof supported on two 30.5cm (12in.) wide RC beams with a 33cm (13in.) drop, running in the N-S axis. Discoloration of paint due to dampness is observed at the top of the walls in the north east corner. Flaking of paint is also observed on the northern wall.

Fst-S/02

The space built in 1978 is used as a *Store*. The space could not be accessed for measurements during the survey, thus the measurements are approximate. The space is 3.5m x 1.83m (11ft. 6in. x 6ft.) with the floor at +3.83m (12ft. 7in.) above the plinth and the soffit of the ceiling at + 7.53m (24ft. 8in.) above the plinth.

The space is accessed through a door in its southern wall. On the northern wall there is a window. There are no architectural features of importance on the eastern and the western walls. The space has an RC slab roof.

The condition of the space could not be observed.

Fst-S/03

The space built in 1978 functions as a *Toilet*. The space could not be accessed for measurements during the survey, thus the measurements are approximate. The space is 2.58m x 1.86m (8ft. 6in. x 6ft.) with the floor at +3.83m (12ft. 7in.) above the plinth and the soffit of the ceiling at + 7.53m (24ft. 8in.) above the plinth.

The space is accessed through a door in its southern wall. On the northern wall there is a window. There are no architectural features of importance on the eastern and the western walls. The space has an RC slab roof.

The condition of the space could not be observed.

Fst-S/04

The space built in 1985 functions as the Museum's *Record Room*. It is 6.2m x 3m (20ft. 4in. x 9ft. 10in.) with the floor at +5.22m (17ft. 1in.) above the plinth and the soffit of the ceiling at + 8.2m (26ft. 11in.) above the plinth.

Figure B.108: Fst-S/04 – Record Room (2015)
Looking West (left) Looking East (right)

The space is accessed through a door in the southern wall, west of the door on the same wall is a window. On the western wall a book shelf has been built into the wall. There are no architectural features of importance on the northern wall. The eastern wall has two windows. The space has an RC slab roof. Flaking and powdering of paint due to dampness is observed near the top of the southern, eastern and western walls.

Western Part – Auditorium, Library, Reserves & Stores

Fst-W/01

The space built in 1893 functions as the *Stair Hall.* It is 9.1m x 3.77m (29ft. 10in. x 12ft. 4in.) with the floor at +4.38m (14ft. 4in.) above the plinth and the soffit of the ceiling at + 7.41m (24ft. 4in.) above the plinth.

The space is accessed through a staircase that rises up from space Gnd-W/09 on the ground floor, at the western side of the space. The stair continues to climb up to space Snd-W/01. The staircase is 1.1m (3ft. 7in.) wide and each step has an average riser of 0.2m (8in.). The northern wall has three arched openings which have been fitted with a CI balustrade; above the balustrade the windows have been fitted with iron grilles.

There are no architectural features of importance on the eastern wall. The southern wall has a door at the eastern end which opens onto space Fst-W/03; west of this door on the same wall is another door that leads onto space Fst-W/02. The space has an RC slab roof.


Figure B.109: Fst-W/01 – Stair Hall for Auditorium and Library (2015)
Looking East (left) Looking West (right)

No visible signs of deterioration are observed in the space.

Fst-W/02

The space built in 1969 is the *Projector Room* which is currently being used to store the newspaper collection of the Museum's Library. It is 2.7m x 1.96m (8ft. 10in. x 6ft. 5in.) with the floor at +4.38m (14ft. 4in.) above the plinth and the soffit of the ceiling at + 7.41m (24ft. 4in.) above the plinth.

Figure B.110: Fst-W/02 – Projector Room (2015)
Looking South

The space is accessed through a door in the northern wall. There is a small opening in the southern wall for the projector. There are no architectural features of importance on the eastern and the western wall. The space has an RC slab roof. No visible signs of deterioration are observed in the space.

Fst-W/03

The space built in 1969 functions as the *Auditorium Gallery*. It is 9m x 2.7m (29ft. 6in. x 8ft. 10in.) with the soffit of the suspended false ceiling at +6.73m (22ft.) above the plinth. The floor of the space is in three levels. The top level is at +4.38m (14ft. 4in.) while the mid-level is at +4.14m (13ft. 7in.) and the lowest level is at +3.91m (12ft. 10in.) above the plinth.

The space is accessed through a door in the northern wall. The southern side has a 0.68m (2ft. 3in.) high parapet. The eastern and the western wall have no architectural features of importance. The roofing system of the space could not be observed due to the suspended false ceiling. No visible signs of deterioration are observed in the space.

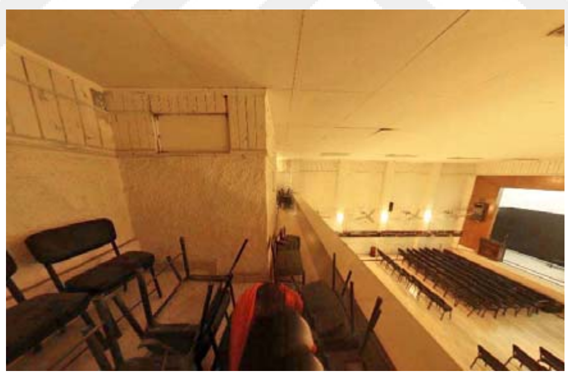

Figure B.111: Fst-W/03 – Auditorium Gallery (2015)
Looking East

Fst-W/04

The space built in 1985 is used as the *Library Store*. The space is L shaped and can be divided into northern and southern parts. The northern half stretched out in the E-W axis is 8.44m x 3.89m (27ft. 8in. x 12ft. 9in.) while the southern half is 4.81m x 3.64m (15ft. 9in. x 11ft. 11in.). The largest dimensions of the space are 8.44m x 7.53m (27ft. 8in. x 24ft. 8in.). Its floor is at +4.77m (15ft. 8in.) above the plinth and the soffit of the ceiling is at +8.19m (26ft. 10in.) above the plinth.

Figure B.112: Fst-W/04 – Library Store (2015)
Looking South

The space is accessed through a staircase descending from space Snd-W/04, along the eastern wall. On the southern wall there is a door leading onto space Fst-W/05. The western wall is in two sections; in the northern section it has a window while in the southern section there is a door opening onto space Fst-W/08. The northern wall is also in two sections; its western section is blank while there are two windows in the eastern section of the wall. The space has an RC slab roof. Drip marks and discoloration of paint is observed around every electric point on the ceiling. Slight flaking of paint is also observed.

Fst-W/05

The space built in 1985 is the *Transition Space* between spaces Fst-W/04, Fst-W/06 and Fst-W/07. It is 3.15m x 3.95m (10ft. 4in. x 13ft.) with the floor at +4.9m (16ft.) above the plinth and the soffit of the ceiling at + 8.24m (27ft.) above the plinth.

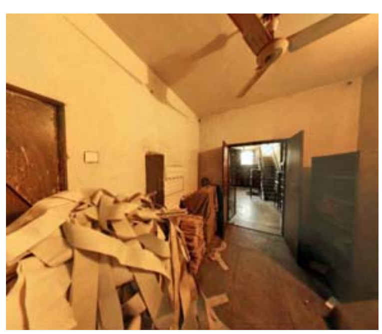

Figure B.113: Fst-W/05 – Transition Space (2015)
Looking North

The space can be accessed through the door in the northern wall from space Fst-W/04 as well as the door in the western wall from space Fst-W/06. The door in the southern wall leads onto space Fst-W/07. There are no architectural features of importance on the eastern wall. The space has an RC slab roof. No visible signs of deterioration are observed in the space.

Fst-W/06

This space built in 1985 functions as part of the *Stairwell*. It is 5m x 3.8m (16ft. 5in. x 12ft. 6in.) with the floor at +4.9m (16ft.) above the plinth while the soffit of the ceiling is at +9.64m (31ft. 8in.) above the plinth.

The space is accessed through a staircase that rises up from space Gnd-W/06 on the ground floor, at the western side of the space. There is a door in the eastern wall that opens onto space Fst-W/05. There are no architectural features of importance on the northern and the southern walls. The space has an RC slab roof.

No visible signs of deterioration are observed in the space.

Fst-W/07

This space built in 1985 functions as the *Reserves Storage*. It is an L shaped room which can be divided into northern and the southern parts. The northern section stretched out in the N-S axis is 8.41m x 16.15m (27ft. 7in. x 53ft.) while the southern section is 4.47m x 3.53m (14ft. 8in. x 11ft. 7in.). The largest dimensions of the space are 8.41m x 19.68m (27ft. 7in. x 64ft. 7in.). Its floor is at +4.9m (16ft.) above the plinth and the soffit of the ceiling is at +9.52m (31ft. 3in.) above the plinth.

The space is accessed through a door in the northern wall. The eastern wall has four 0.5m (1ft. 8in.) wide pilasters, set forward by 7.6cm (3in.) from the wall. The southern wall is in two sections; there is a ventilator in the eastern section while the western section is blank. There are five ventilators on the western wall. In the south west corner of the northern part of the space there is a 1.1m (3ft. 7in.) high raised platform measuring 4.17m x 3.47m (13ft. 8in. x 11ft. 5in.) in size. The space has an RC slab supported on four 0.5m (1ft. 8in.) wide RC beams with a 0.6m (2ft.) drop running in the E-W axis.

Figure B.114: Fst-W/07 – Reserves Storage (2015)
Looking South (left) Looking North (right)

Drip marks are observed flowing from the ventilators on the western wall. Swelling of plaster along with powdering and flaking of paint is observed on the eastern wall.

Fst-W/08

This space built in 1985 is used as the *Toilet.* It is 1.24m x 3m () with the floor at +4.77m (15ft. 8in.) above the plinth while the soffit of the ceiling is at +8.19m (26ft. 10in.) above the plinth.

The space is accessed through a door in the eastern wall. There are no architectural features of importance on the remaining three walls. The space has an RC slab roof.

The condition of the space could not be observed.

Second Floor

This section provides description of the spaces located on the second floor, all located in the Western Part of the building. The only space open to public on this floor is the Library (Snd-W/03) which is accessed through the stairs starting from space Gnd-W/09 on the ground level.

Snd-W/01

The space built in 1893 functions as the *Stair Hall.* It is 5.26m x 3.6m (17ft. 3in. x 11ft. 10in.) with the floor at +7.62m (25ft.) above the plinth and the soffit of the ceiling at + 12.35m (40ft. 6in.) above the plinth.

The space is accessed through a staircase at the western side. The stairs rise up from space Fst-W/01 which in turn continues from space Gnd-W/09 on the ground floor. There are two arched windows set within recessed rectangular frames on the western wall. There are two triangular arched windows in the northern wall. The eastern wall is constructed with plywood sheets fixed onto a wooden frame. There is a door at the southern end of the wall that opens onto space Snd-W/02. The southern wall has a door that leads onto space Snd-W/03. The space has an RC slab roof. Flaking of paint due to dampness is observed on the northern wall.

Figure B.115: Snd- W/01 – Stair Hall (2015)
Looking East (left) Looking West (right)

Snd-W/02

The space built in 1893 is used as the *Chief Librarian's Office.* It is 3.77m x 3.6m (12ft. 5in. x 11ft. 10in.) with the floor at +7.62m (25ft.) above the plinth and the soffit of the ceiling at + 12.35m (40ft. 6in.) above the plinth.

The space is accessed through a door in the western wall which is constructed with plywood sheets fixed onto a wooden frame. The northern wall has no architectural features of importance. There are two arched windows set within recessed rectangular frames on the eastern wall. On the southern wall is a door that leads onto space Snd-W/03. The space has an RC slab roof. No visible signs of deterioration are observed in the space.

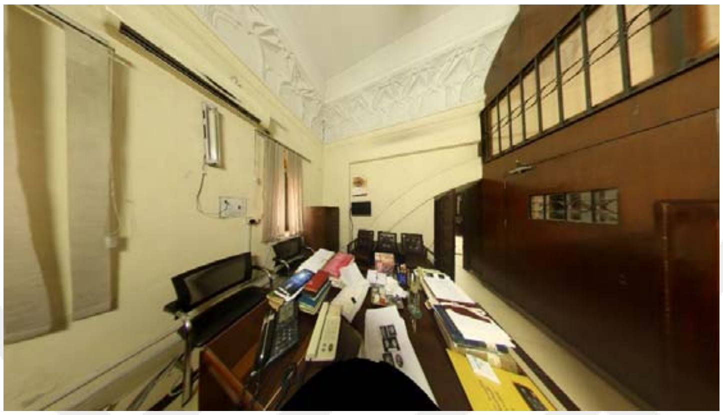

Figure B.116: Snd-W/02 – Chief Librarian's Office (2015)
Looking South

Snd-W/03

The space functions as the *Museum Library*. The space was created during the 1969 renovation through the addition of an inter-floor slab in an existing space that was built in 1893 and functioned as a Lecture Hall. It is 9m x 18.4m (29ft. 6in. x 60ft. 5in.) with the floor at +7.62m (25ft.) above the plinth and the soffit of the ceiling at + 12.35m (40ft. 6in.) above the plinth.

The space can be accessed through a door in the northern wall; east of the door on the same wall is another door that opens onto space Snd-W/02. There are no architectural features of importance on the eastern wall. There are five windows in the southern wall. On the western wall there are ten arched openings framed in recessed rectangles. At the southern end of the wall the first arch has been dismantled and the opening enlarged to fit in a door that leads onto space Snd-W/05. The next five arched openings north of the door are windows that have been boarded up with plywood. The seventh arch has also been dismantled and the opening enlarged to fit in a door that leads onto space Snd-W/04. The remaining three arched at the northern end of the wall are windows. The space has an RC slab supported on I-Beams running along the shorter span in the E-W axis. No visible signs of deterioration are observed in the space.

Figure B.117: Snd-W/03 – Museum Library (2015)
Looking South

Snd-W/04

The space built in 1985 houses the *Staircase* that descends to space Fst-W/04 on the first floor. It is 0.91m x 2.74m (3ft. x 9ft.) with the soffit of the ceiling at +10.43m (34ft. 3in.) above the plinth.

The space is accessed through a door in the eastern wall. The western wall has two windows while the northern and the southern wall have no architectural features of importance. The space has an RC slab roof.

No visible signs of deterioration are observed in the space.

Snd-W/05

The space built in 1985 functions as the *Digitizing Room* for the Library. It is 3.1m x 4.13m (10ft. 2in. x 13ft. 6in.) with the floor at +8.6m (28ft. 3in.) above the plinth and the soffit of the ceiling at + 11.81m (38ft. 9in.) above the plinth.

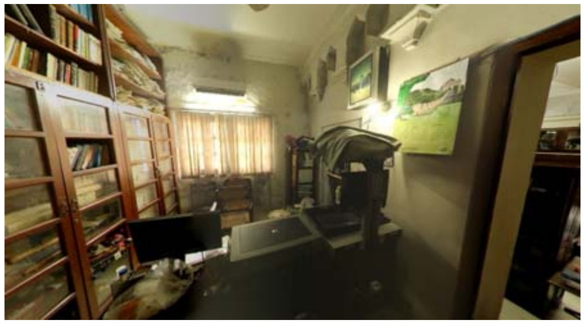

Figure B.118: Snd-W/05 – Digitizing Room (2015)
Looking North

The space is accessed through a door in the eastern wall. There is a window in the northern wall. There are no architectural features of importance on the western and the southern walls. The space has an RC slab roof. Flaking of paint due to dampness is observed on the northern wall.

Third Floor

This section describes the spaces located on the third floor built only in the Northern part of the building. All of the spaces on this floor have been constructed as part of the ornamentation of the building. These spaces are not open to the public and are accessed by the administration only for servicing or surveillance.

Northern Part – The Staging Area

Thd-N/01

The space built in 1893 and repaired in 1993, is a *Domed Canopy* and is part of Gnd-N/11 (Spiral Stairwell) rising from the ground level and built within the north-western pier of the Gnd-N/02 (Entrance Vestibule). It measures 1.29m x 1.29m (4ft. 3in.) with the floor at +12.65m (41ft. 6in.) above the plinth and the soffit of the center of the domed canopy at +16.4m (53ft. 9in.) above the plinth.

The space has four corner columns and identical arched openings on all four sides. The arched openings on the southern and eastern side allow access to the roof from which space Thd-N/05 can be approached. The arched openings at the northern and western sides extend onto small balconies supported on four brackets each. The balconies on three sides have sandstone balustrades which are fitted with terracotta *jalis.* The roofing system comprises of a dome constructed in brick masonry. Repair work in cement plaster has been carried out also some of the steps have lost their pointing.

Figure B.119: Thd-N/01 – Domed Canopy – North-Western (2015)
Looking North-East (left) Looking down (right)

Thd-N/02

The space built in 1893 and repaired in 1993, is a *Domed Canopy* and is part of Gnd-N/10 (Spiral Stairwell) rising from the ground level and built within the north-eastern pier of the Gnd-N/02 (Entrance Vestibule). It is a mirrored space of Thd-N/01 described above. Repair work in cement plaster has been carried out. No visible signs of deterioration are observed.

Figure B.120: Thd-N/02 – Domed Canopy – North-Eastern (2015)
Looking South-West (left) Looking upwards at the domical ceiling (right)

Thd-N/03

The space built in 1893 is a *Domed Canopy*. It measures 1.29m x 1.29m (4ft. 3in.) with the floor at +12.65m (41ft. 6in.) above the plinth and the soffit of the center of the domed canopy at +16.4m (53ft. 9in.) above the plinth.

The space has four corner columns and identical arched openings on all four sides. The space can be accessed through the arched opening on the northern side as well as the arched opening on the western side. On the southern side the arched opening has been blocked off by a brick masonry wall which has been fitted with an electric box. The arched openings at the eastern side extends onto a small balcony supported on four brackets. The balcony on three sides has a sandstone balustrade which is fitted with terracotta *jalis*. The roofing system comprises of a dome constructed in brick masonry. The dome has lost most of its lime plaster. Parts of the canopy's interior have been repointed with cement mortar.

Figure B.121: Thd-N/03 – Domed Canopy – South-Eastern (2015)
Looking South (left) Looking West (right)

Thd-N/04

The space built in 1893 is a *Domed Canopy* and is a mirrored space of Thd-N/03 described above. Except all of the arched openings in space Thd-N/04 are open unlike space Thd-N/03.


Figure B.122: Thd-N/04 – Domed Canopy – South-Western (2015)
Looking East (left), Looking upwards at the domical ceiling (right)

The dome has partially lost its lime plaster. Repointed with cement plaster has been carried out in parts of the interior of the canopy.

Thd-N/05

The space built in 1893 is the inside of the *Main Dome*. It is a circular space and has a 5.84m (19ft. 2in.) diameter, the floor is at +12.73m (41ft. 9in.) above the plinth and the soffit of the center of the dome is at +20.28m (66ft. 6in.) above the plinth.

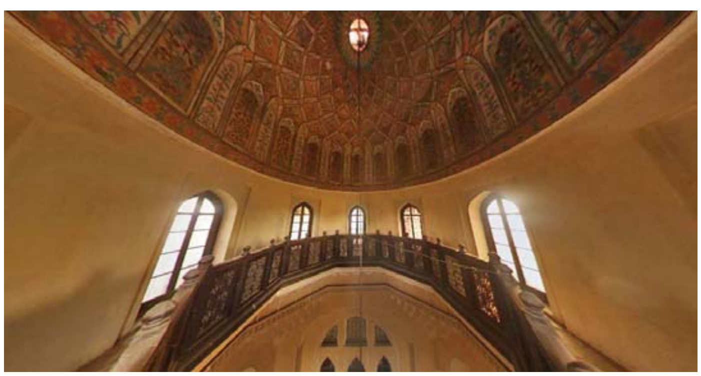
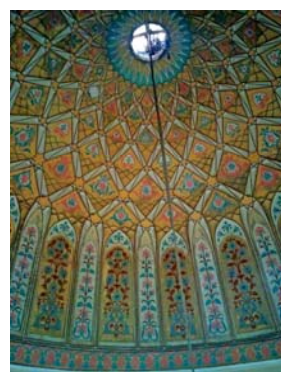

Figure B.123: Thd-N/05 – Main Dome (2015)
Looking South (left) Close-up of the dome showing the fresco details (right)

The main dome is raised on a drum that forms the circular wall of the space and is 4.3m (14ft.) high. A 0.3m (1ft.) molding runs around the top of the drum; visually separating the drum and the dome. The drum is punctured at equal intervals with eight arched openings inset into recessed rectangular frames. Seven of the openings are windows while the eight opening facing north is a door and the only means of accessing the space. In the middle of the floor is an octagonal opening which visually connects the space with spaces Gnd-N/02 and Fst-N/06 directly below. The balcony around the opening is 0.99m (3ft. 3in.) wide and has a carved wooden balustrade. The roofing system is a brick masonry dome with a roofed oculus of 0.57m (1ft. 10in.) diameter in its center.

Slight cracks are observed in the fresco that adorns the interior surface of the dome.

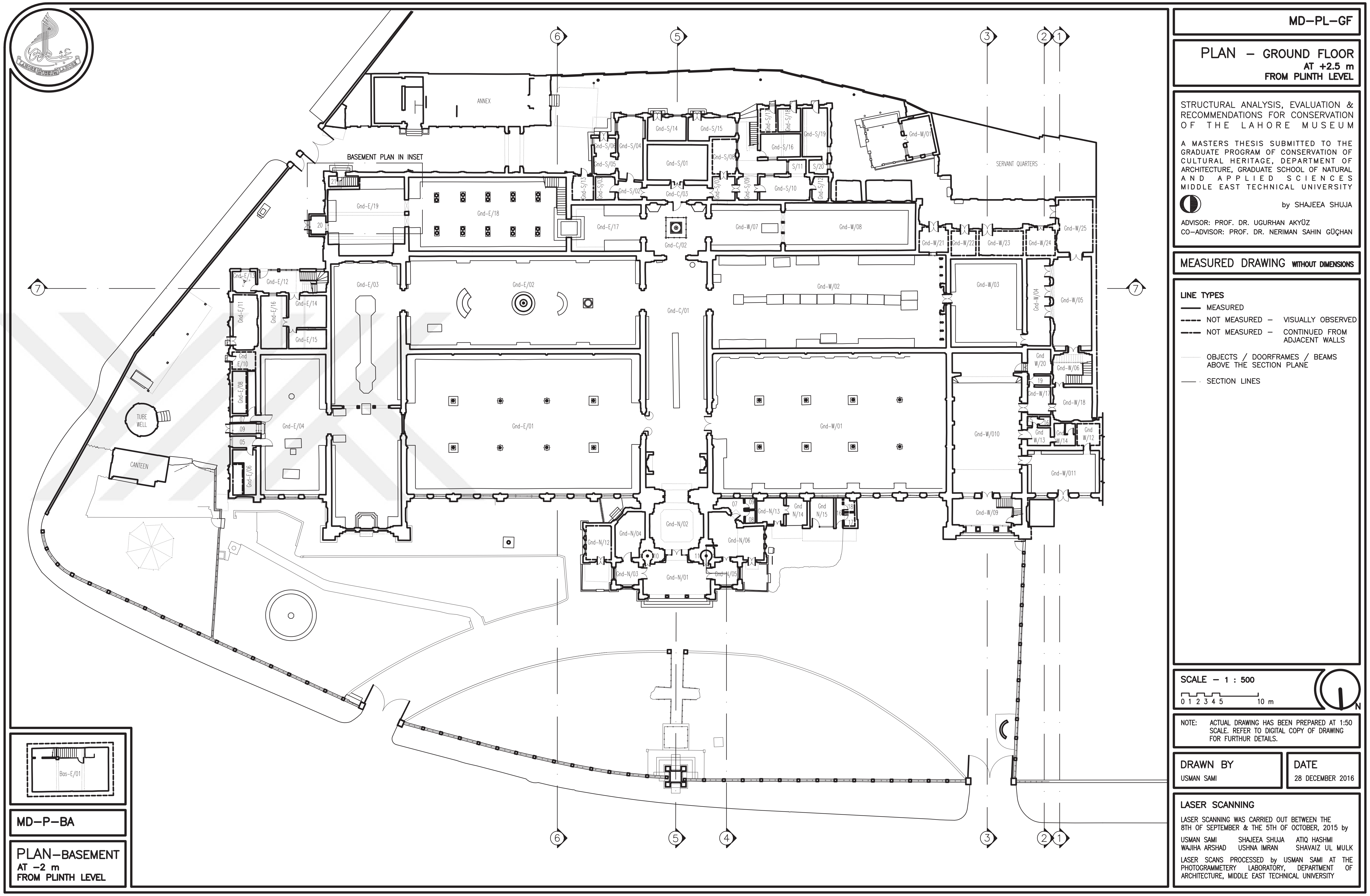

Figure B.124: MD-PL-GF / BA – Measured Drawing – Plan – Ground Floor (2016)

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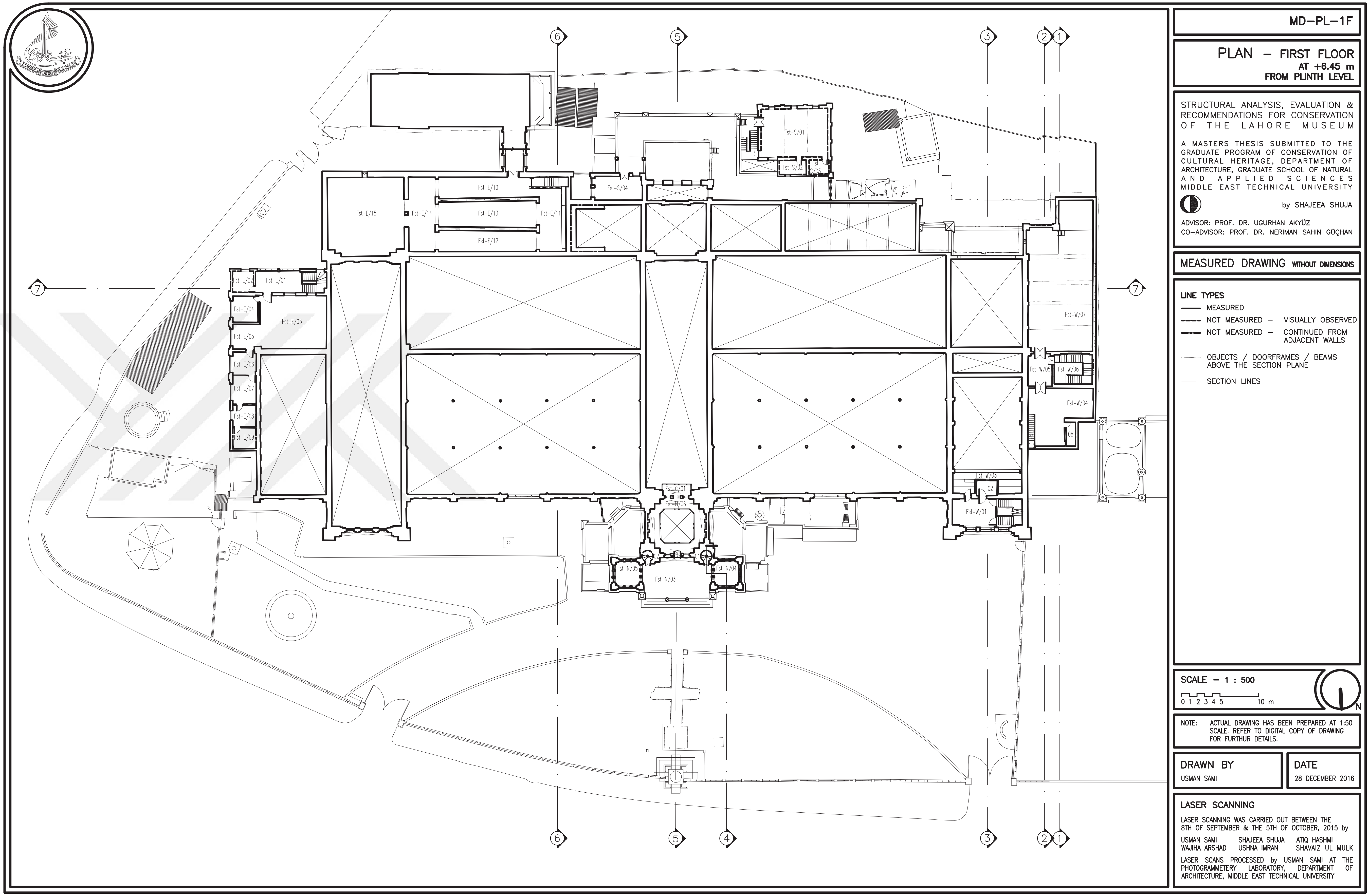

Figure B.125: MD-PL-1F – Measured Drawing – Plan – First Floor (2016)

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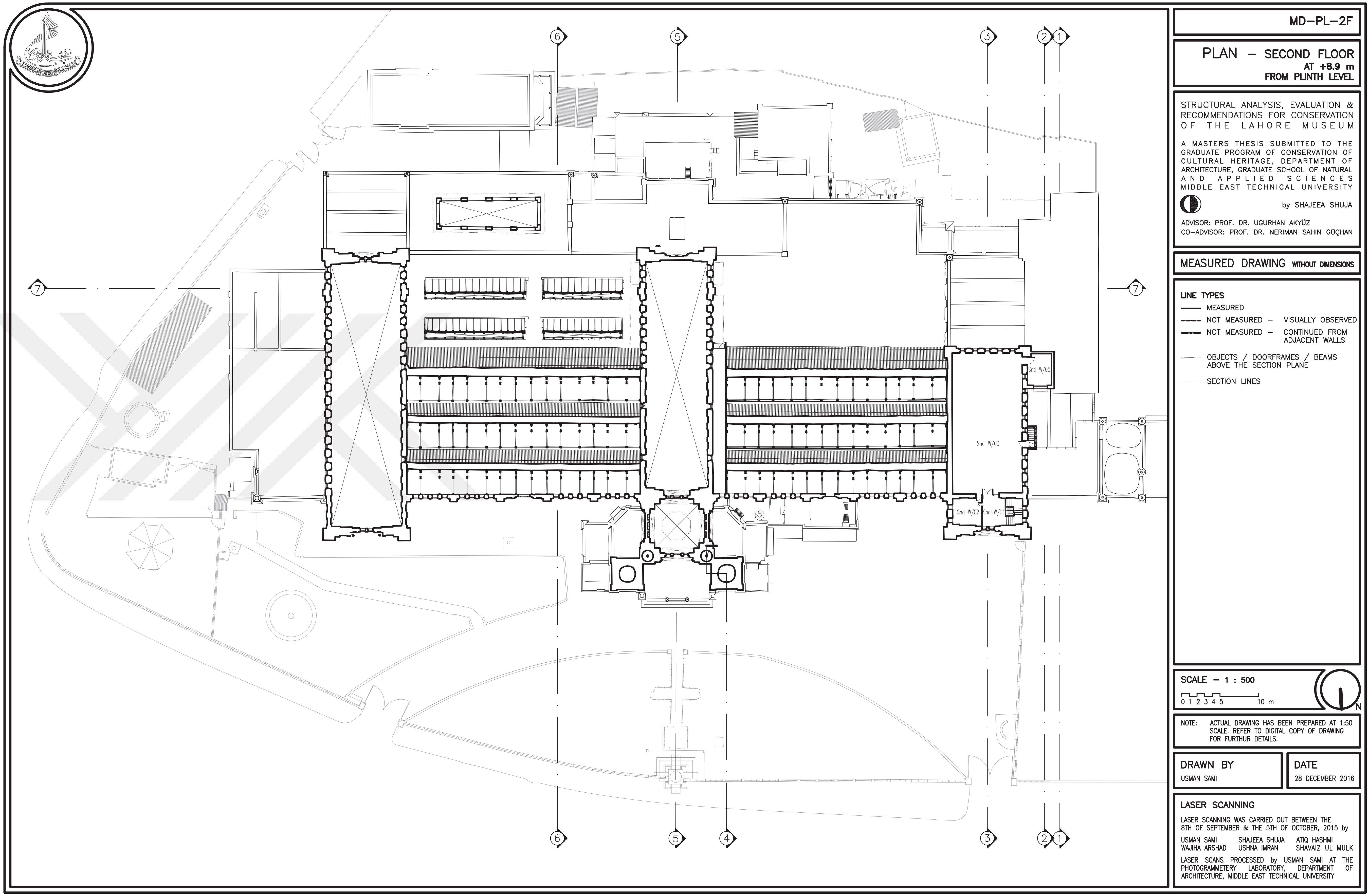

Figure B.126: MD-PL-2F – Measured Drawing – Plan – Second Floor (2016)

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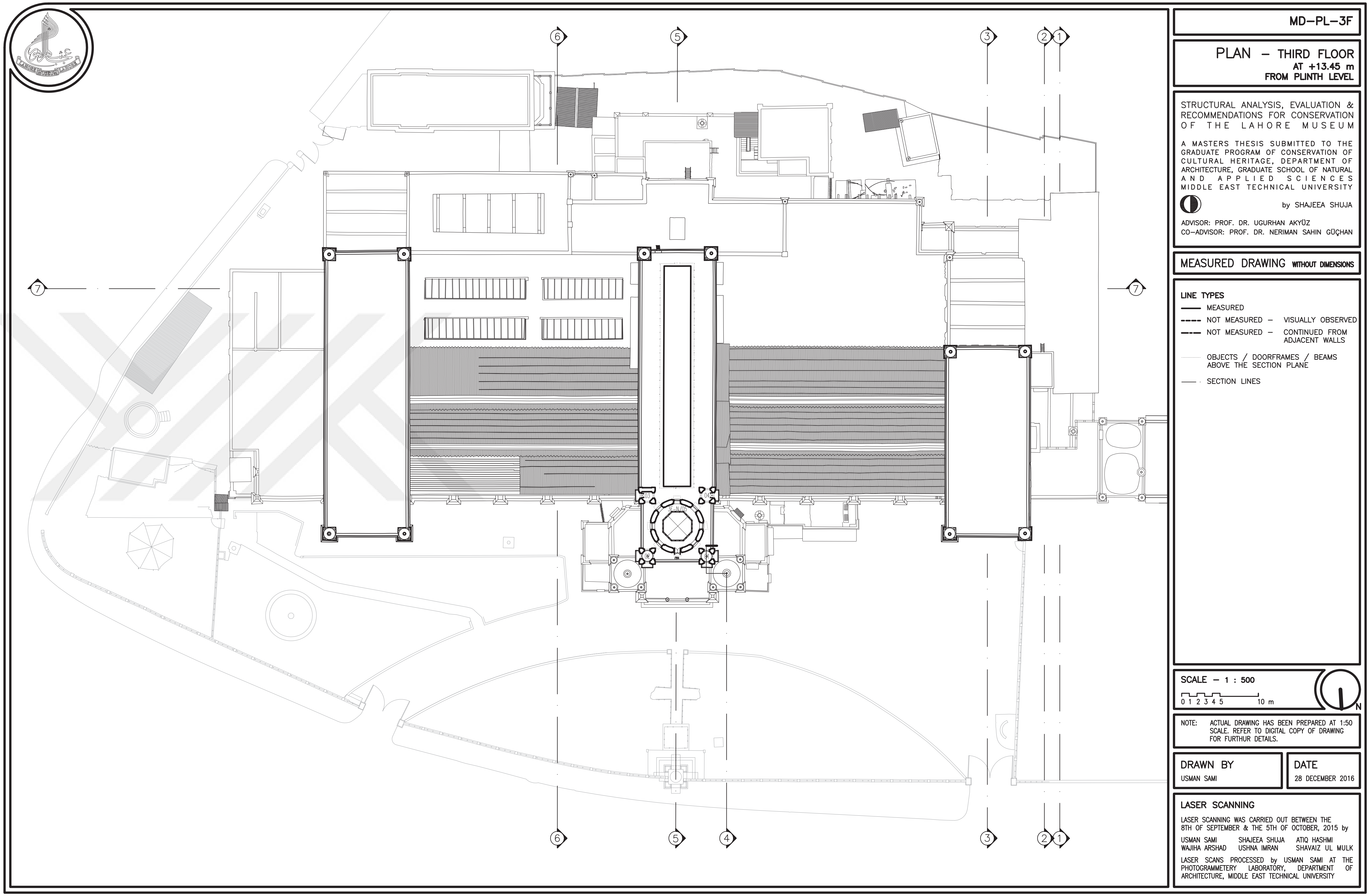

Figure B.127: MD-PL-3F – Measured Drawing – Plan – Third Floor (2016)

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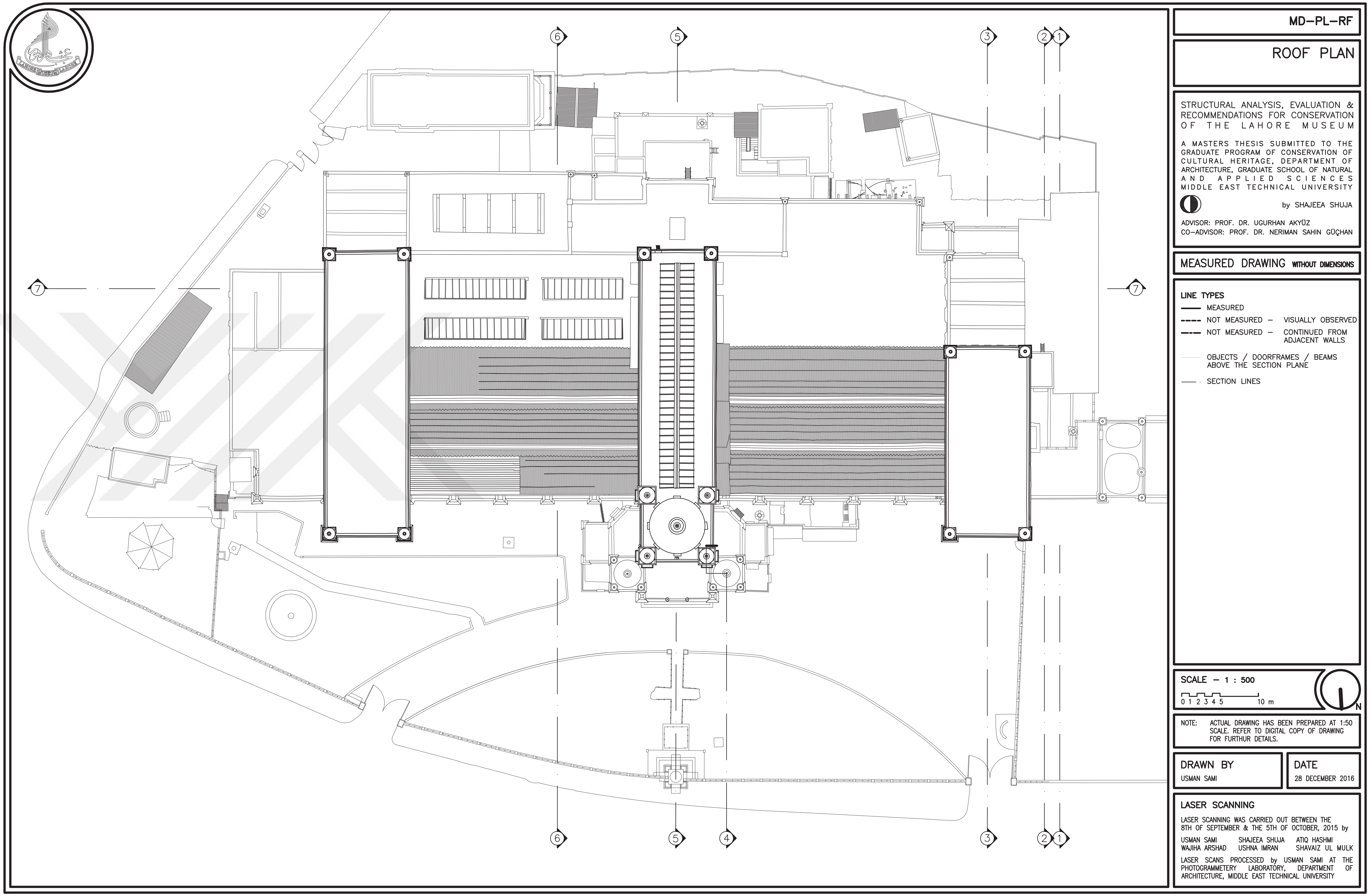

Figure B.128: MD-PL-RF – Measured Drawing – Roof Plan (2016)

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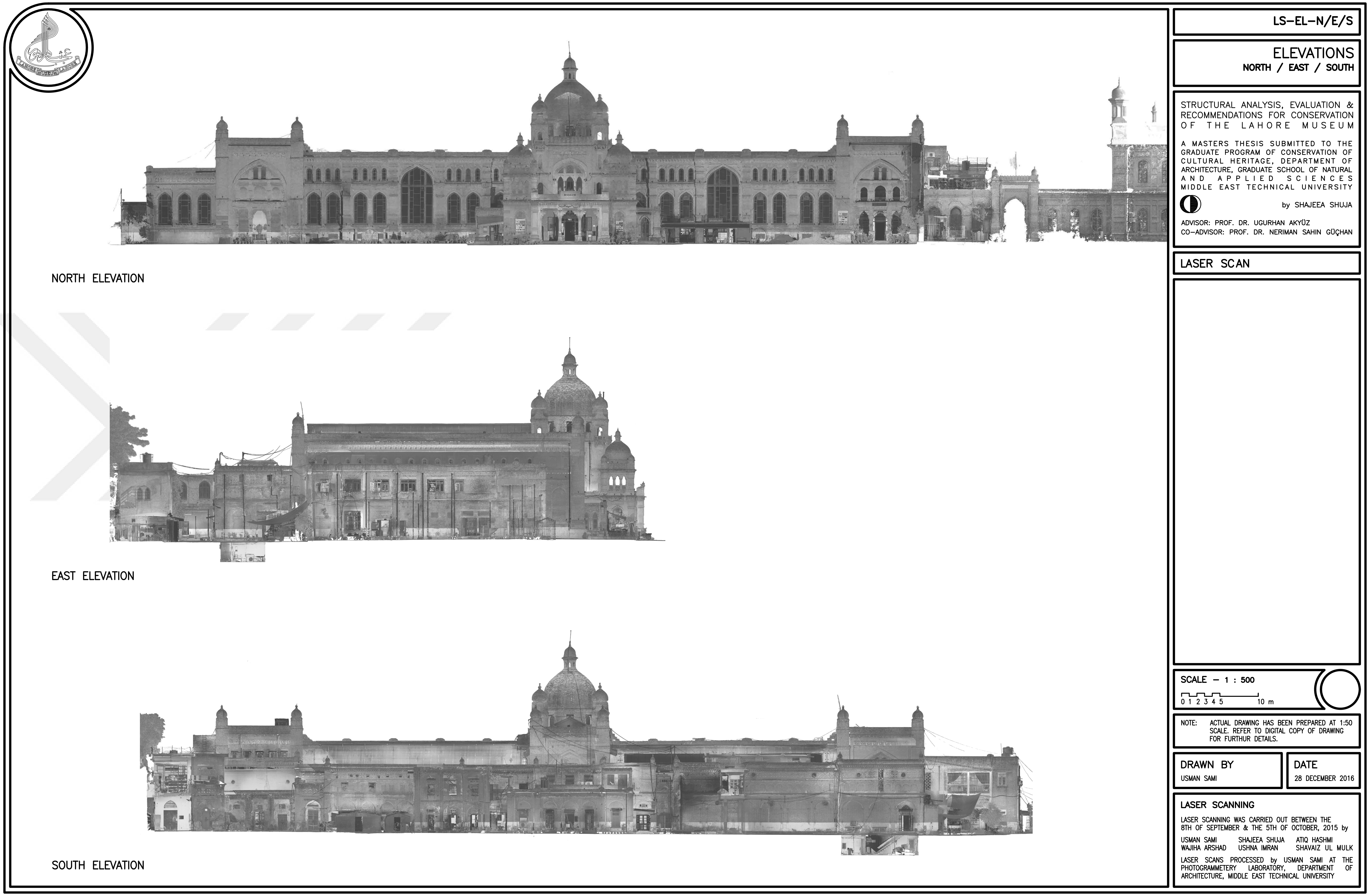

Figure B.129: LS-EL-N/E/S – Laser Scan – Elevation –North / East / South (2016)

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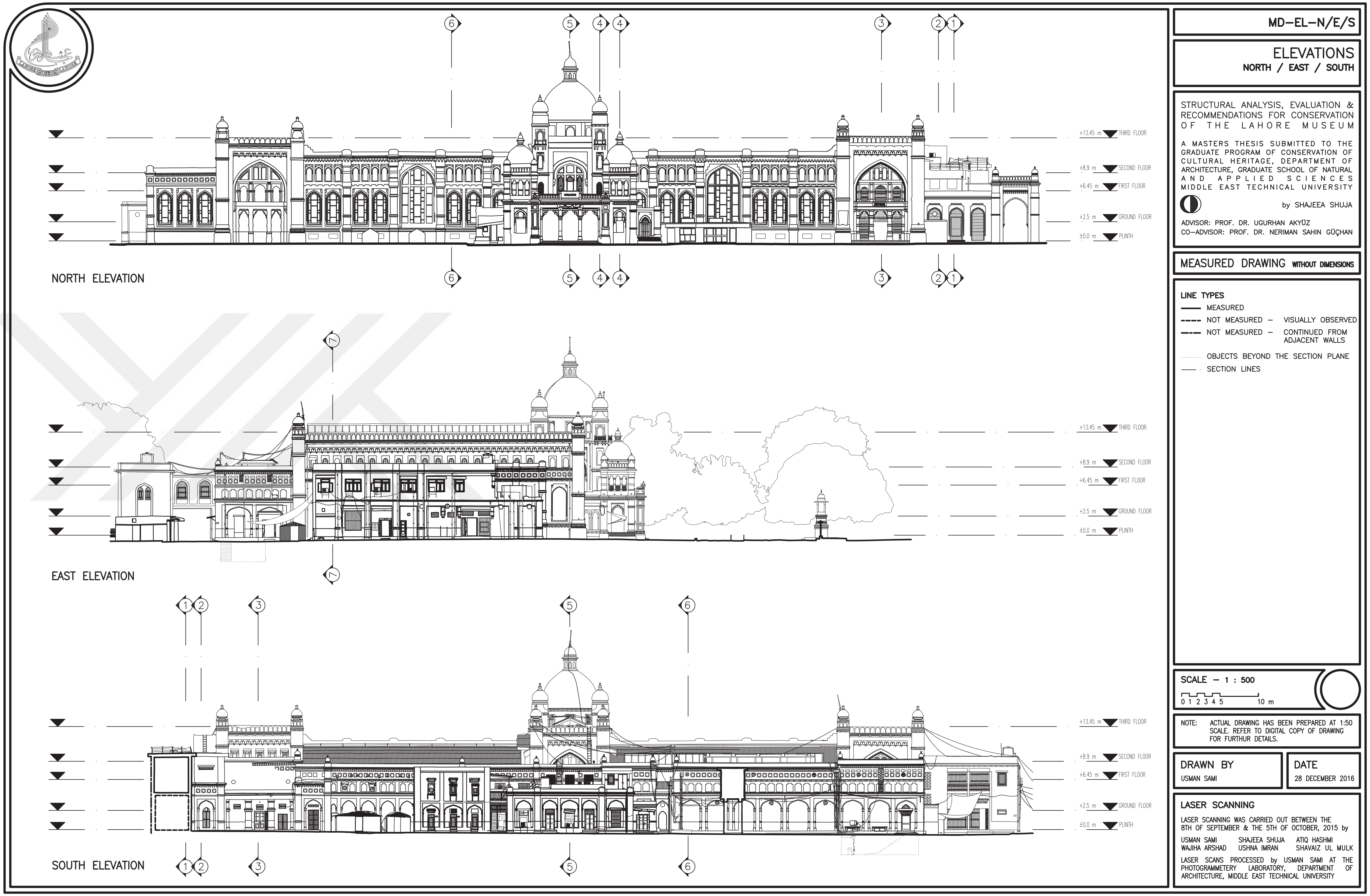

Figure B.130: MD-EL-N/E/S – Measured Drawing – Elevation – North / East / South (2016)

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Figure B.131: LS-SE-1/2/3 – Laser Scan – Sections – 1 / 2 / 3 (2016)

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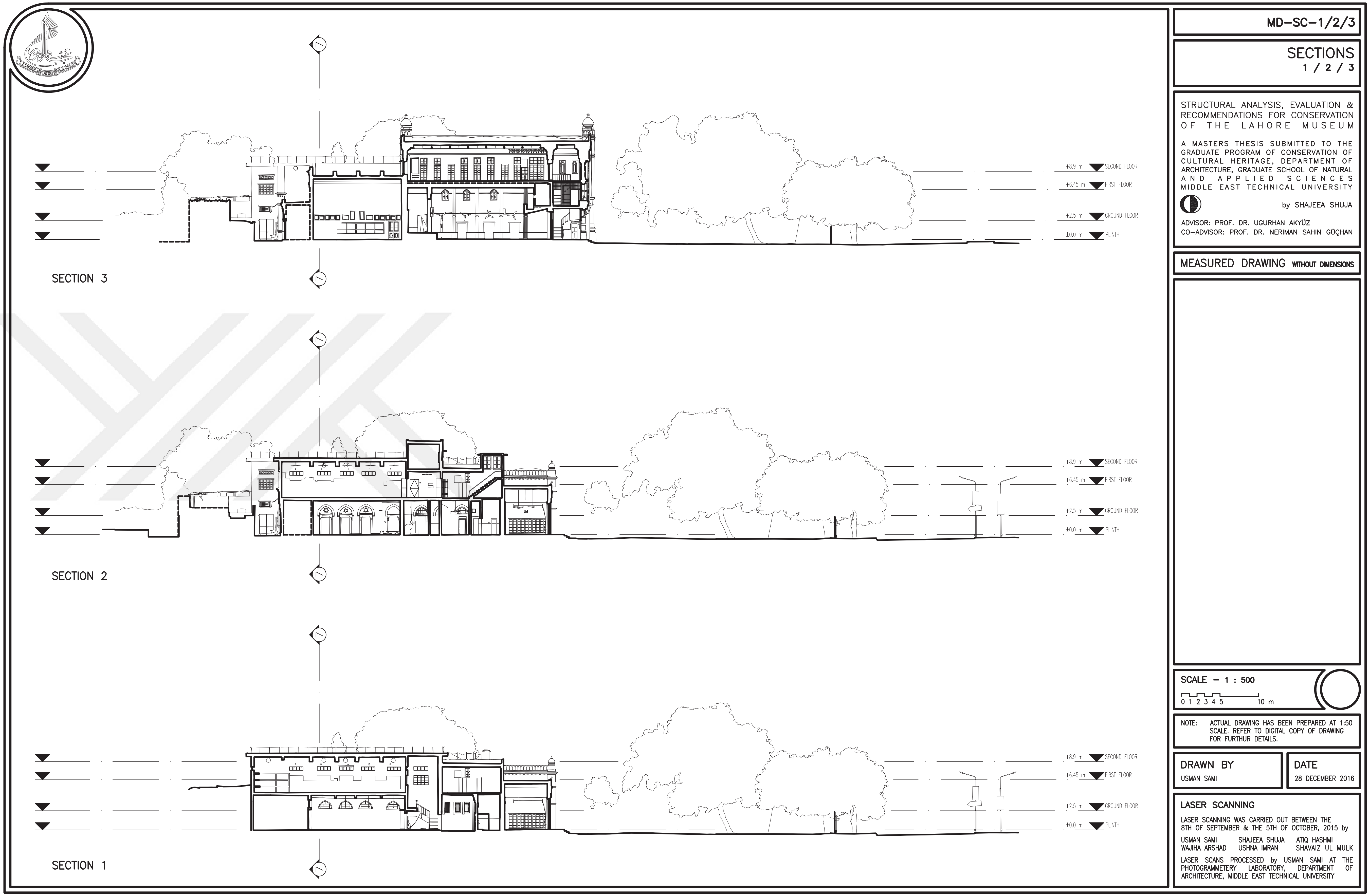

Figure B.132: MD-SE-1/2/3 – Measured Drawing – Sections – 1 / 2 / 3 (2016)

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Figure B.133: LS-SE-5/6/7 – Laser Scan – Sections – 5 / 6 / 7 (2016)

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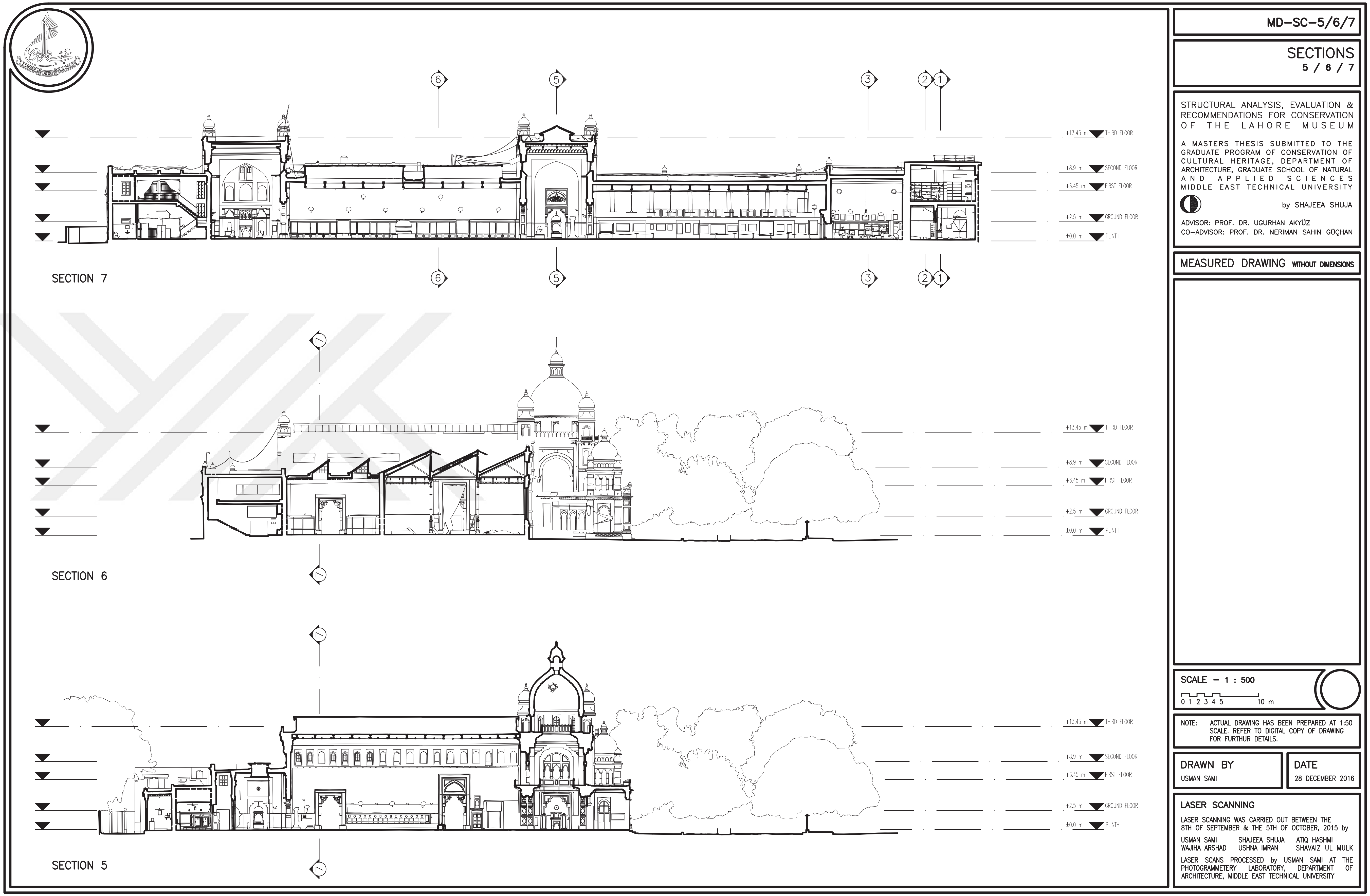

Figure B.134: MD-SE-5/6/7 – Measured Drawing – Sections – 5 / 6 / 7 (2016)

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C. PUNJAB SPECIAL PREMISES (PRESERVATION) ORDINANCE, 1985

Pb. Ord. XXXIV of 1985

An Ordinance to provide for the preservation of certain premises in the Punjab

[27 February 1985]

Preamble. – Whereas it is expedient to preserve certain premises of historical, cultural and architectural value in the Punjab and to control and regulate alterations therein and demolition and re-erection thereof and for matters ancillary thereto;

NOW, THEREFORE, in pursuance of the Proclamation of the fifth day of July, 1977, read with the Laws (Continuance in force) Order, 1977 (C.M.L.A. Order No. 1 of 1977), and the Provisional Constitution Order, 1981 (C.M.L.A. Order No. 1 of 1981), the Governor of the Punjab is pleased to make and promulgate the following Ordinance:–

1. **Short title and commencement**. –
   (1) This Ordinance may be called the Punjab Special Premises (Preservation) Ordinance, 1985;
   (2) It shall extended to the whole of the Punjab;
   (3) It shall come into force at once.

2. **Definition**. –

   In this Ordinance unless the subject or context otherwise requires –

   (a) "Special Premises" means any premises of historical, cultural or architectural value declared as such by the Government by notification and includes the land externally appurtenant thereto and the outer walls thereof;
   (b) "Committee" means a Committee constituted under section 3 (1) of this Ordinance.

3. **Constitution of Committees. –**
   (1) The Government may by notification appoint one or more Committees for the purposes of this Ordinance which shall perform such functions as the Government may determine.
   (2) The Government or a Committee may appoint a Committee of Experts to advise the Government or a Committee with regard to matters relating to this Ordinance.

4. **Ordinance to override other laws. –**

The provisions of this Ordinance shall have effect notwithstanding anything to the contrary contained in any other law for the time being in force.

5. **Prohibition of destruction etc. of Special Premises. –**

No alteration in or renovation, demolition or re-erection of such portion of a Special Premises as is visible from outside, or any part of such portion, shall be effected without the prior permission in writing of the Government or a Committee.

6. **Restriction on sanctioning of plan. –**

No authority or local body shall approve any plan in relation to a Special Premises without the prior permission of the Government or a Committee and any such plan sanctioned before the coming into force of this Ordinance shall be of no effect unless approved by the Government or a Committee.

7. **Prohibition of destruction etc. of Special Premises. –**

No person shall, except for carrying out the purposes of this Ordinance destroy, break, damage, injure, deface or mutilate or scribble, write or engrave any inscription or sign on such portion of a Special Building as is mentioned in section 5.

8. **Direction for restoration of original position. –**

(1) If such work as is mentioned in section 5 has been carried out in relation to a Special Premises before the coming into force of this Ordinance or in contravention of section 5, 7 or 8 the Government or a Committee may by order direct the owner thereof to restore it to its original position within such time as may be specified in the order.

(2) If the owner fails to comply with the order the Government or a Committee may take all necessary measures to give effect to it and the expenses incurred for the purpose shall be

9. **Direction to the owner to take measures for preservation of Special Premises. –**

(1) Where the Government or a Committee considers that any Special Premises is not being preserved or conserved properly by its owner, the Government or a Committee may, by order in writing, direct the owner to take such measures for its proper preservation and conservation, and within such time and on such terms and conditions as may be specified in the order.

(2) If the owner fails to take the measures specified in the order referred to in sub-section (1), the Government or a Committee may take all such measures in respect of the Special Premises and the expenses incurred for the purposes shall be recoverable from the owner as arrears of land revenue unless the Government directs otherwise.

10. **Compulsory acquisition of Special Premises. –**

If the Government apprehends that a Special Premises is in danger of being destroyed, injured or allowed to fall into decay, it may, acquire it or a part thereof under the Land Acquisition Act, 1894 (1 of 1894), as for a public purpose.

11. **Execution of development schemes and new constructions in proximity to Special Premises. –**

No development plan or scheme or new construction on, or within a distance of two hundred feet of a Special Premises shall be undertaken or executed except with the approval of the Government or a Committee.

12. **Prohibition of bill posting, neon signs, other kinds of advertisements, etc. –**

No person shall put any neon signs or other kinds of advertisement, including hoardings, bill postings, commercial signs, poles or pylons electricity or telephone cables and television aerials, on or near any Special Premises without the prior permission in writing of the Government or a Committee.

13. **Voluntary contributions. –**

The Government may receive voluntary contributions and donations for the acquisition, preservation or restoration of Special Premises and may make suitable arrangements for the management and application of the money so received:

Provided that a contribution or donation made for any specified purpose shall not be applied to any purpose other than that for which it has been made.

14. **Penalty. –**

(1) Whoever contravenes the provisions of this Ordinance or the rules shall be liable to imprisonment which may extend to one year or with fine or with both.

(2) The Court trying an offence under sub-section (1) may direct that the whole or any part of the fine recovered shall be applied for defraying the expenses of restoring the Special Premises to the condition in which it was before the commission of an offence relating thereto.

15. **Jurisdiction to try offences. –**

No court shall take cognizance of an offence punishable under this Ordinance except upon a complaint in writing made by an officer generally or specially empowered in this behalf by the Government and no Court inferior to that of a Magistrate of the first class shall try any such offence.

16. **Rules. –**

The Government may frame rules to carry out the purposes of this Ordinance

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D. SAP2000 RESULTS

1. **Stress Results of Masonry Walls for All Seismic Load Combinations**
2. **Stress Results for Walls with Critical Area Elements**

1. Stress Results of Masonry Walls for all Seismic Load Combinations

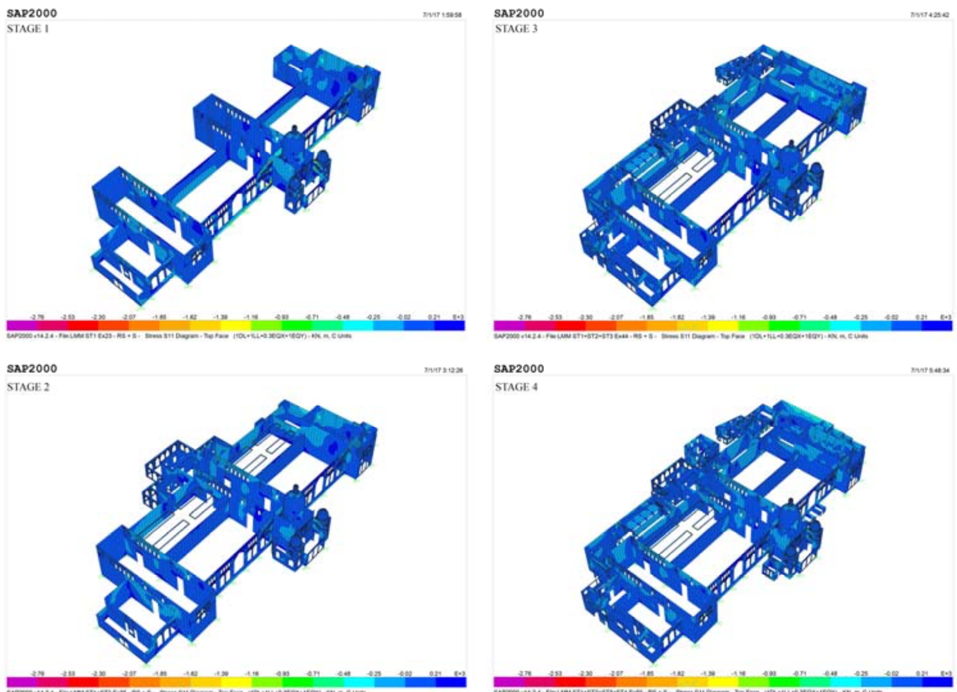

Figure D.1: Load Combo 1D+1L+0.3EQX+EQY In-plane Normal Stresses – Horizontal Dir.

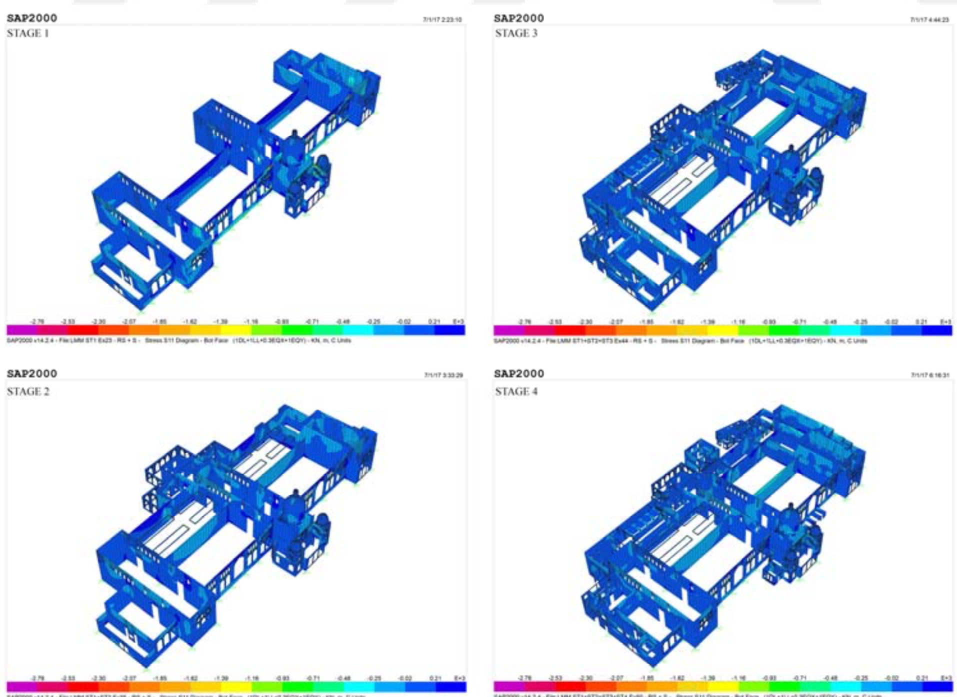

Figure D.2: Load Combo 1D+1L+0.3EQX+EQY In-plane Normal Stresses – Horizontal Direction (Bottom Face)

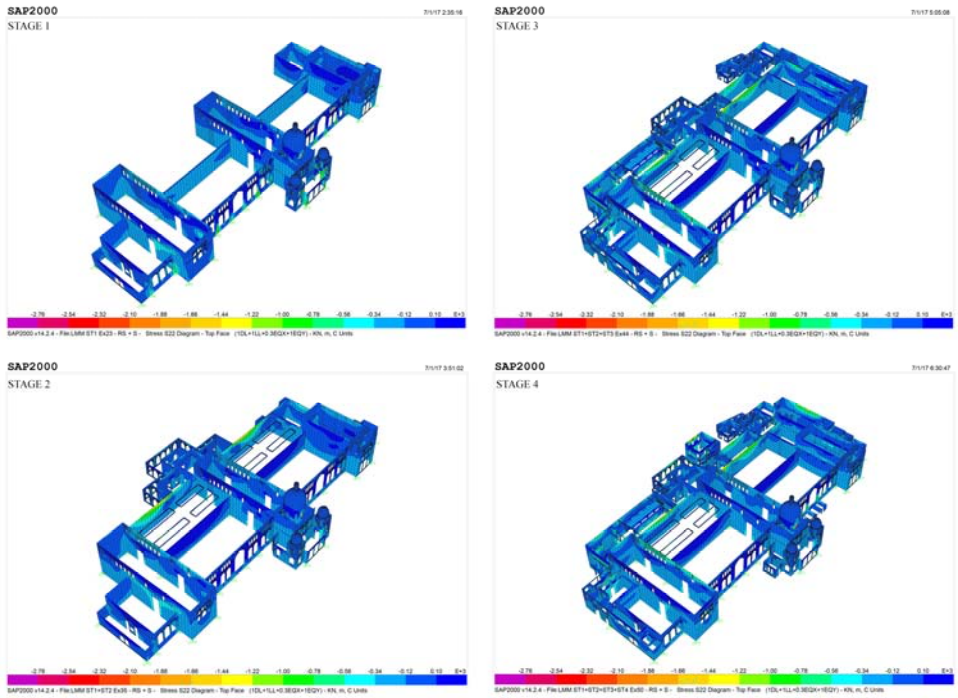

Figure D.3: Load Combo 1D+1L+0.3EQX+EQY In-plane Normal Stresses – Vertical Direction (Top Face)

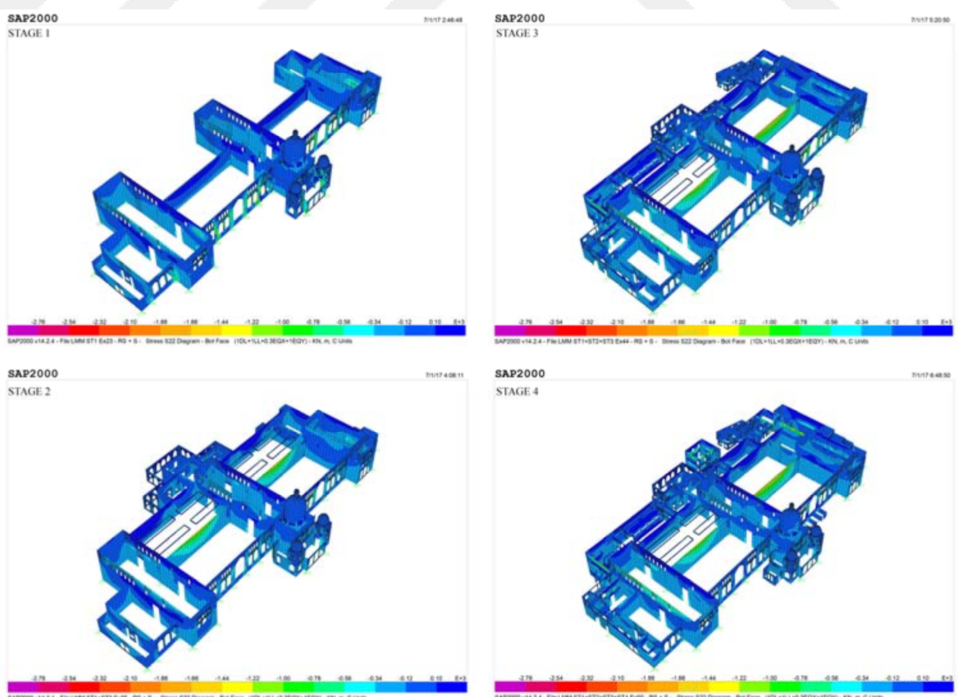

Figure D.4: Load Combo 1D+1L+0.3EQX+EQY In-plane Normal Stresses – Vertical Direction (Bottom Face)

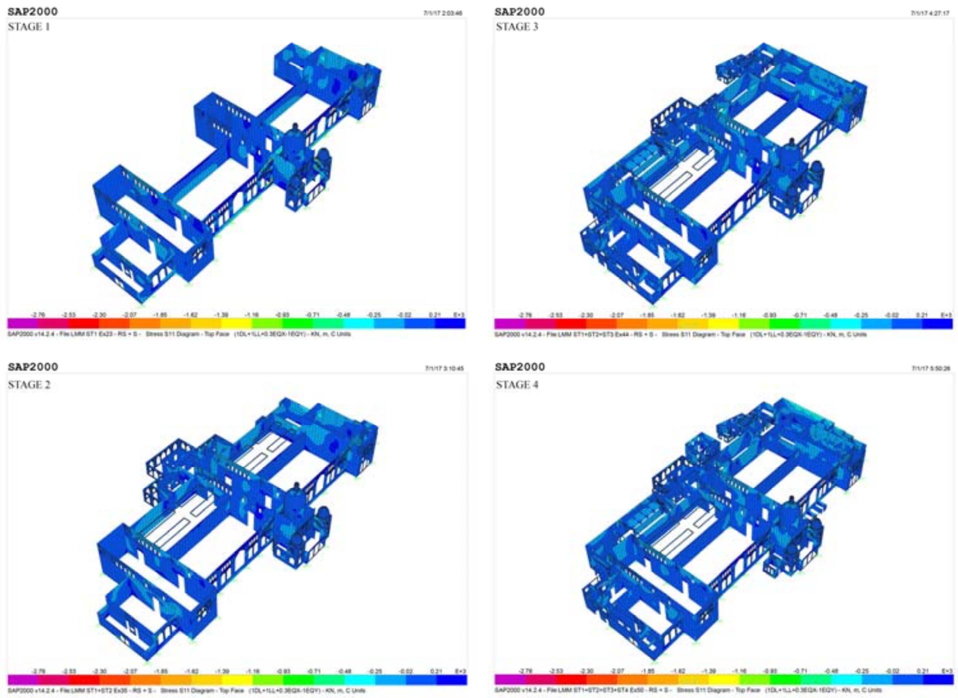

Figure D.5: Load Combo 1D+1L+0.3EQX-EQY In-plane Normal Stresses – Horizontal Direction (Top Face)

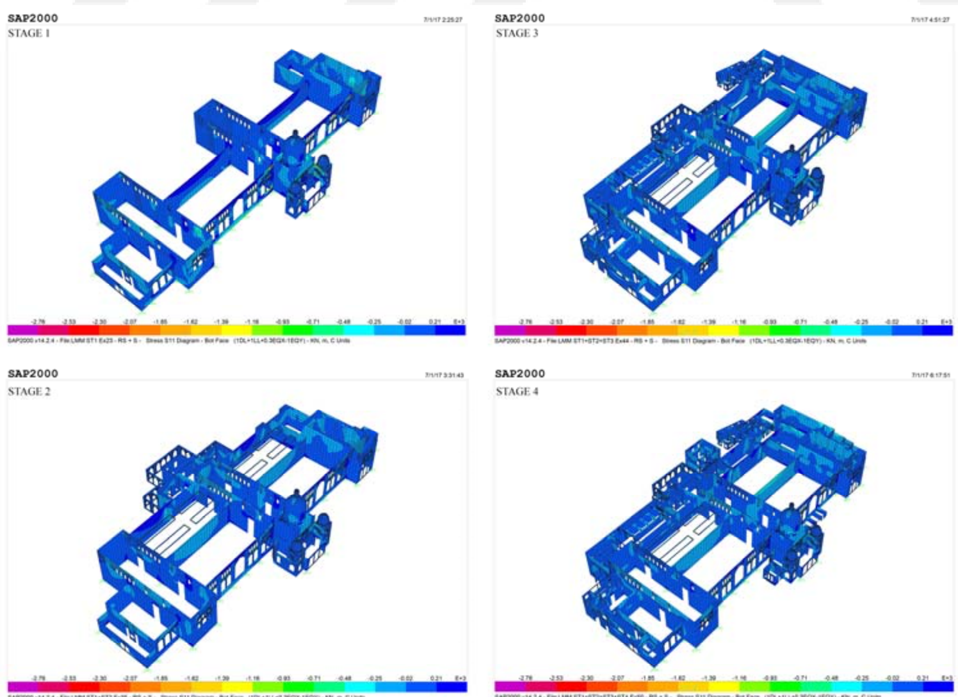

Figure D.6: Load Combo 1D+1L+0.3EQX-EQY In-plane Normal Stresses – Horizontal Direction (Bottom Face)

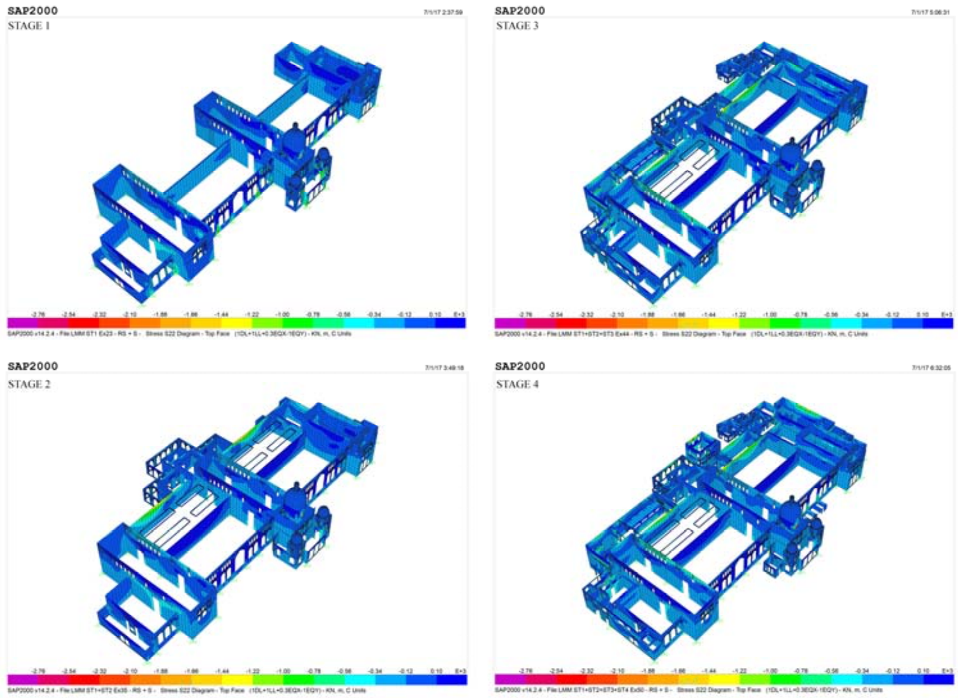

Figure D.7: Load Combo 1D+1L+0.3EQX-EQY In-plane Normal Stresses – Vertical Direction (Top Face)

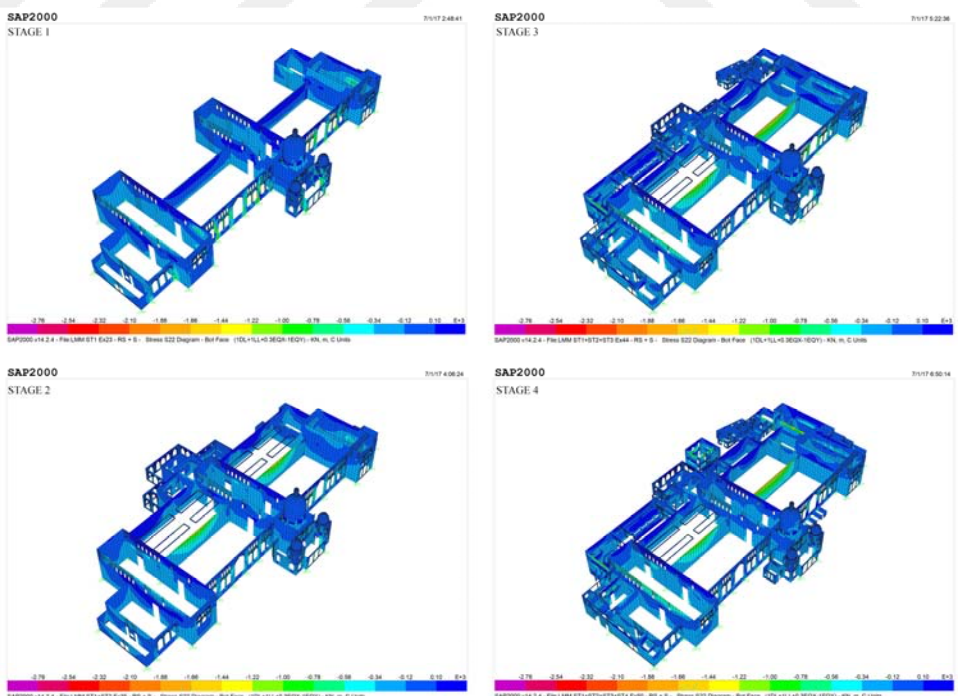

Figure D.8: Load Combo 1D+1L+0.3EQX-EQY In-plane Normal Stresses – Vertical Direction (Bottom Face)

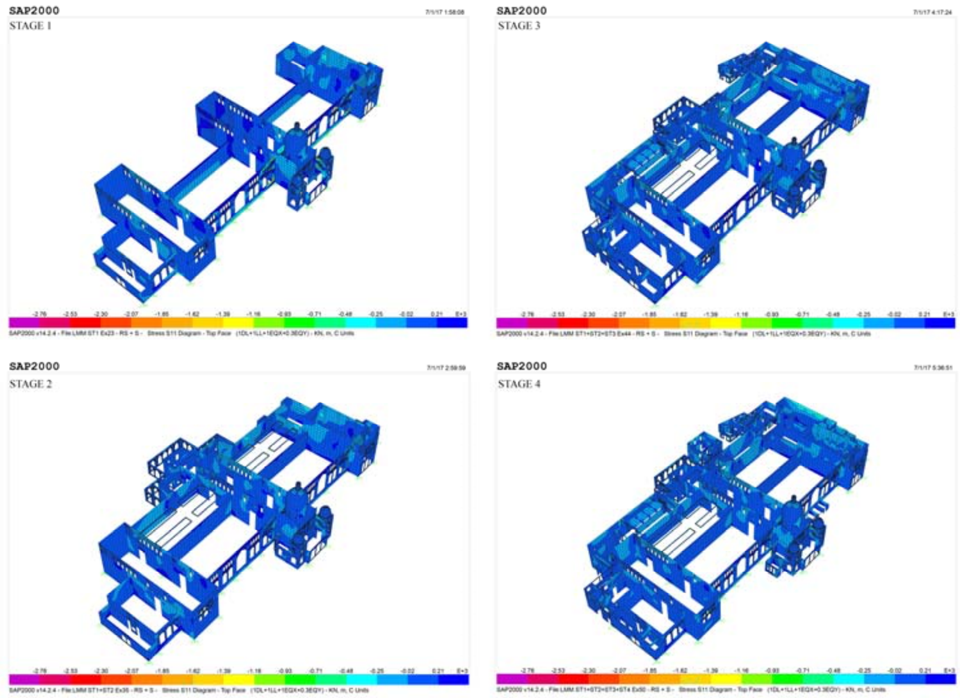

Figure D.9: Load Combo 1D+1L+EQX+0.3EQY In-plane Normal Stresses – Horizontal Direction (Top Face)

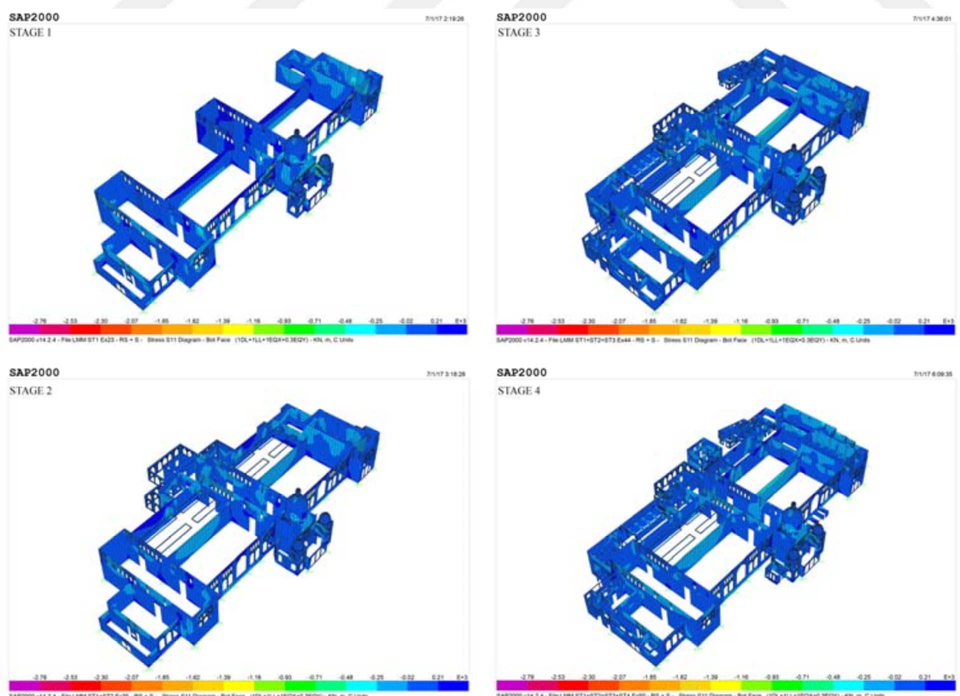

Figure D.10: Load Combo 1D+1L+EQX+0.3EQY In-plane Normal Stresses – Horizontal Direction (Bottom Face)

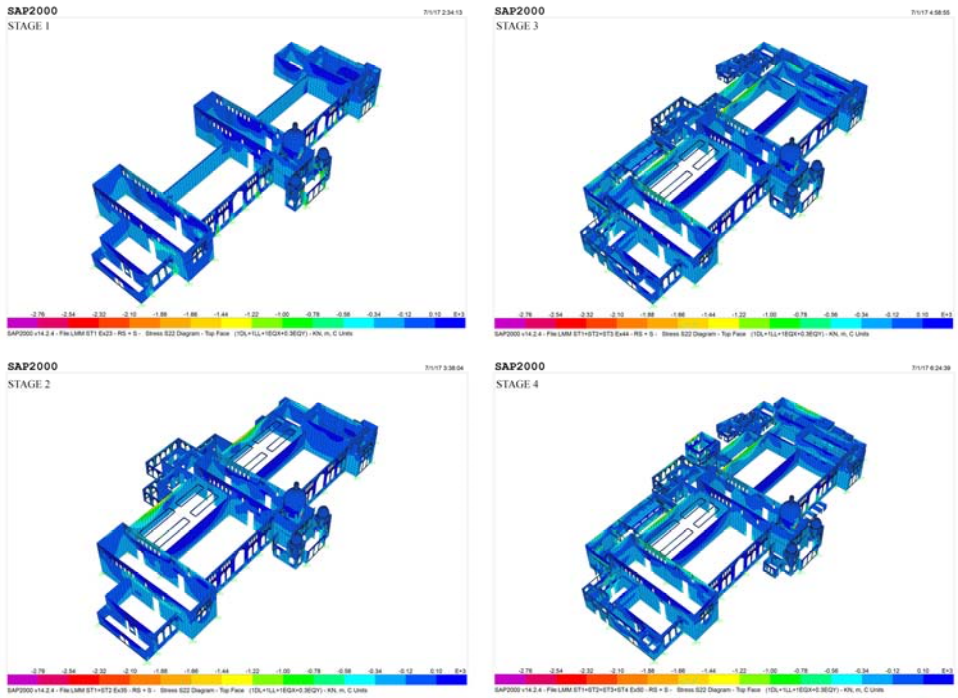

Figure D.11: Load Combo 1D+1L+EQX+0.3EQY   In-plane Normal Stresses – Vertical Direction (Top Face)

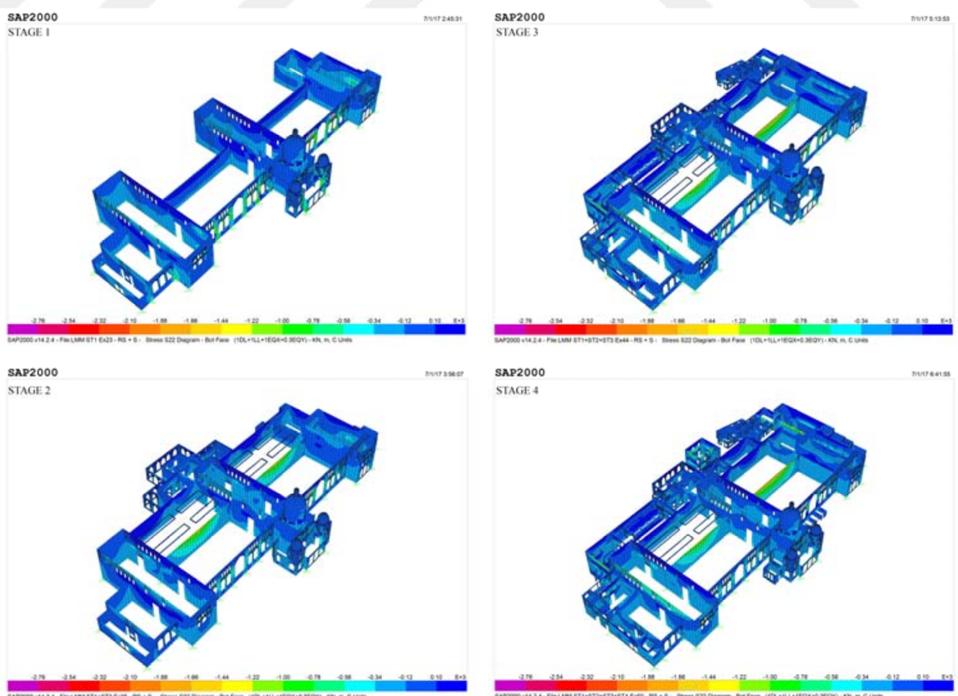

Figure D.12: Load Combo 1D+1L+EQX+0.3EQY In-plane Normal Stresses – Vertical Direction (Bottom Face)

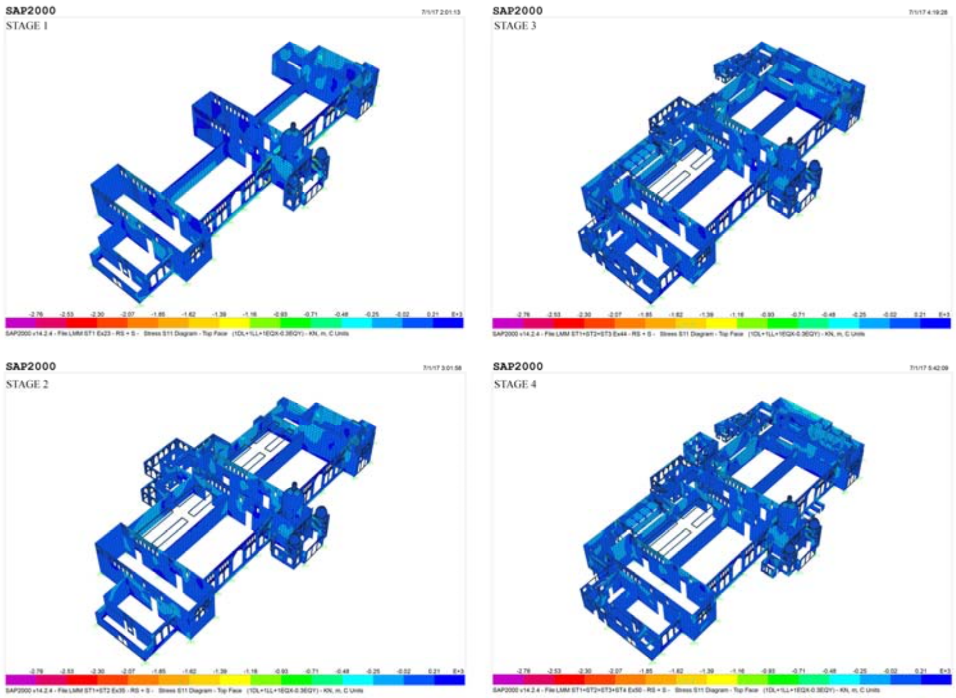

Figure D.13: Load Combo 1D+1L+EQX-0.3EQY In-plane Normal Stresses – Horizontal Direction (Top Face)

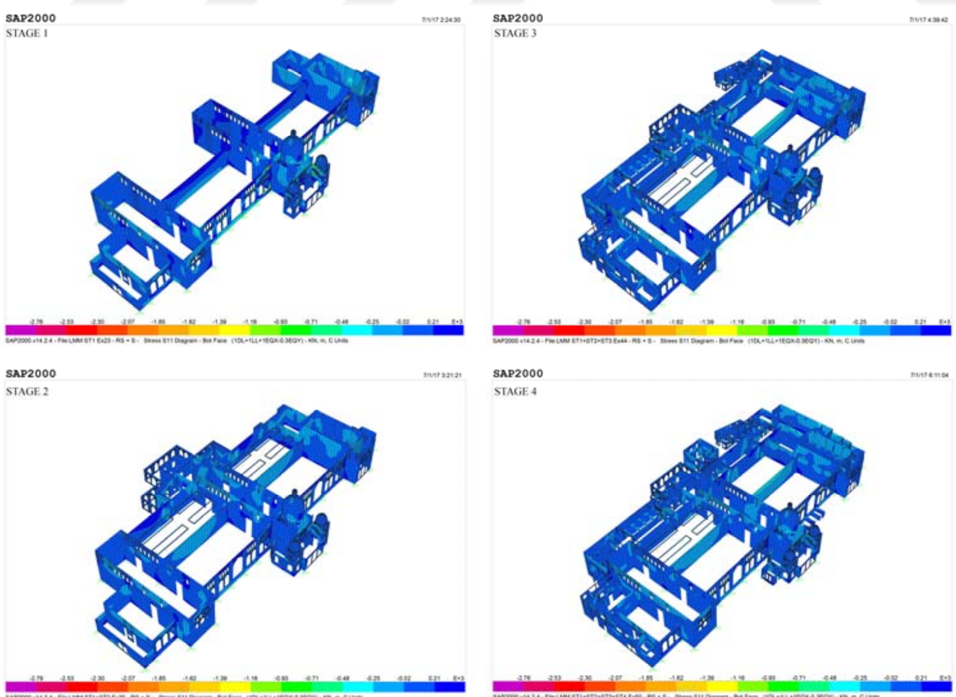

Figure D.14: Load Combo 1D+1L+EQX-0.3EQY In-plane Normal Stresses – Horizontal Direction (Bottom Face)

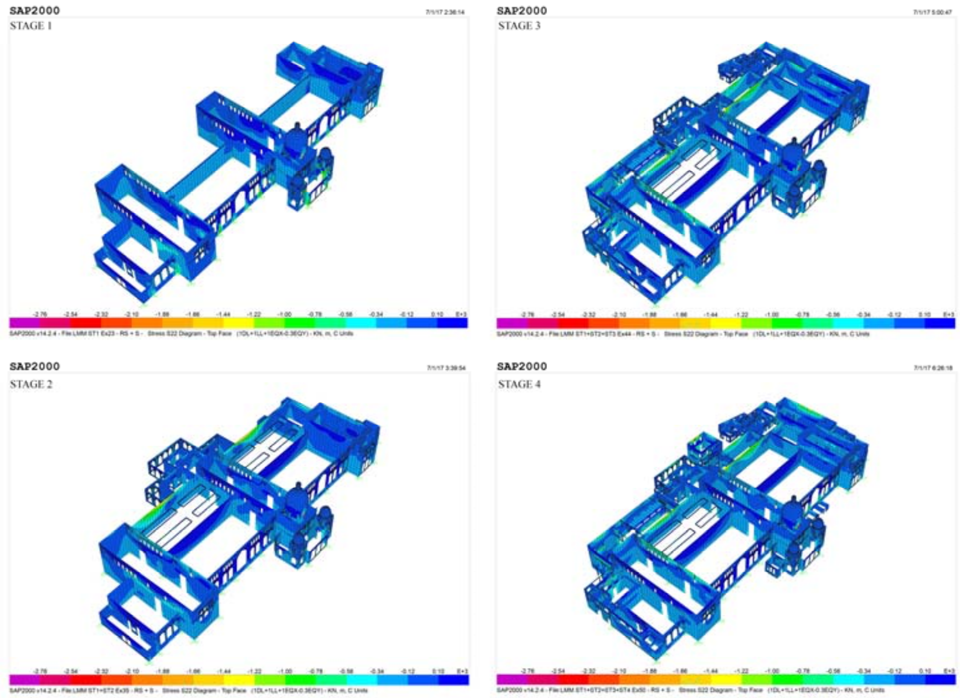

Figure D.15: Load Combo 1D+1L+EQX-0.3EQY In-plane Normal Stresses – Vertical Direction (Top Face)

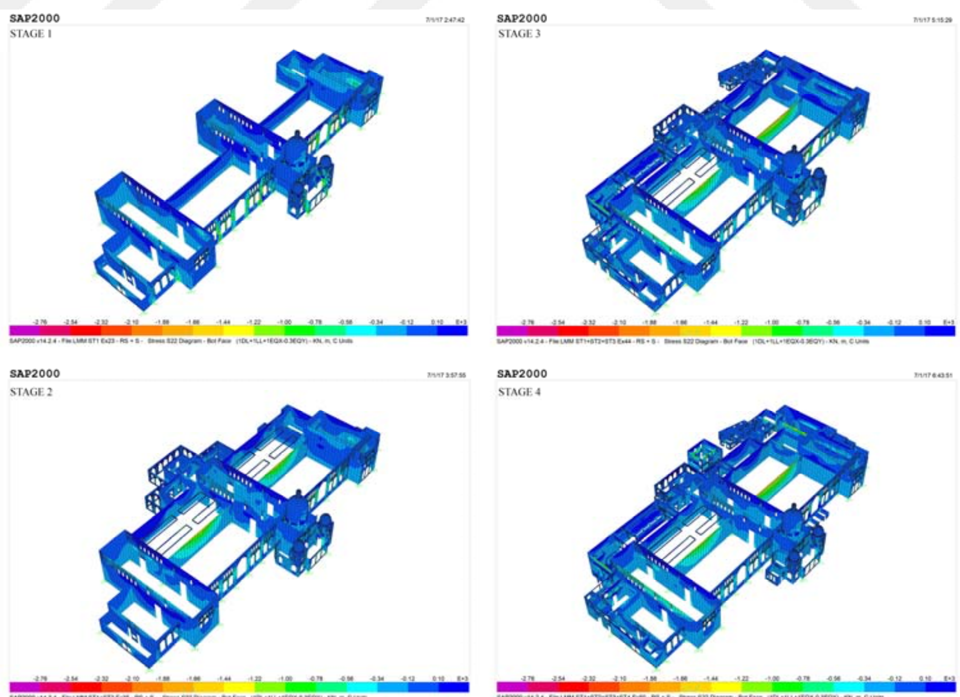

Figure D.16: Load Combo 1D+1L+EQX-0.3EQY In-plane Normal Stresses – Vertical Direction (Bottom Face)

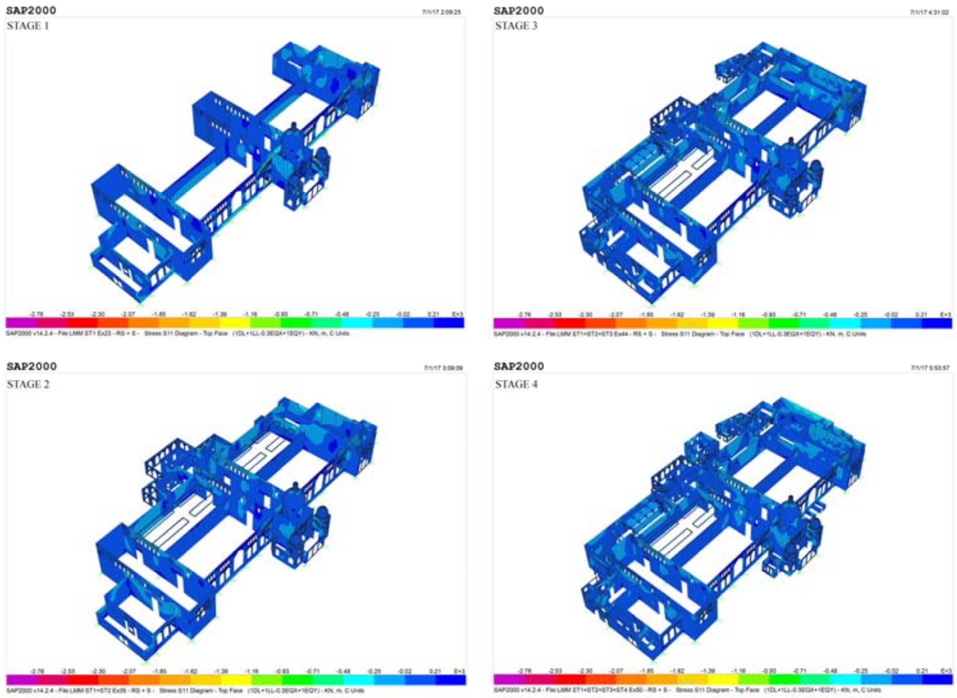

Figure D.17: Load Combo 1D+1L-0.3EQX+EQY In-plane Normal Stresses – Horizontal Direction (Top Face)

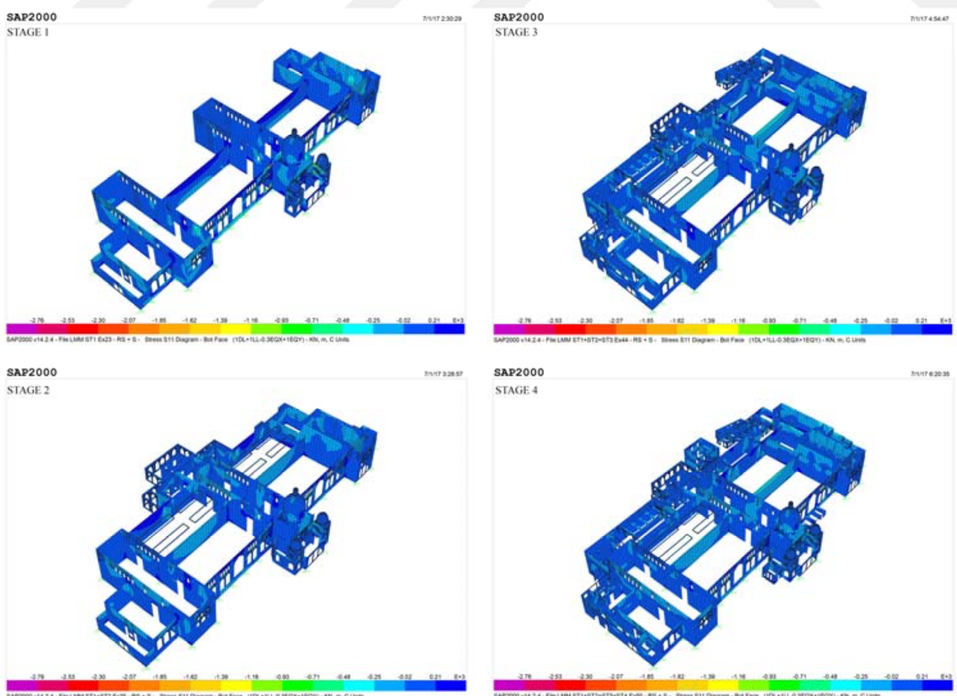

Figure D.18: Load Combo 1D+1L-0.3EQX+EQY In-plane Normal Stresses – Horizontal Direction (Bottom Face)

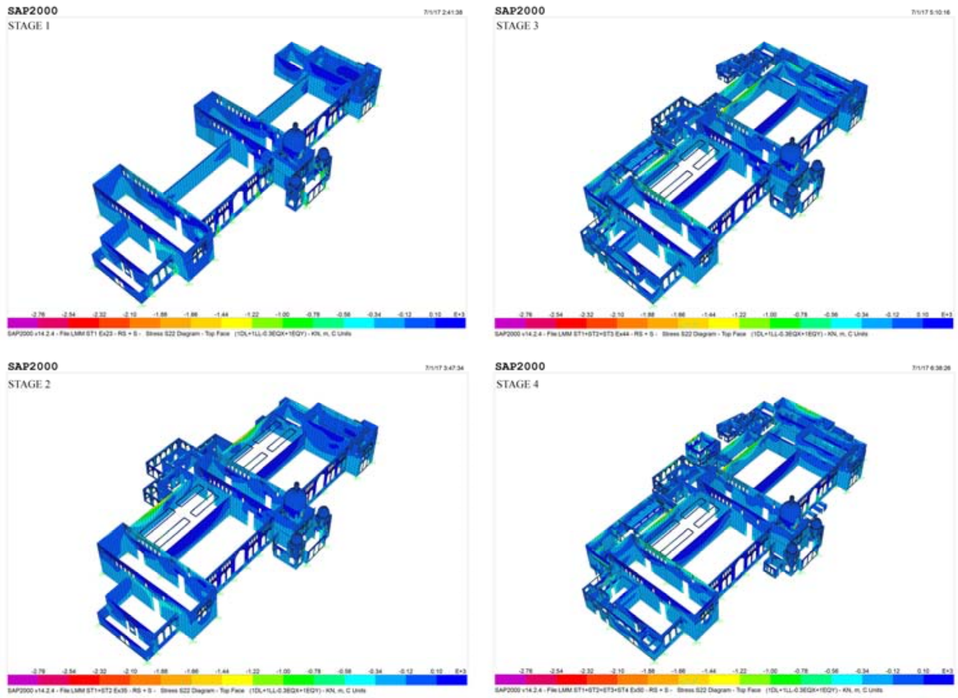

Figure D.19: Load Combo 1D+1L-0.3EQX+EQY   In-plane Normal Stresses – Vertical Direction (Top Face)

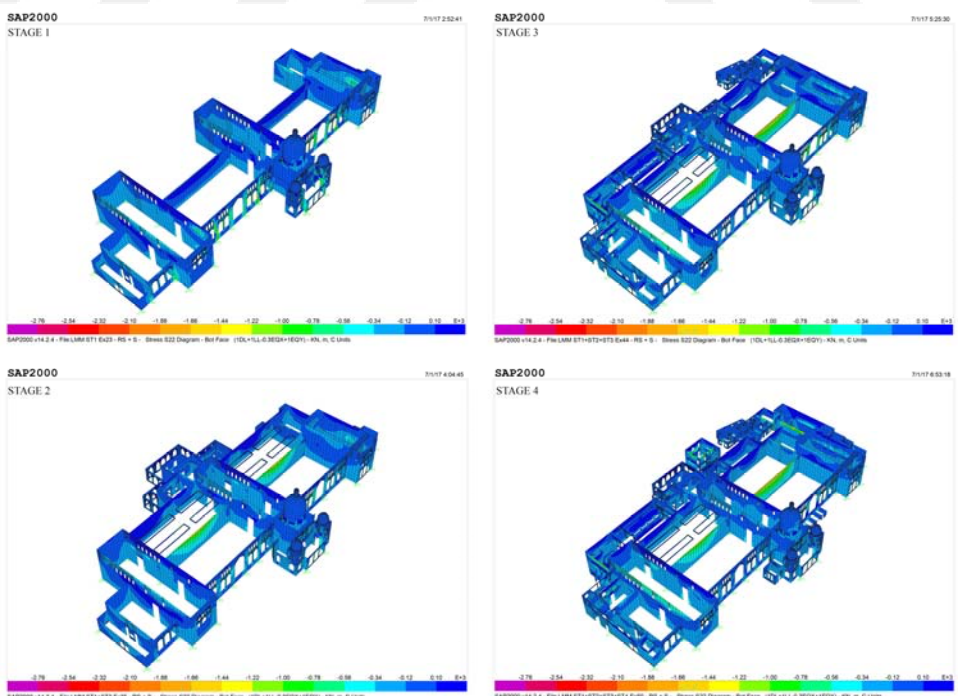

Figure D.20: Load Combo 1D+1L-0.3EQX+EQY In-plane Normal Stresses – Vertical Direction (Bottom Face)

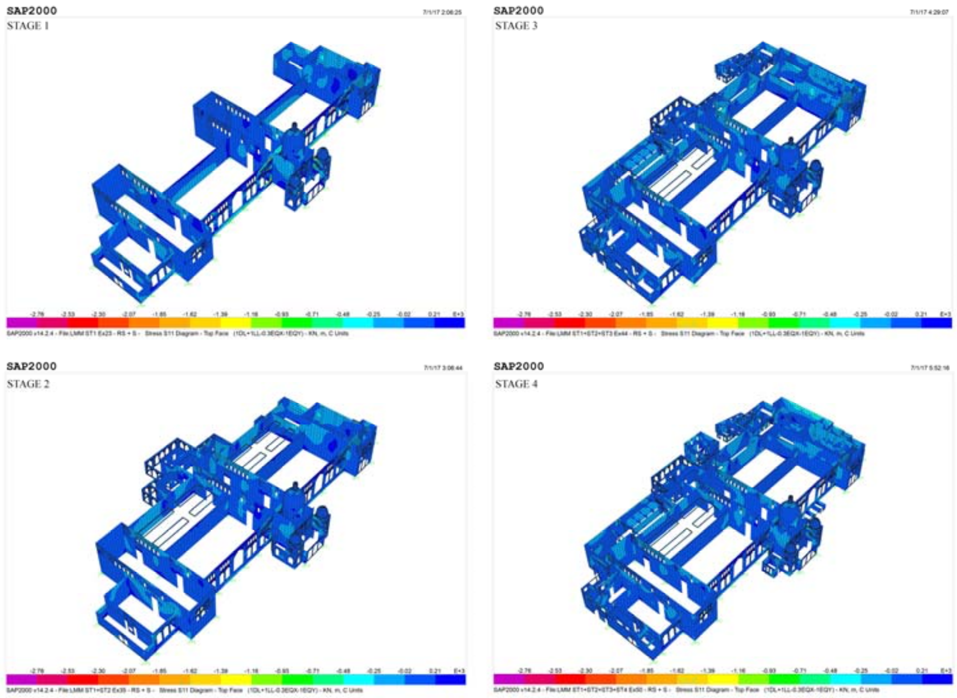

Figure D.21: Load Combo 1D+1L-0.3EQX-EQY In-plane Normal Stresses – Horizontal Direction (Top Face)

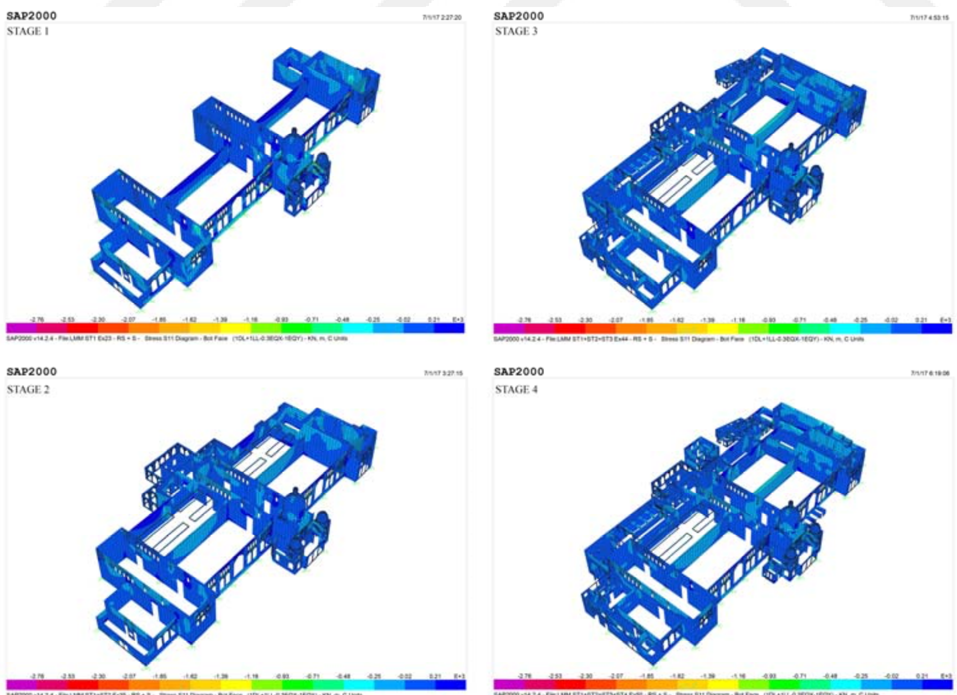

Figure D.22: Load Combo 1D+1L-0.3EQX-EQY In-plane Normal Stresses – Horizontal Direction (Bottom Face)

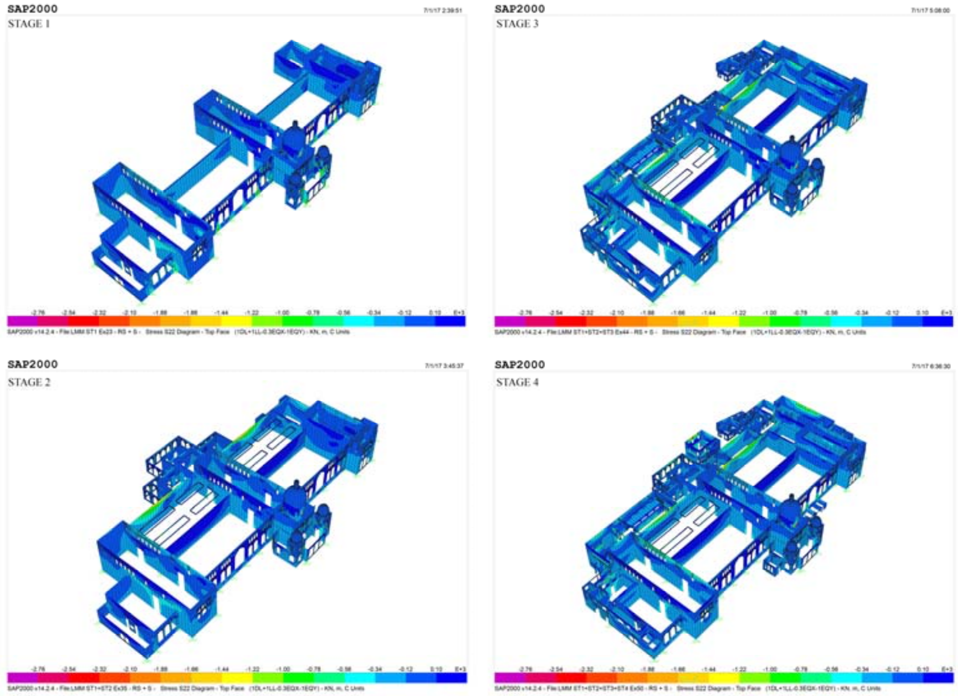

Figure D.23: Load Combo 1D+1L-0.3EQX-EQY In-plane Normal Stresses – Vertical Direction (Top Face)

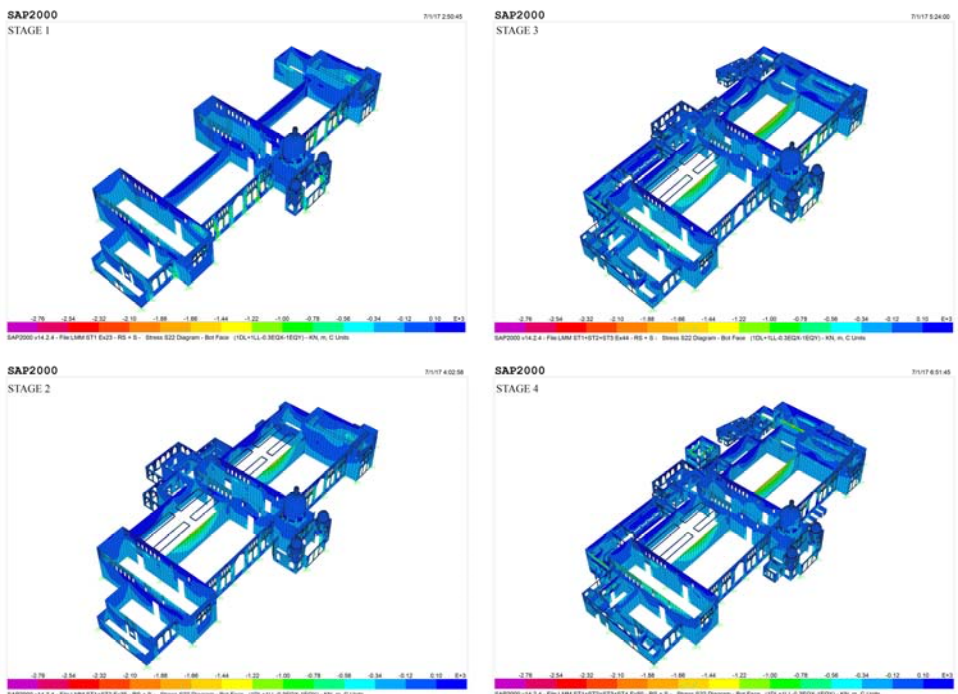

Figure D.24: Load Combination 1D+1L-0.3EQX-EQY In-plane Normal Stresses – Vertical Direction (Bottom Face)

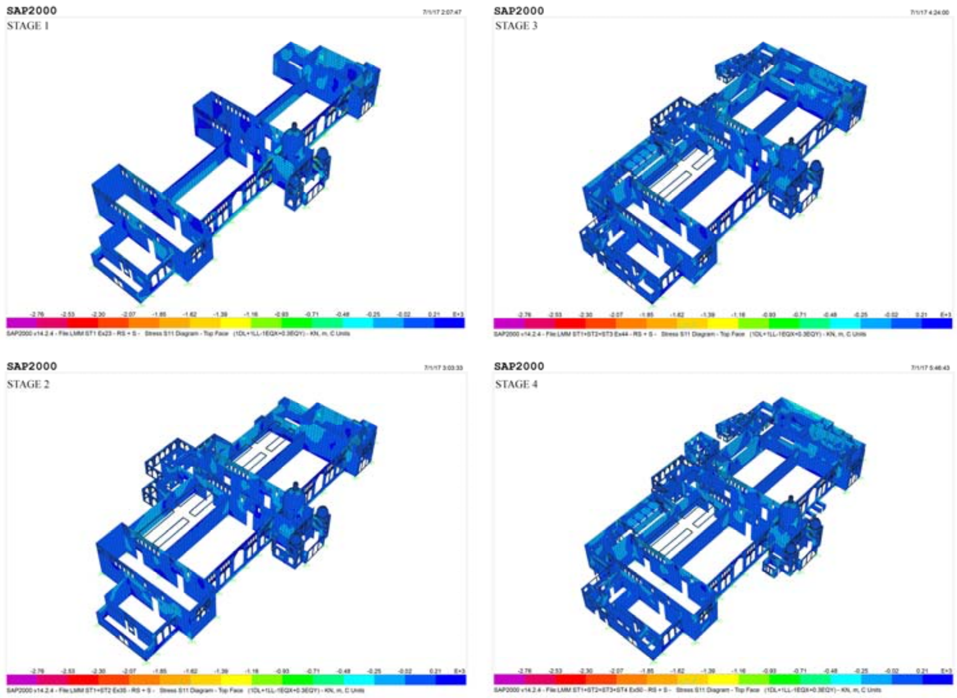

Figure D.25: Load Combo 1D+1L-EQX+0.3EQY In-plane Normal Stresses – Horizontal Direction (Top Face)

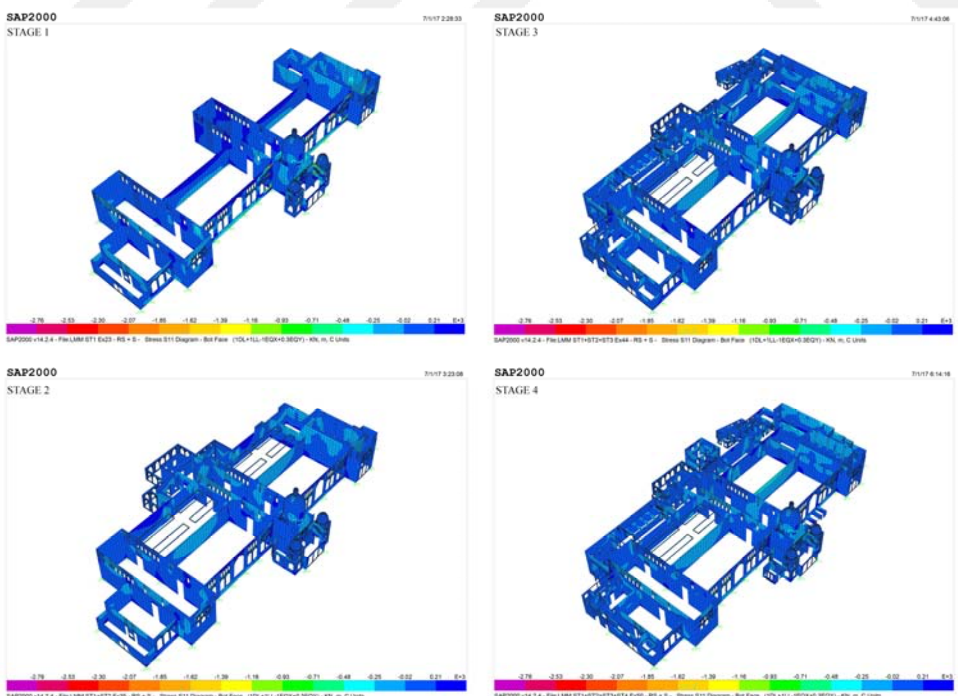

Figure D.26: Load Combo 1D+1L-EQX+0.3EQY In-plane Normal Stresses – Horizontal Direction (Bottom Face)

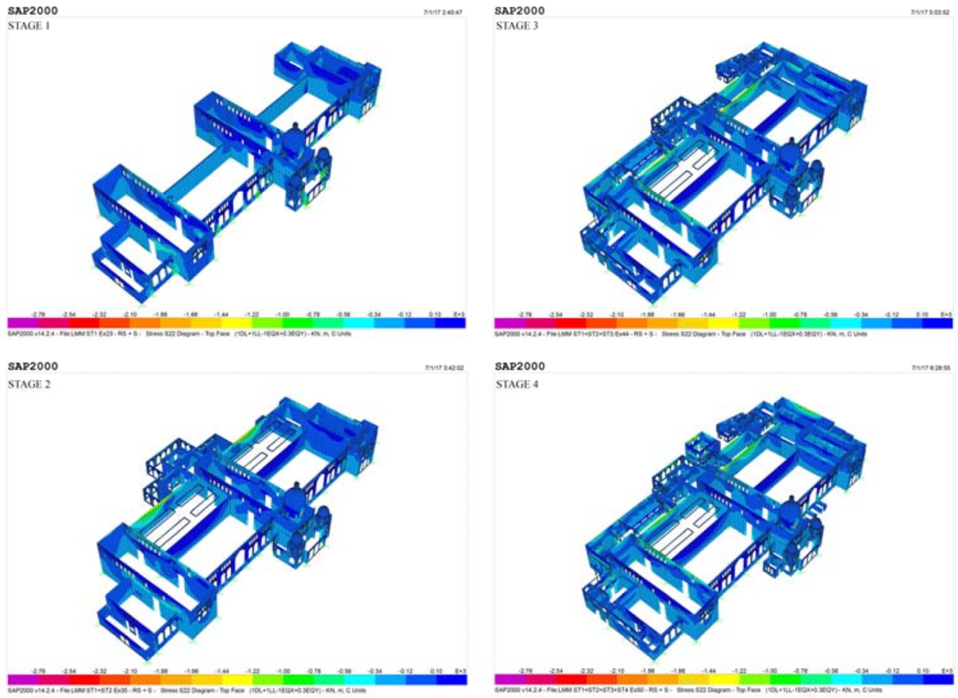

Figure D.27: Load Combo 1D+1L-EQX+0.3EQY In-plane Normal Stresses – Vertical Direction (Top Face)

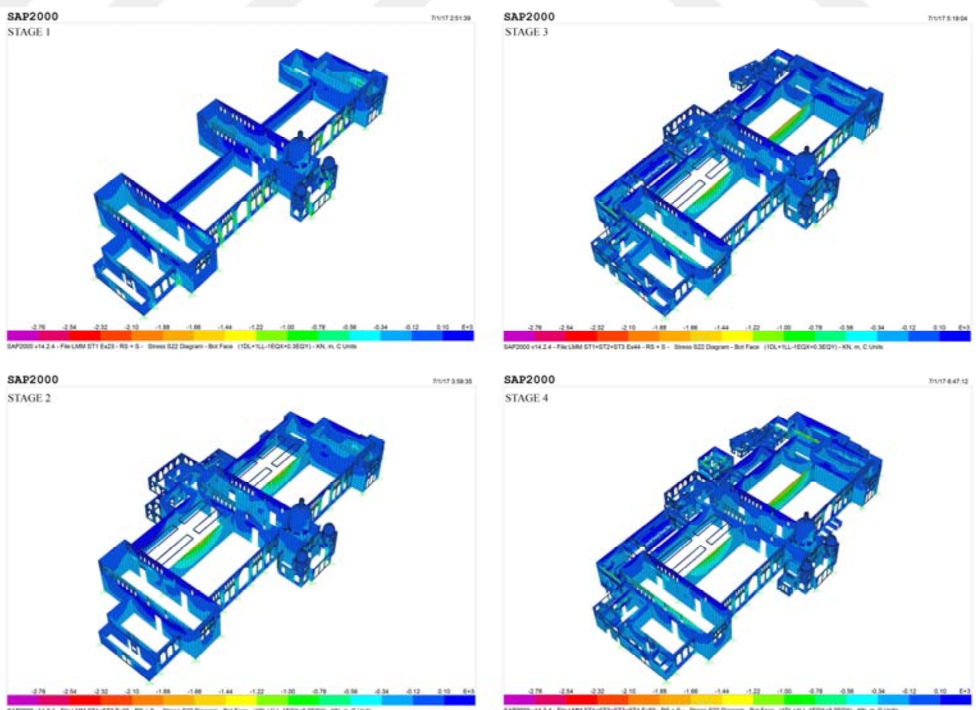

Figure D.28: Load Combo 1D+1L-EQX+0.3EQY In-plane Normal Stresses – Vertical Direction (Bottom Face)

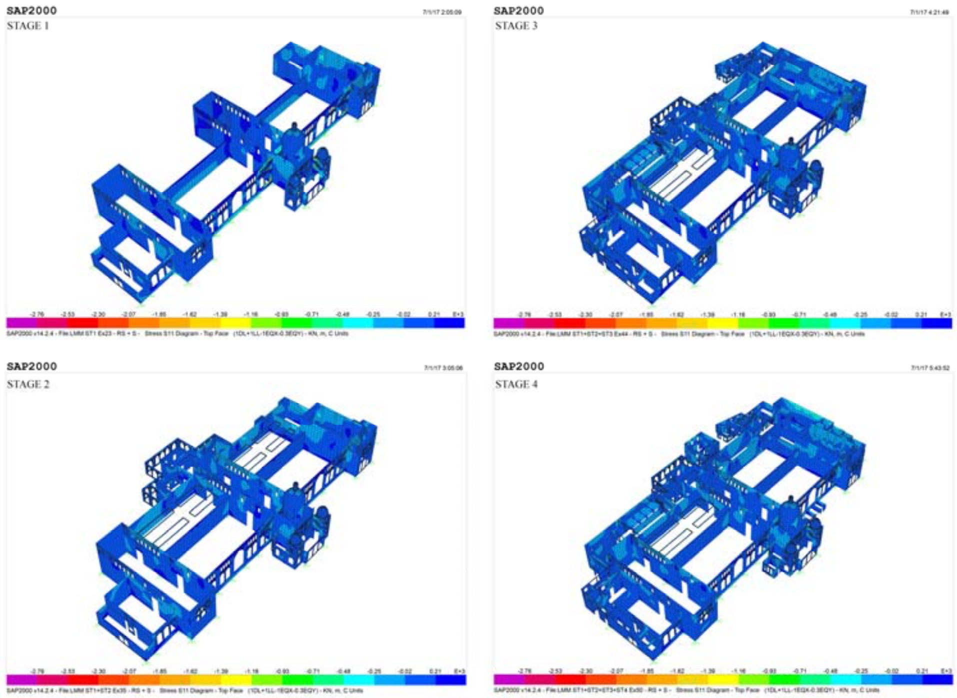

Figure D.29: Load Combo 1D+1L-EQX-0.3EQY In-plane Normal Stresses – Horizontal Direction (Top Face)

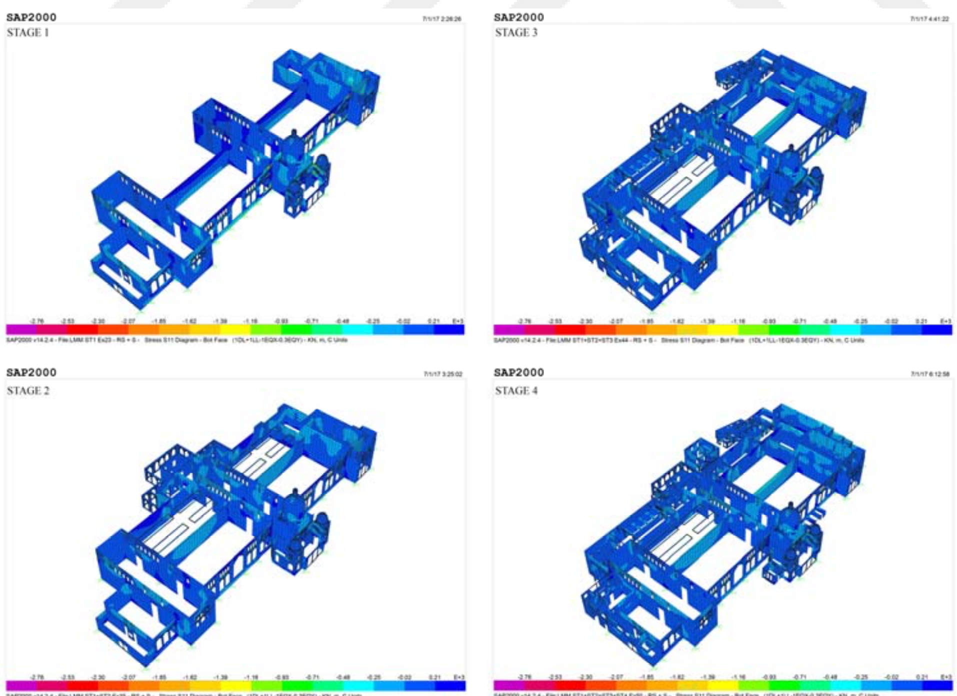

Figure D.30: Load Combo 1D+1L-EQX-0.3EQY In-plane Normal Stresses – Horizontal Direction (Bottom Face)

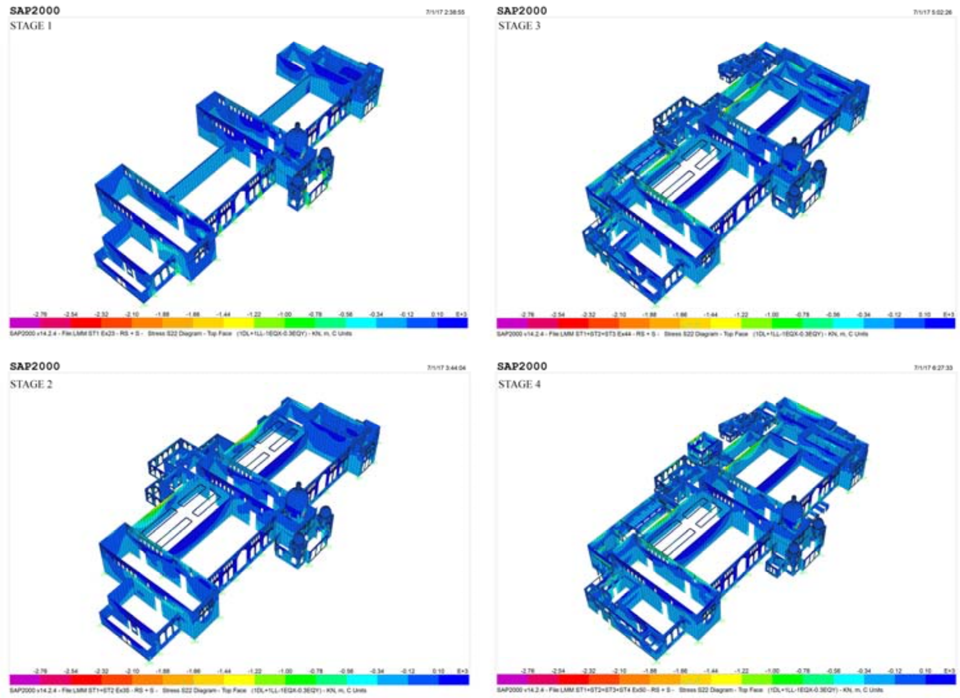

Figure D.31: Load Combo 1D+1L-EQX-0.3EQY In-plane Normal Stresses – Vertical Direction (Top Face)

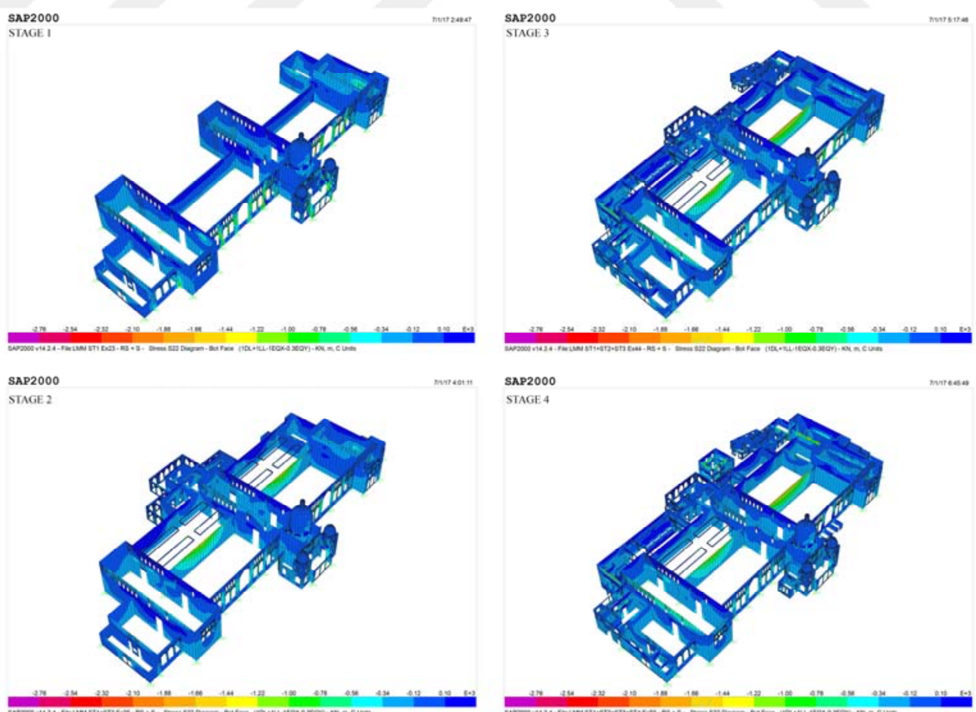

Figure D.32: Load Combo 1D+1L-EQX-0.3EQY In-plane Normal Stresses – Vertical Direction (Bottom Face)

2. Stress Results for Walls with Critical Area Elements

S11 - Inplane Stresses for Horizontal Dir.
Exterior (North) Face

S11 - Inplane Stresses for Horizontal Dir.
Interior (South) Face

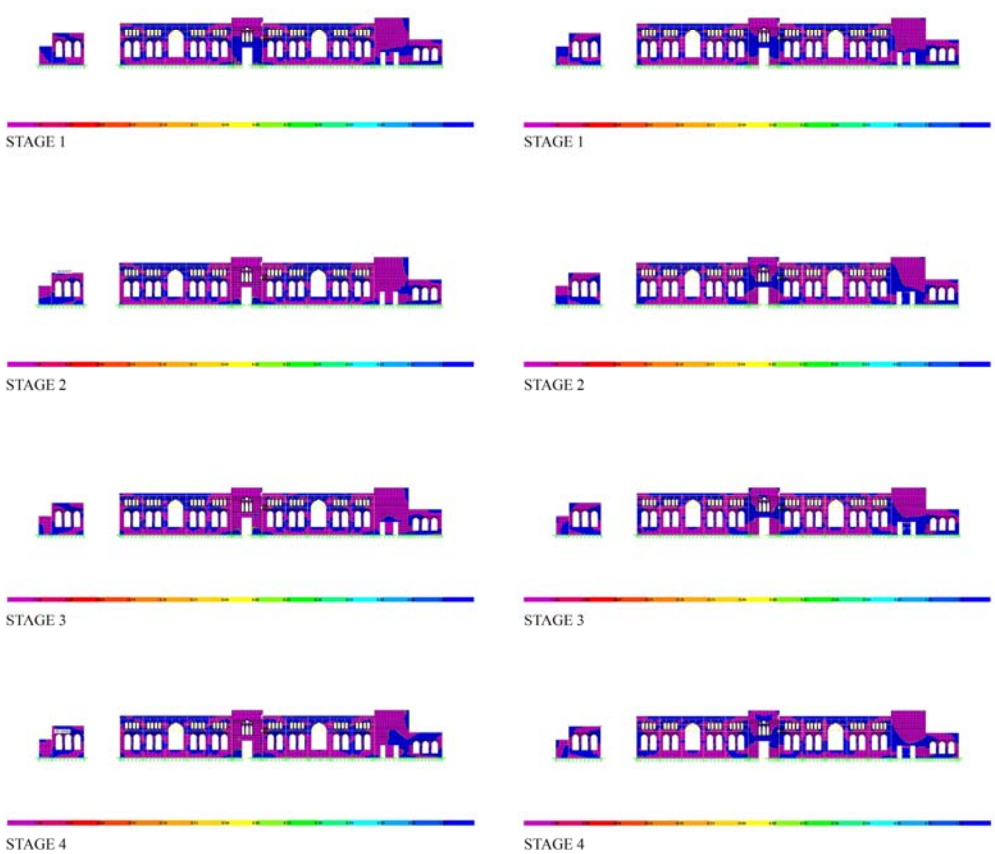

Figure D.33: Gnd-E/01-N-W & Gnd-W/01-N-W; In-Plane Stresses – Horizontal Direction

Figure D.34: Gnd-E/01-N-W & Gnd-W/01-N-W; In-Plane Stresses – Vertical Direction

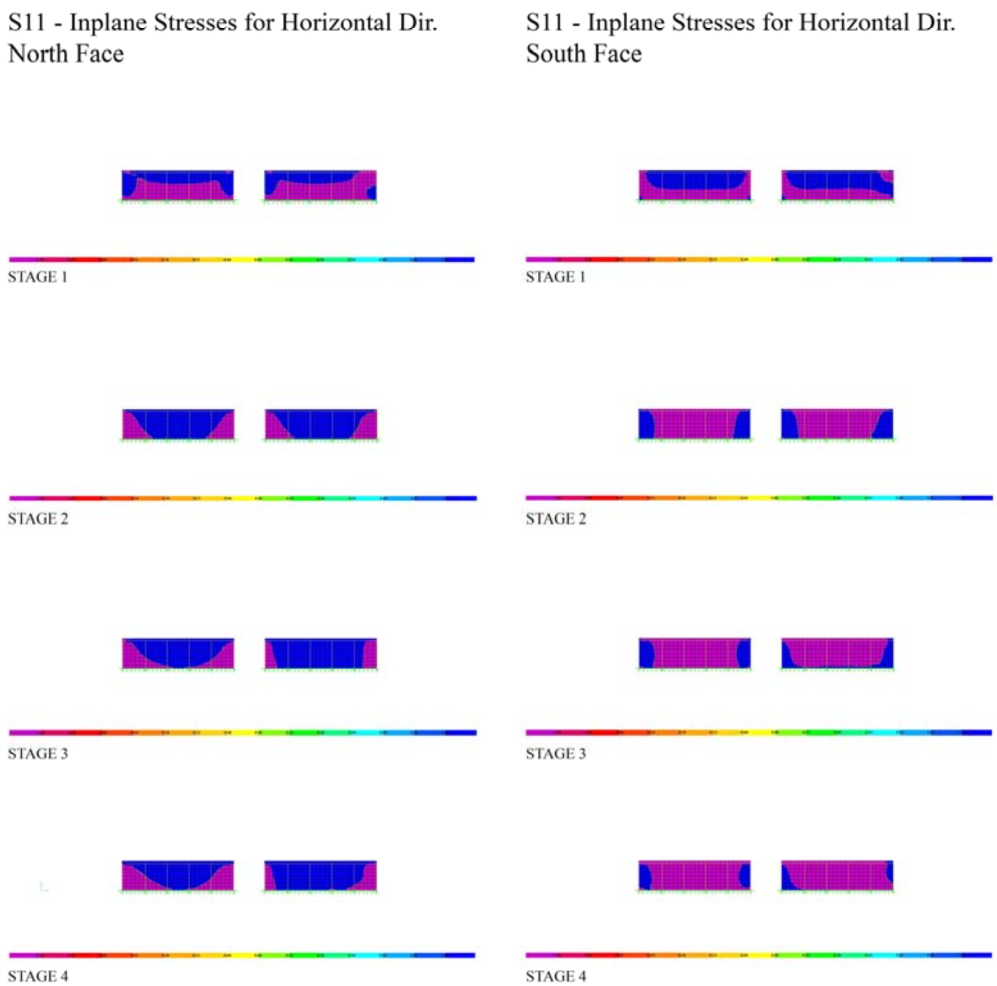

Figure D.35: Gnd-E/01-S-W & Gnd-W/01-S-W; In-Plane Stresses – Horizontal Direction

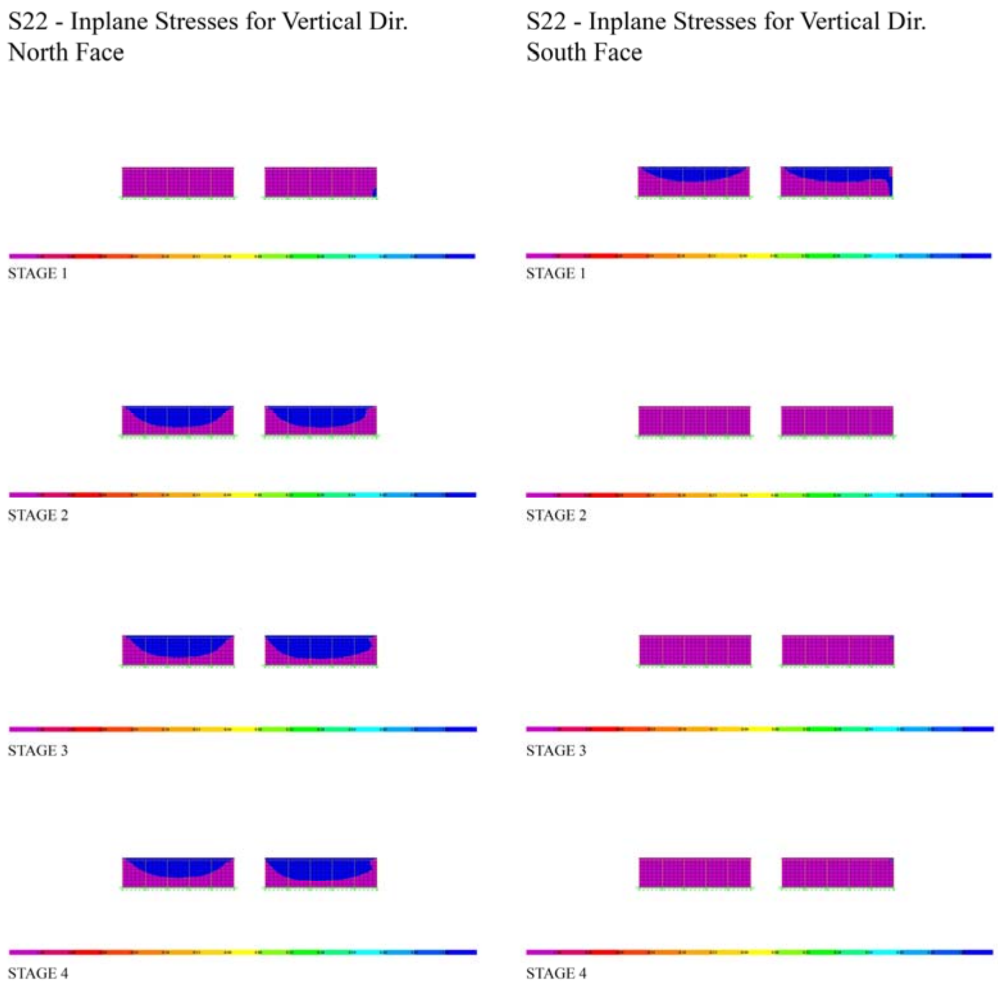

Figure D.36: Gnd-E/01-S-W & Gnd-W/01-S-W; In-Plane Stresses – Vertical Direction

S11 - Inplane Stresses for Horizontal Dir.
North Face

S11 - Inplane Stresses for Horizontal Dir.
South Face

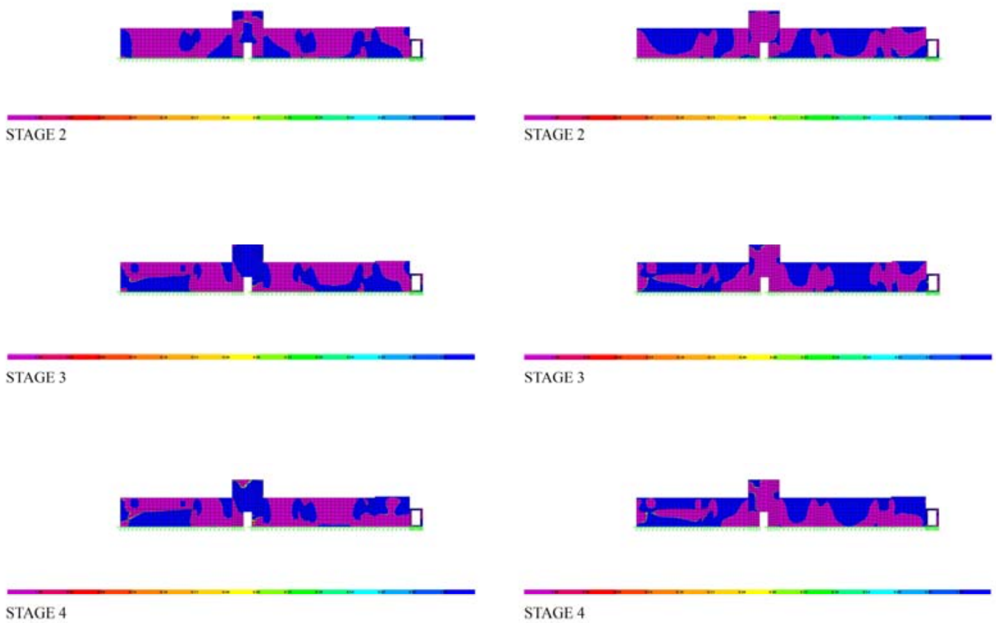

Figure D.37: Gnd-E/02-S-W & Gnd-W/02-S-W; In-Plane Stresses – Horizontal Direction

S22 - Inplane Stresses for Vertical Dir.
North Face

S22 - Inplane Stresses for Vertical Dir.
South Face

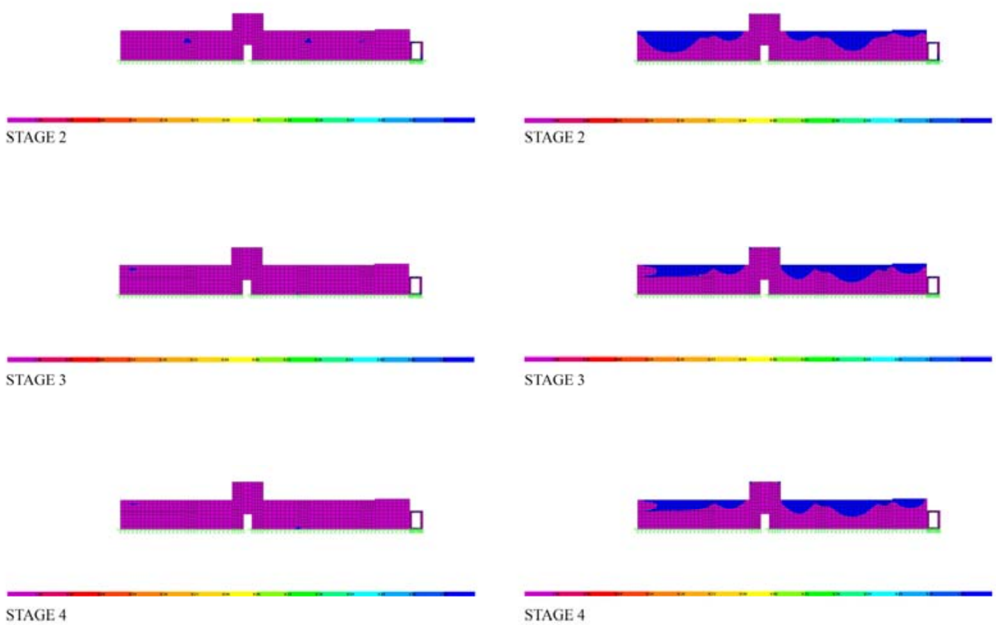

Figure D.38: Gnd-E/02-S-W & Gnd-W/02-S-W; In-Plane Stresses – Vertical Direction

S11 - Inplane Stresses for Horizontal Dir.
West Face

S11 - Inplane Stresses for Horizontal Dir.
East Face

Figure D.39: Gnd-E/03-W-W; In-Plane Stresses – Horizontal Direction

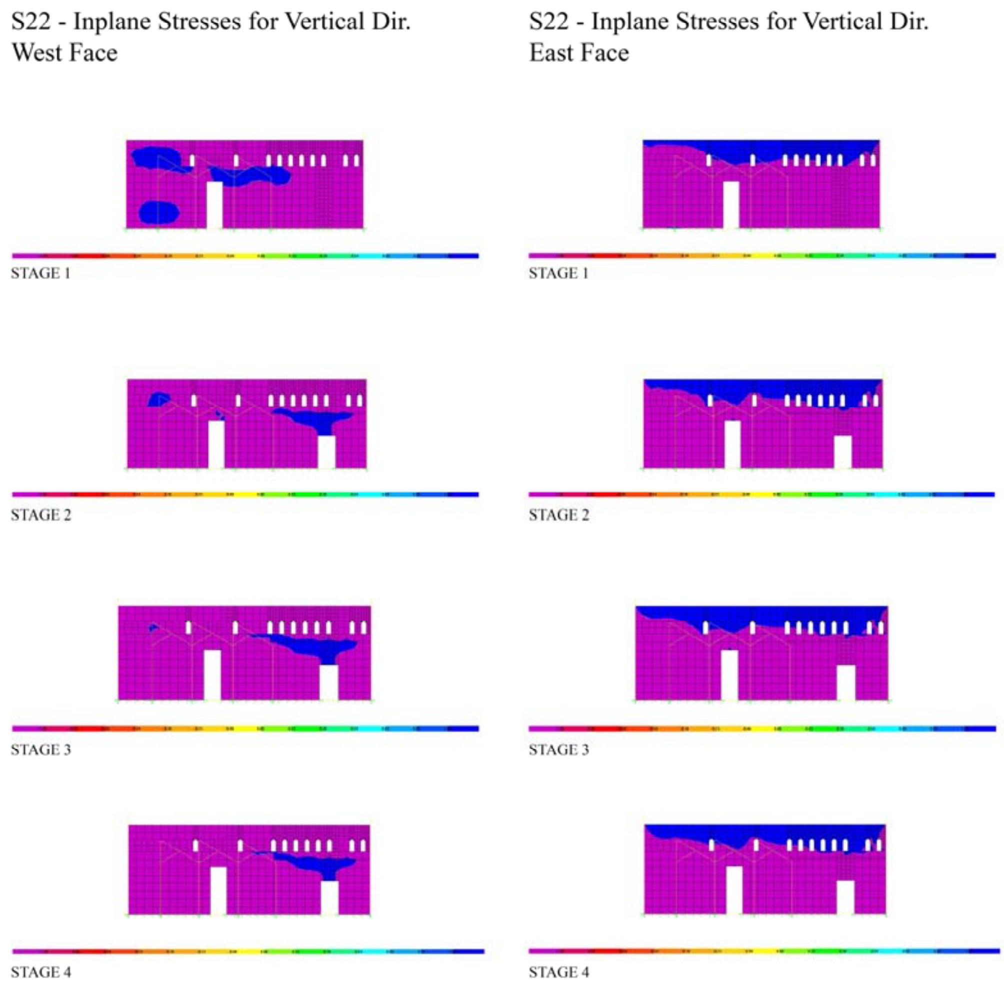

Figure D.40: Gnd-E/03-W-W; In-Plane Stresses – Vertical Direction

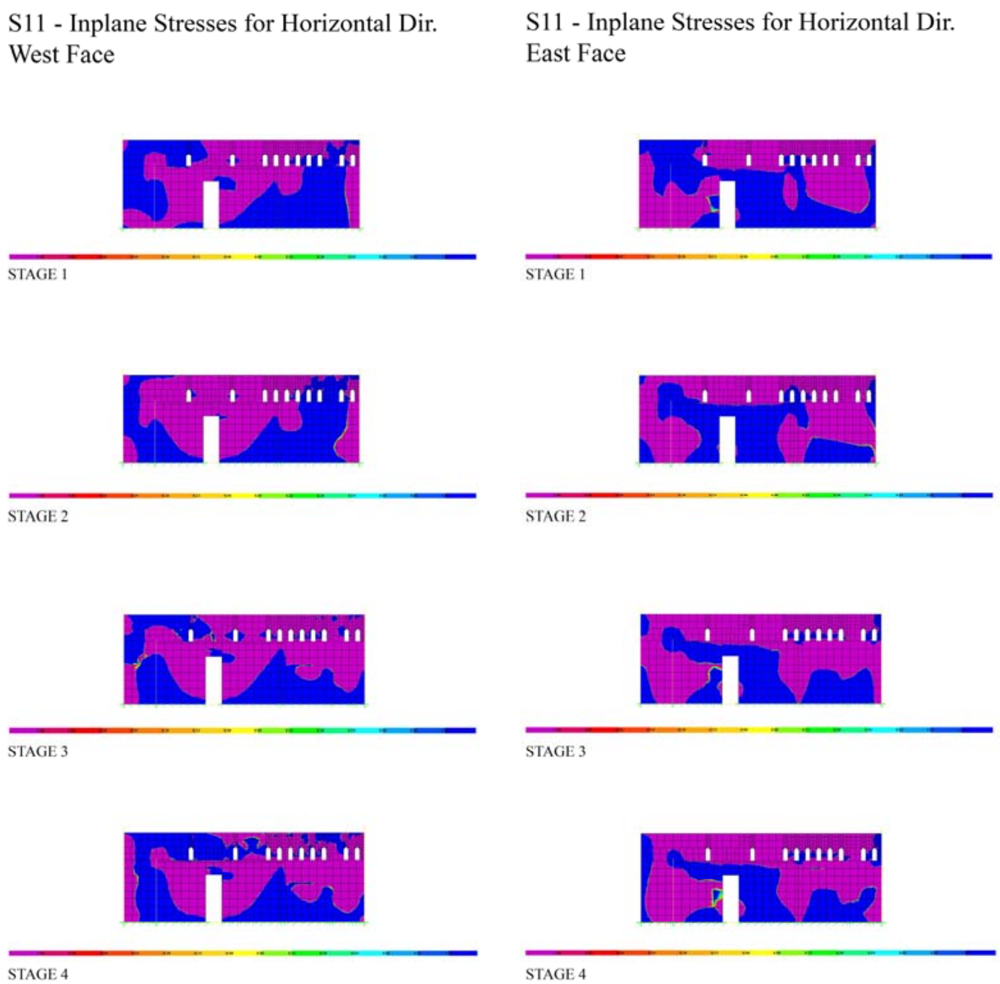

Figure D.41: Gnd-E/03-E-W; In-Plane Stresses – Horizontal Direction

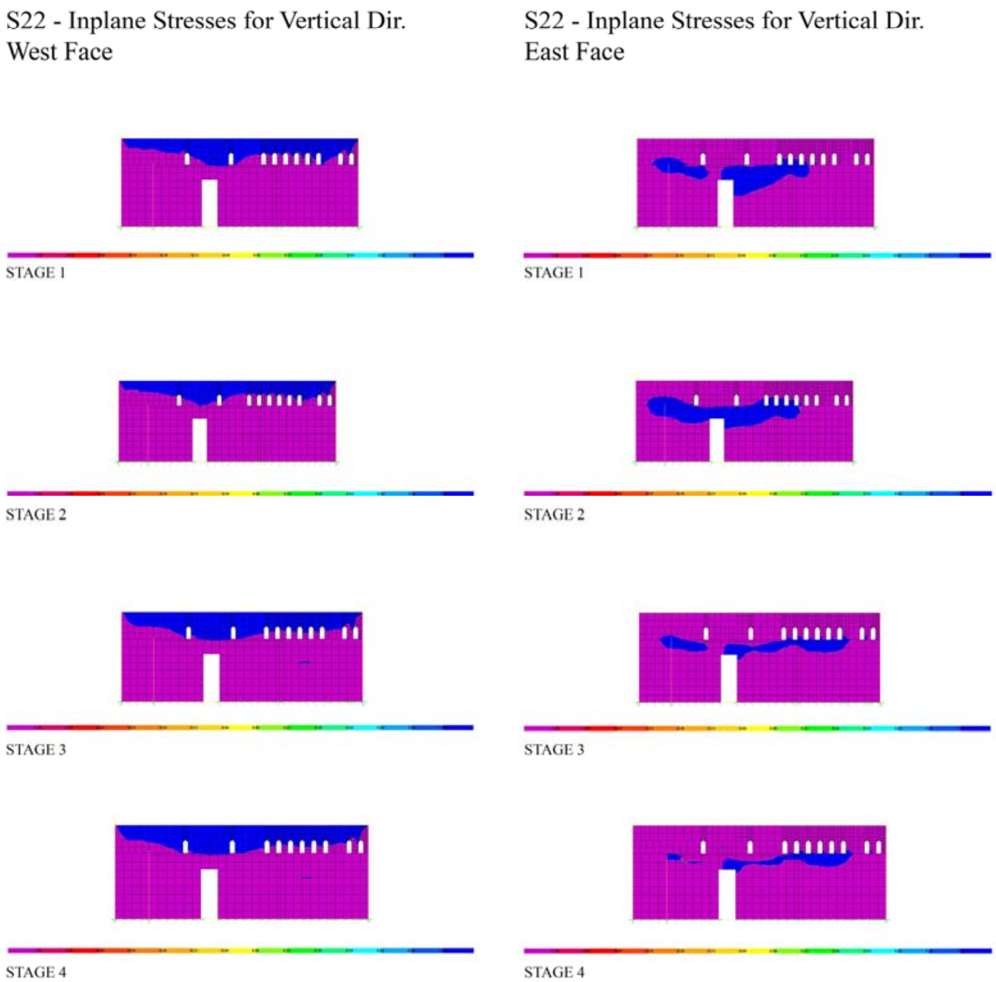

Figure D.42: Gnd-E/03-E-W; In-Plane Stresses – Vertical Direction

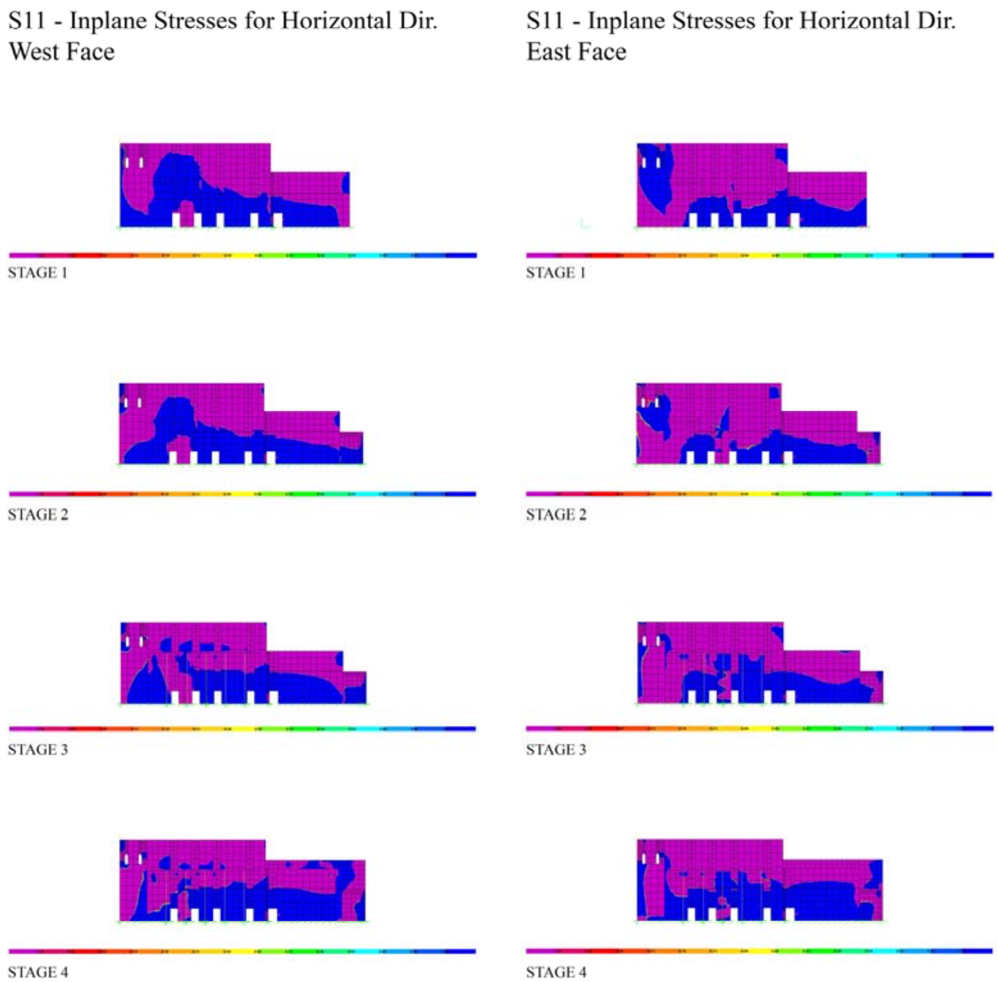

Figure D.43: Gnd-W/10-W-W; In-Plane Stresses – Horizontal Direction

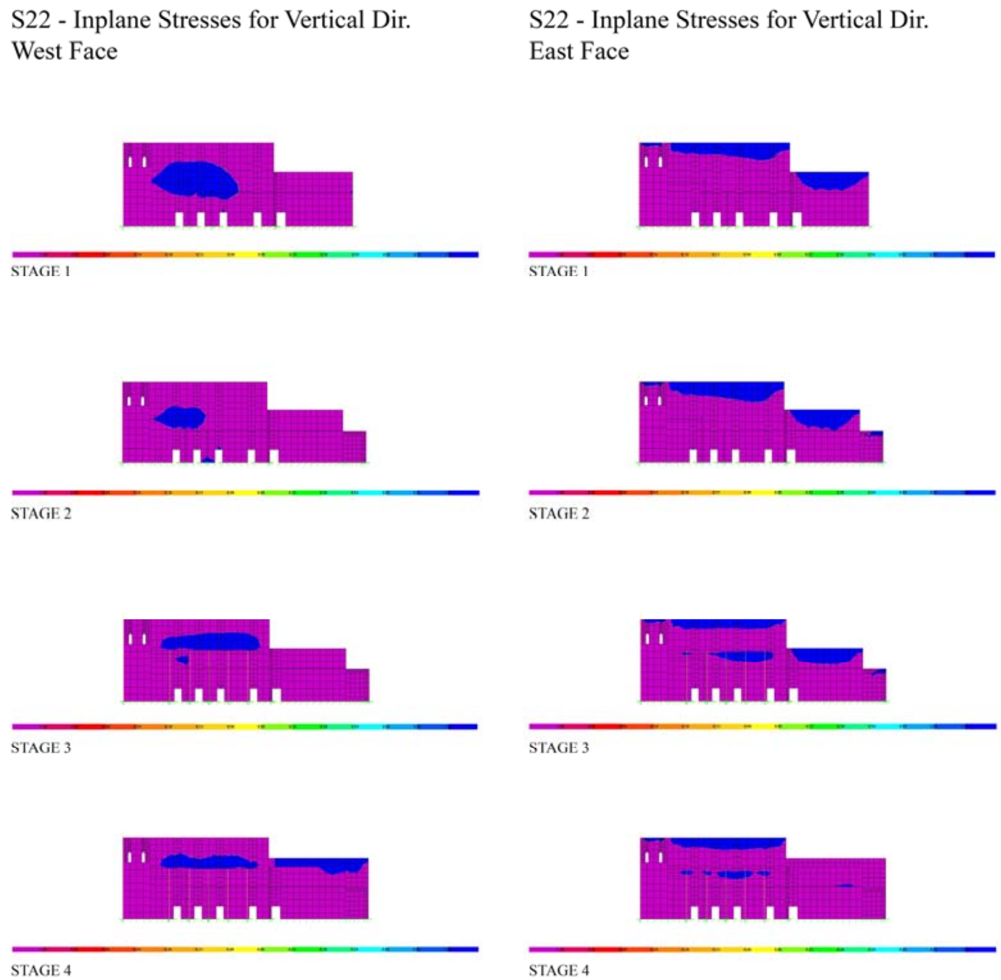

Figure D.44: Gnd-W/10-W-W; In-Plane Stresses – Vertical Direction

S11 - Inplane Stresses for Horizontal Dir.
West Face

S11- Inplane Stresses for Horizontal Dir.
East Face

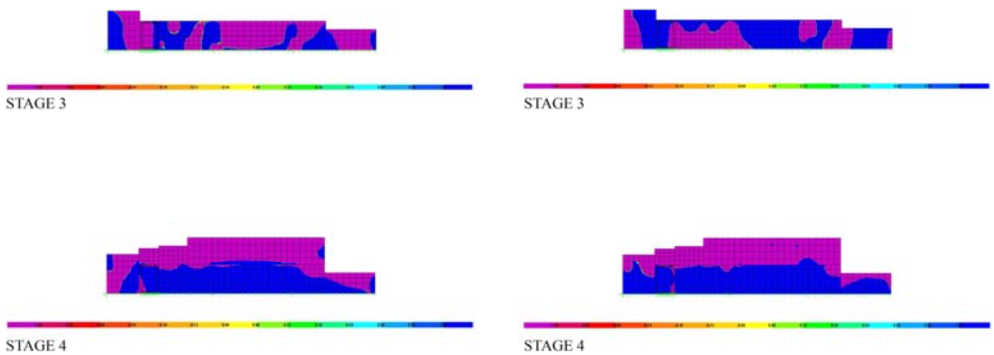

Figure D.45: Gnd-W/05-W-W; In-Plane Stresses – Horizontal Direction

S22 - Inplane Stresses for Vertical Dir.
West Face

S22- Inplane Stresses for Vertical Dir.
East Face

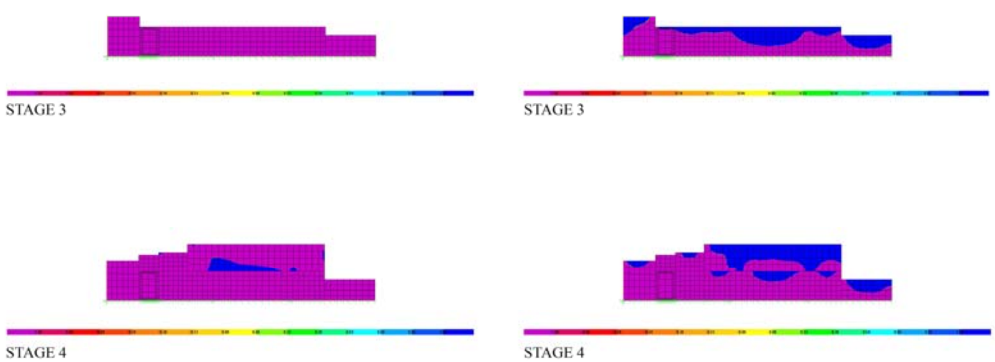

Figure D.46: Gnd-W/05-W-W; In-Plane Stresses – Vertical Direction

E. IMAGES & DRAWINGS CD