

ASSESSMENT OF STRUCTURAL INTEGRITY AND SEISMIC RETROFIT OF
MASONRY BRIDGES USING MICROPILES

BY
FERIT CAKIR

DEPARTMENT OF
CIVIL, ARCHITECTURAL AND ENVIRONMENTAL ENGINEERING

Submitted in partial fulfillment of the
requirements for the degree of
Master of Science in Civil Engineering
in the Graduate College of the
Illinois Institute of Technology

Approved J. Mohammadi
Adviser

Chicago, Illinois
July 2011

ACKNOWLEDGEMENT

I am grateful to many people that have contributed to this thesis and supported me along the way. I would first like to thank my graduate adviser and thesis supervisor, Prof. Jamshid MOHAMMADI, for his continuous support and exceptional guidance, advice and patience. My special thanks are also extended to Prof. David ARDITI for his support and help.

My special thanks to the Republic of Turkey, Ministry of National Education, for financial support of my graduate education in the USA. I am also thankful to my thesis defense committee members for their attention to my thesis defense and their challenging questions.

My thanks also go to my roommates for their unchanging friendship and their support during my hard times. I am also thankful to my friend and brother Suleyman DOST who is a Ph.D. candidate at the University of Chicago, Near Eastern Languages and Civilizations Department. Suleyman became a guide for historical structures in the Middle East and read the draft of my thesis. I also want to extend my gratitude to Sevilay DEMIRKESEN, a Civil Engineer, for reading and commenting on my thesis.

And I owe countless thanks to my lovely family for their endless supports, encouragements and prayers even if they are thousands of miles far away from me.

TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENT	iii
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF SYMBOLS	x
ABSTRACT	xi
CHAPTER	
1. INTRODUCTION.....	1
1.1 Historical Background.....	1
1.2 Current Situation.....	7
1.3 Purpose and Scope of the Study	8
1.4 Contents of the Thesis	8
2. STRUCTURAL ELEMENTS AND MATERIALS	10
2.1 Arches.....	11
2.2 Spandrels	19
2.3 Piers and Abutments.....	21
2.4 Foundations	24
2.5 Construction Materials	28
2.5.1 Stones	29
2.5.2 Bricks	31
2.5.3 Mortars	33
2.5.3 Timbers	36
3. STRUCTURAL BEHAVIORS OF MASONRY ARCH BRIDGES	37
3.1 Loads on Masonry Arch Bridges.....	37
3.1.1 Dead Load.....	38
3.1.2 Live Load.....	40
3.1.3 Lateral Load.....	42
3.2 Causes of Masonry Arch Bridges Failures.....	44
3.2.1 Earthquakes.....	44
3.2.2 Settlement Problems.....	46
3.2.3 Flooding and Scours.....	48

3.2.4	Overloading	49
3.2.5	Failures of Construction Materials.....	50
3.2.6	Demolition and Vandalism.....	51
3.3	Collapse Mechanism of Masonry Arch Bridges.....	52
3.3.1	Shear Mechanism	53
3.3.2	Hinge Mechanism.....	53
3.3.3	Combined Shear – Hinge Mechanism	55
4.	SEISMIC RETROFITTING USING MICROPILES	56
4.1	Introductory Remarks	56
4.2	Designing and Seismic Applications.....	59
4.3	Case Studies	62
4.4	Concluding Remarks	65
5.	CONCLUSIONS AND SUGGESTIONS	67
5.1	Summary	67
5.2	Recommendation for Future Studies.....	68
	BIBLIOGRAPHY	69

LIST OF TABLES

Table	Page
2.1 Different empirical arch thickness formulas	18
2.2 Construction materials for masonry bridge engineering	29
2.3 Stone types and cutting tools	31
2.4 Types of masonry bricks	33
3.1 Gross vehicle weights.....	41
3.2 The main causes of masonry arch bridge failures	44

LIST OF FIGURES

Figure	Page
1.1 The oldest stone bridge in the world	2
1.2 The natural arch - Arches National Park in Utah / USA.....	3
1.3 The Arkadiko Bridge in Greece.....	5
1.4 The Long Bridge in Edirne / Turkey	5
1.5 The Rockville Bridge in Pennsylvania / USA.	6
1.6 The Malabadi Bridge in Anatolia, Turkey	7
1.7 Flow chart showing the process of thesis	9
2.1 Main components of a masonry arch bridge.....	10
2.2 Masonry arch nomenclature.....	12
2.3 Some examples of arch forms.....	13
2.4 Hooke's hanging chain.....	14
2.5 Thrust lines for some arched structures.....	15
2.6 Couplet's determination of the position and size of the arch.....	17
2.7 Spandrel walls in the masonry arch bridges.....	19
2.8 Some examples of open spandrel bridge in China, (a) Chawzhou Bridge, (b) Huanghugang Bridge, (c) Jiuxigou Bridge, (d) Danhe Bridge).....	20
2.9 Abutments and Piers in the masonry arch bridges	22
2.10 Some pier shapes	23
2.11 Hollow spaces in piers.....	23
2.12 Some examples of abutment shapes.....	24
2.13 The Buttes Chaumon Bridge in France	25
2.14 Malabadi Bridge in Turkey.....	25

2.15 The foundation model of the Aspendos Bridge in Turkey.....	26
2.16 Multiplex foundations (the foundations are exposed due to the scour effect of streams)	27
2.17 Timber piles in masonry bridge.....	27
2.18 Timber raft foundation in masonry bridges	28
2.19 Classification of stones.....	30
2.20 Some stone examples (a-Igneous, b-Sedimentary, c-Metamorphic).....	31
2.21 The Roman aqueducts in Nimes, France.....	32
2.22 Common types of bricks	34
2.23 The hardest form of mortar after application for stone structure and its volume.....	35
2.24 The timber raft foundation for masonry bridges (a) and the timber pile elevation drawing (b).....	36
3.1 Effect of Dead Load	39
3.2 Unit weights of materials for computing dead load	39
3.3 Effect of Live Load.....	40
3.4 AASHTO Standard H and HS lane loadings	41
3.5 AASHTO Standard H and HS design trucks	42
3.6 Collapse of spandrel of a masonry bridge during the Umbria-Marche earthquake of 1997	45
3.7 Damages occurred in superstructure of the Misis Bridge during the 1998 Adana-Ceyhan earthquake	45
3.8 Settlement of pier and induced damages.....	46
3.9 Differential settlement or transverse rotation on the longitudinal axis of a pier or abutment	47

3.10 Substructure failures due to settlement problems on the Mataraci Bridge	47
3.11 Local scour actions on a bridge foundation	48
3.12 Trees come with flooding.....	49
3.13 An example of overload vehicle	50
3.14 Deterioration of construction materials.....	51
3.15 Mostar Bridge (a) in 1993, (b) in 2004	52
3.16 Shear mechanisms	53
3.17 Hinge mechanisms.....	54
3.18 Hendry’s experiment	54
3.19 Combined shear – hinge mechanism.....	55
4.1 Schematics of pile main construction phases.....	60
4.2 Some micropile application types.....	61
4.3 Different types of micropile applications for some masonry bridges	63
4.4 Elevation views of the micropiles as strengthening reinforcement.....	64
4.5 Micropile retrofit scheme of the Three Arches Bridge	65

LIST OF SYMBOLS

Symbol	Definition
AASHTO	American Association of State Highway and Transportation Officials
ICOM	International Council of Museums
LRFD	Load and Resistance Factor Design
UNESCO	United Nations Educational, Scientific, and Cultural Organization
e	The thickness of the arch
R	The radius of the circle
l	The bridge span, meter
ρ	The curvature radius
f	The ratio of the rise

ABSTRACT

Masonry arch bridges are regarded as the oldest examples of engineered structures in the world; and they reflect the previous civilizations in the world with their various sizes, styles, and spans. The preservation of these structures is receiving a great deal of attention in the structural engineering community. And as such, restoration, strengthening and reinforcement of historical masonry bridges have become a challenge for civil engineers.

At the present time, most important problems of masonry arch bridges are heavy traffic loads and destructive natural disasters. These bridges were constructed centuries ago and they addressed the load-carrying problems of old times. With the passing of the time, the traffic changed and many natural disasters occurred. Correspondingly, loads on masonry arch bridges have increased and the traffic on the bridges have become more intense in the course of time. However, the bridges keep up to their initial performance; and this shows the complexity of their structural behaviors.

This study provides the background information about masonry arch bridges and their components. It also helps us better understand the construction materials, structural properties and structural behavior of masonry arch bridges. In light of this background information, this study presents an overview of seismic retrofit for masonry arch bridges and a comprehensive study on the type, mechanism of failure and structural integrity of masonry arch bridges.

CHAPTER 1

INTRODUCTION

Masonry arch bridges have undertaken a very important and fundamental role in the transportation systems in many parts of the world. Ancient people had to overcome with difficult terrains and earth features, such as rivers, hollows and holes; and as the result, they soon realized that building bridges was an unavoidable option to overcome these difficulties in their everyday transportation needs. They used simple structural forms with natural materials in order to cross over simple openings. However, for long openings, they had to come up with more engineered systems that would sustain the structural issues such as large deflections, damaging load concentration points and stability. Ancient master builders soon learned that arches offered an efficient method of spanning over long-span openings and could be built rather easily within their capabilities.

In the present time, there are thousands of these masonry arch bridges all over the world still carrying heavy traffic. In many places, replacing them with modern bridges will bear an enormous cost and service disruption, especially considering the fact that many of them are considered national monuments.

1.1 Historical Background

Throughout the history, roads and bridges constitute one of the most important ways of connecting people and businesses. While people were using paths which were formed by animal trails or natural features, such as dried riverbed and split made from earthquakes, after the invention of the wheel, they started to construct roads. With the increase of travel demand, people constructed not only suitable roads but also shortcut

roads. During the building phase, people met with difficult features such as rivers, hollows and holes that had to be crossed over. One of the fundamental problems for people was to link these openings. And as such, they used natural materials such as timbers and stones in order to cross over simple openings. These efforts paved the way to the birth of bridge engineering.

The simplest solution for this problem is the horizontal beams and lintels or slabs supported by walls, columns or rocks. The oldest known simple stone bridge is in the Bogazkoy (Hattusas), which was the capital city of Hittites, in Corum, Turkey. It was built in 13th century B.C. founded 54.5 ft (16.62 m) above the water level. It connects the two steep crags with 28 ft (8.5 m) span (Figure 1.1) (KGM 2009).

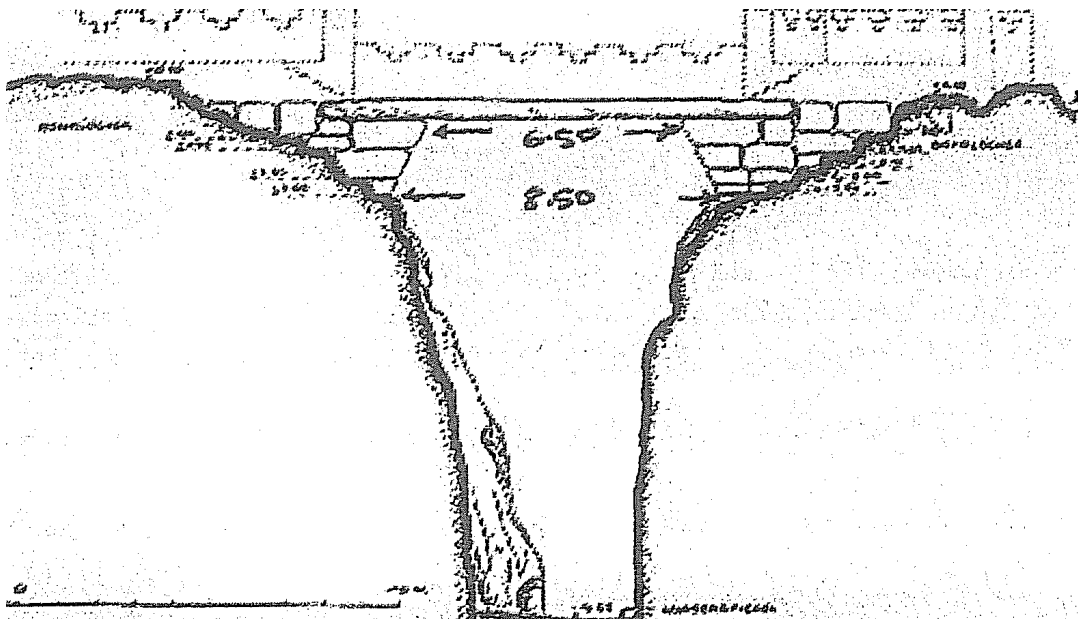


Figure 1.1 The oldest known stone bridge in the world (KGM 2009)

This method has been used ever since by using beams of stone and timber. Being granular and fragile, stone breaks up very easily in tension; and because tension is caused by bending, only very short spans can be covered by using horizontal simple stone

beams. Longer spans can be bridged by timber; however, it is unsuitable (in the solid form) for very long spans because of the difficulty in obtaining timber with suitable sizes (Morgan 1970). Therefore, early engineers started their effort toward building bridges with longer spans by resorting to natural earth features. The ancient master builders, then, learned the form of an arch, which can also be found in the nature, in order to cover large spans (Ozer 2004). The arch offered a suitable and durable system, which could also handle the axial loads safely (Figure 1.2).



Figure 1.2 The natural arch – Arches National Park in Utah / USA (Ozer 2004)

Undoubtedly, the ancient builders made many efforts about how they could utilize the great strength of stone and brick in compression and develop geometrical designs that would minimize tension forces. The discovery of the arch was truly a great achievement in that the arch makes use of the ability of stones and bricks to resist compression and minimizes tensile stress effects (see for example, Morgan 1970).

The first arches were formed by two ‘V’ shaped stones that covered the span. In this way, engineers tried many arch shapes with trial and error methods and came up with

many different shapes for arch structures. Arches were used in the Middle East since the time of Sumerians. The first examples of arches were seen in tombs in Mesopotamia about 3000 B.C. The first arches were very small and they were used to cover tombs' dome. In addition to this, the ancient Romans also used stone arches for large bridges and aqueducts in medieval and Renaissance Europe (Ural et al. 2008). The Roman engineers, in particular, were masters of the arch form. Their arched bridges and aqueducts have lasted for over two millennia, not only because they were made of durable materials, but also because they combined innovations in construction technology with centuries of experience and empirical knowledge (Miller et al. 2000).

Possibly the oldest existing arch bridge is the Mycenaean Arkadiko Bridge in Greece built about 1300 B.C (Figure 1.3). The Arkadiko Bridge is only one of four known Mycenaean corbel arch bridges near Arkadiko, all belonging to the same Bronze Age highway between the two cities, and all of similar design and age. The structure is 72.17 ft (22 m) long, 18.37 ft (5.60 m) wide at the base and 13.12 ft (4 m) high. The width of the roadway at the very top is about 8.20 ft (2.50 m) (Body 1978).

As the arch construction knowledge developed, engineers started to use multiple arches to cover longer spans. Two well known examples of multiple arch bridges in the world are Long Bridge and Rockville Bridge. The "Long Bridge" (Turkish: Uzunköprü) was built between 1426 and 1443 by the Ottoman Empire. The ancient stone-built bridge, which has 174 arches, is 4,360 ft (1,329 m) long and up to 22.3 ft (6.80 m) wide. Some of the arches are pointed and some are round. Uzunköprü is the longest stone arch bridge in the world (Figure 1.4) (KGM 2009). The "Rockville Bridge", at the time of its completion in 1902, was, and still remains, the longest stone

masonry arch railroad viaduct in the world (Figure 1.5.). It has 48 spans and every span has 70 ft (21,34 m) width, for a total length of 3,791 ft (1,155 m) (HAER 2001).

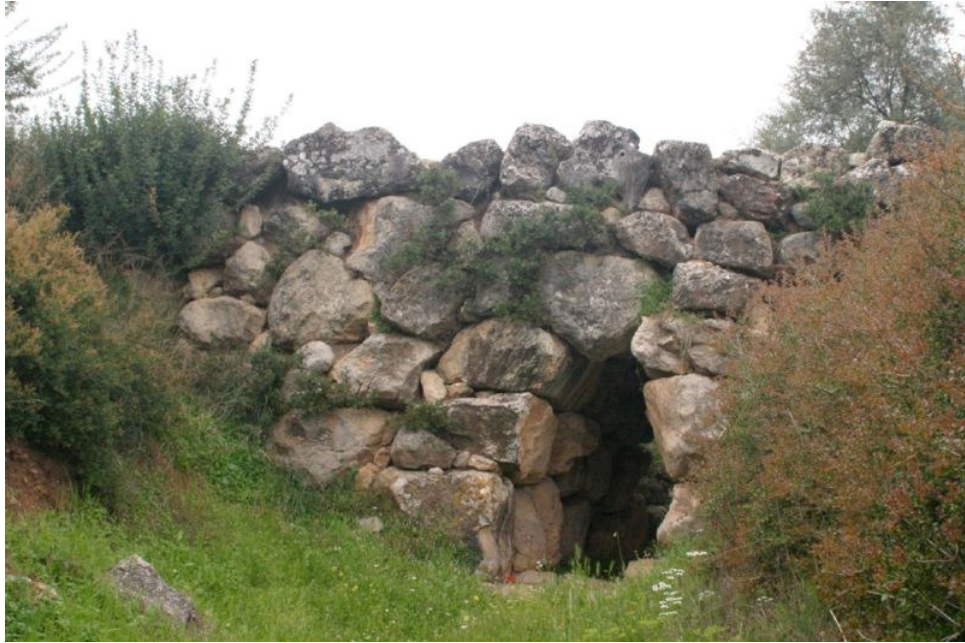


Figure 1.3 Arkadiko Bridge in Greece



Figure 1.4 The Long Bridge in Edirne / Turkey

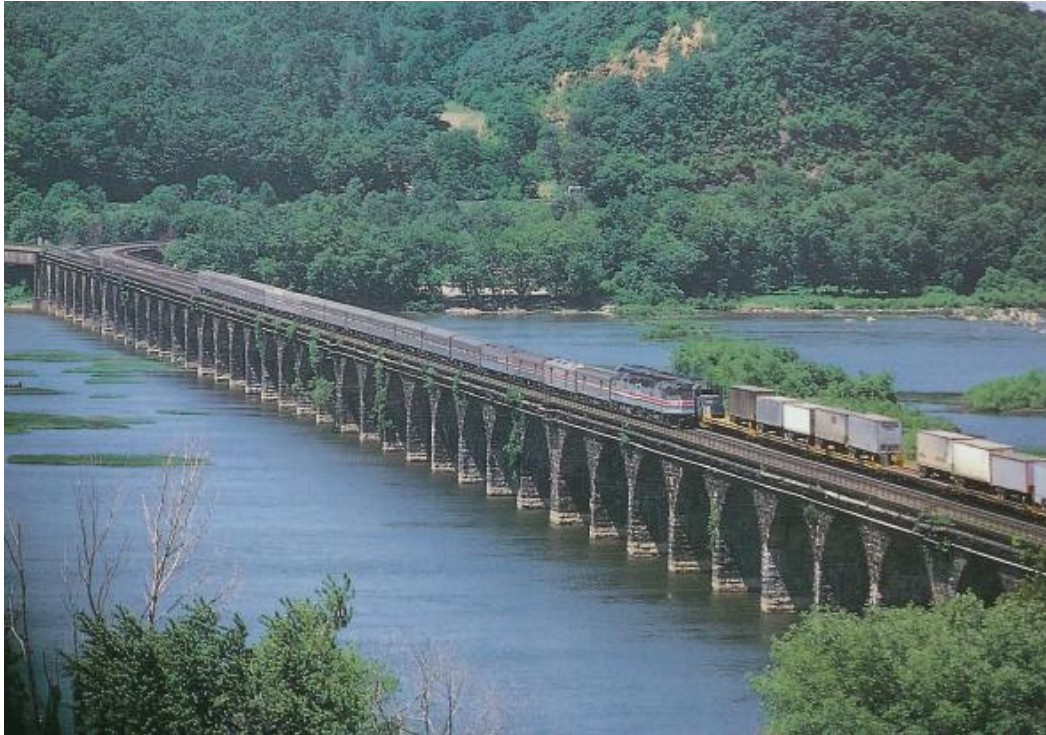


Figure 1.5 The Rockville Bridge in Pennsylvania / USA

As engineering skills improved, single arch systems became the method of choice over multiple arch options. The best example of this type is the Malabadi Bridge located in Diyarbakır, Turkey. The Malabadi Bridge, one of the most famous historical heritage bridges, has a very long arch span around 133,85 ft (40.80 m). The Malabadi Stone Arch Bridge is a magnificent structure crossing the Batman River in Anatolia, Turkey (Figure 1.6). According to history, the bridge was built in 1147 – 1148 A.D. during the Artuklu Dynasty. It is the widest of all stone arch bridges existing in the world (KGM 2009).

Today, arch bridges are generally built using reinforced concrete or steel. However, there is still much research on stone arches directed toward estimating their ultimate load capacity, remaining life, stability, maintenance requirements and also finding the most suitable methods for their strengthening and retrofit. The reason for this great interest is, of course, that there are thousands of these stone arch bridges all over the

world still carrying traffic and that it would take an enormous cost to replace them all; especially since many of them are considered national monuments (Chen and Duan 2000).



Figure 1.6 The Malabadi Bridge in Anatolia, Turkey

1.2 Current Situation

At the present time, arch bridges are generally built using modern construction materials such as reinforced concrete or steel. However, a large portion of arch bridges in the world today is still classified as masonry arch bridges. As indicated earlier, many such bridges have been accepted as historical monuments; and as such, they must be protected with convenient restoration methods and suitable construction materials. In 1964, the Special Conservation Committee of the Venice Charter, which is an international charter for the conservation and restoration of monuments and sites,

published documentations for preservation of monumental structures. This charter has introduced important restoration limitations all over the world and has combined all the restoration knowledge under a single entity. In addition, many special organizations such as International Council of Museums and (ICOM) and United Nations Educational, Scientific and Cultural Organization (UNESCO) have been interested in restoration and conservation of historical monuments.

1.3 Purpose and Scope of the Study

This study mainly focuses on two major issues:

(1) An overview and assessment of the structural integrity of historical masonry arch bridges; and,

(2) Review of seismic retrofit of these structures using underpinning methods.

Many masonry bridges have been built in earthquake prone regions of the world; and a large portion of them are not seismically safe. Thus, they have to be retrofitted with convenient restoration methods on a timely basis. In order to determine the seismic protection requirements for these bridges, an understanding of their behavior, structural integrity and failure mechanism is important. Furthermore, it is imperative to identify various types of arch bridges and their capabilities to withstand the modern day traffic and truck loads.

1.4 Contents of the Thesis

This thesis consists of five chapters. Chapter 1 presented a historical overview of masonry arch bridges. The chapter provided information on the type of materials, and construction techniques used for these bridges by presenting several examples of arch bridges, which are still in use, in the world. Chapter 2 touches upon the structural

integrity of these bridges and describes types of structural elements and materials used for them. In Chapter 3, the structural behavior of historical masonry arch bridges under traffic and seismic loads is presented along with information on their potential for collapse (as observed in real failure cases). Chapter 4 presents seismic protection utilizing underpinning methods for masonry bridges. This chapter also presents several case studies regarding seismic protection using micropiles. Finally in Chapter 5, the conclusions of the study and recommendations for additional studies are presented.

Figure 1.7 presents the organization of the thesis.

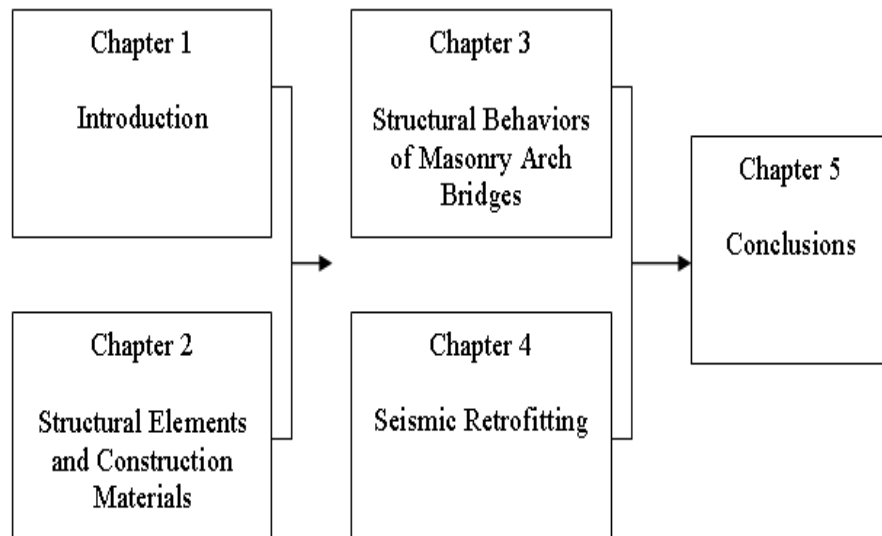


Figure 1.7 The organization of thesis

CHAPTER 2

STRUCTURAL ELEMENTS AND
CONSTRUCTION MATERIALS

Historical arch bridges, encompassing various sizes, styles, and spans reflect the previous civilizations in the world. As such, they constitute an important part of the cultural heritage in the world; and their preservation for the next generation is crucial. Indeed, several of these structures, which are over 2000 years old, are already vital components of transportation systems in many communities (Sevim et al. 2011). Figure 2.1 provides a schematic detail of various components making up a masonry arch bridge. Individual components have their own names that are universally accepted as the terminologies used to identify these components.

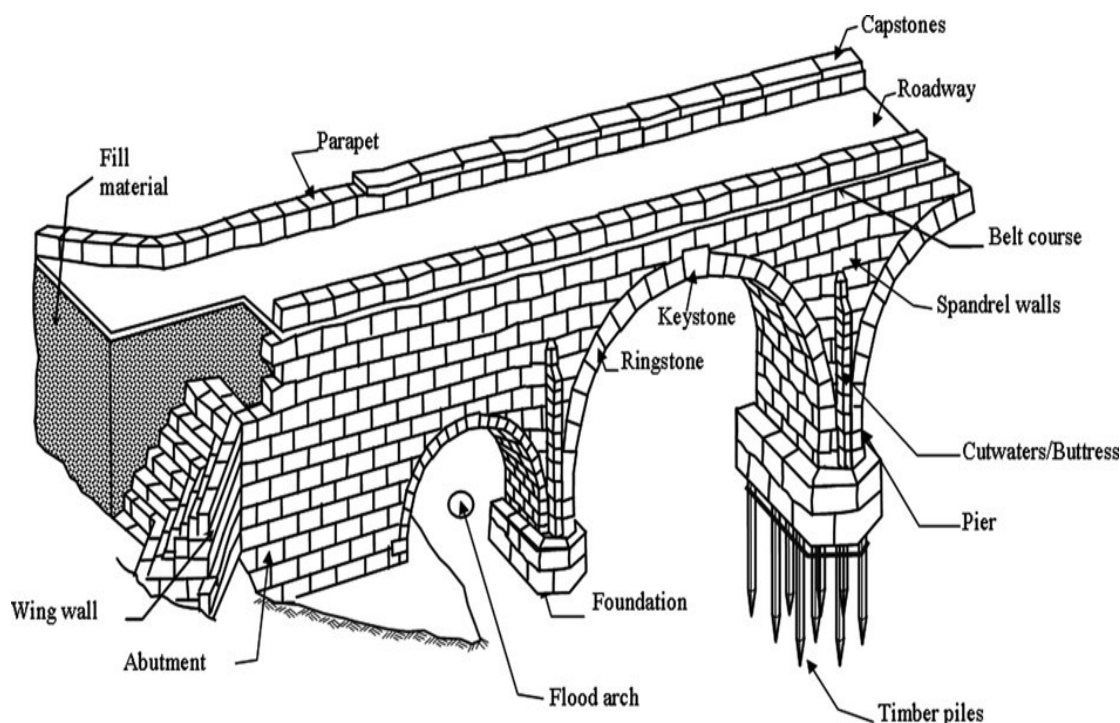


Figure 2.1 Main components of a masonry arch bridge (Ural et al. 2008)

An essential understanding of the structural behavior of masonry arch bridges requires information about their structural elements. Such information is especially necessary for understanding their need for restoration and preservation especially in areas prone to seismic activities. This chapter presents an overview of (1) the type of structural elements that constitute the main load-carrying components of these structures; (2) materials used in their construction; and (3) their overall typical structural behavior. Masonry arch bridges may have many different structural components; but their main load-carrying elements are arches, spandrels, pier and abutments, and foundations. Thus, the following sections focus on arches, spandrels, piers and abutments, foundations and construction materials, respectively.

2.1 Arches

As an engineering terminology, arch is referred to a curved structural element that spans the opening between two piers or columns and supports loads from above. Figure 2.2 illustrates the technical terminology for arches. Voussoirs are the wedge-shaped bricks or stone blocks that constitute the arch. The central one, which is sometimes larger than others, is the keystone. Extrados (upper side) and Intrados (lower side) are the external and internal curves of the arch, respectively. The highest point of the arch circle is the crown. The lower half of the arch between the crown and the skewbacks, which is the inclined surfaces of the abutments from which the arch springs, is the haunch. The crossing points of skewbacks and the intrados are the springing points. Abutments are the piers or the portion of wall supporting the arch (Ozer 2004).

One of the first specific studies of arches used in bridges was written in 1716 by the French engineer, Henri Gautier. Gautier wrote one of the earliest books on the

subject. The book is entitled: “Traité des Ponts,” which treats the subject of bridge engineering from the view point of structural analysis and design. Gautier listed five major tasks for the design process of natural stone arch bridges (Proske and Gerder 2009, Heyman 1998).

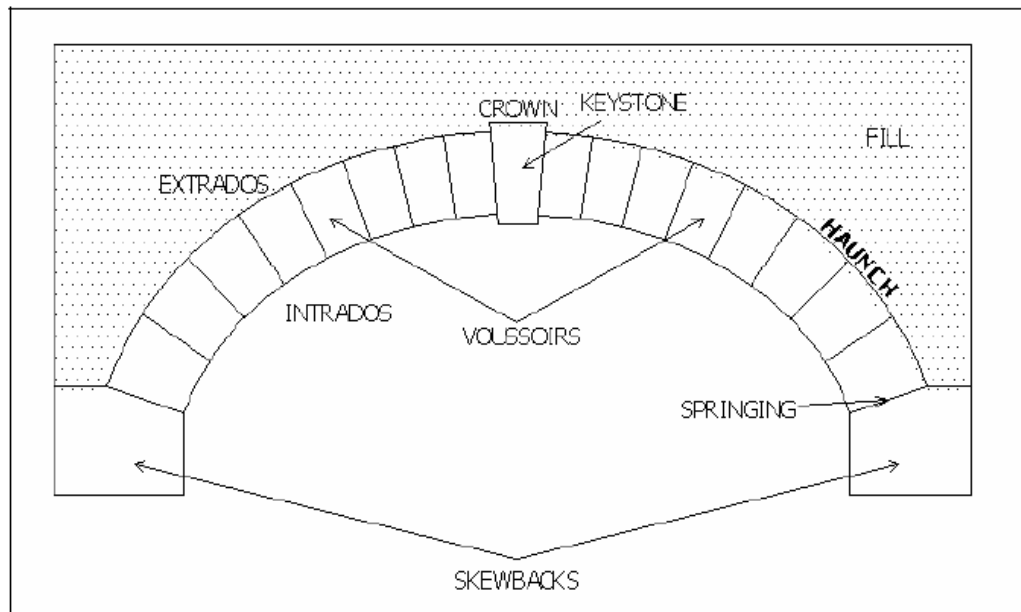


Figure 2.2 Masonry arch nomenclature (Morgan 1977)

These tasks are dealing with the choice of

- The shape of the arch
- The arch thickness at the key
- Thickness of the foundation and abutment
- Thickness of the piers depending on the design of the arch
- The thickness of the wing walls

Determining the shape of the arch perhaps constituted a difficult task to engineers.

At times, they had to resort to several trials before arriving at a desirable shape. This task

was further becoming complicated considering the fact that several possible shapes could be obtained with a change in the stone thicknesses.

The curve of extrados or intrados determines the name of the arch. The most common arch forms can be classified as semicircular, segmental, pointed, elliptical, flat, horse shoe and shallow shaped arches (Ozer 2004). The most common examples of arch form are shown in Figure 2.3.

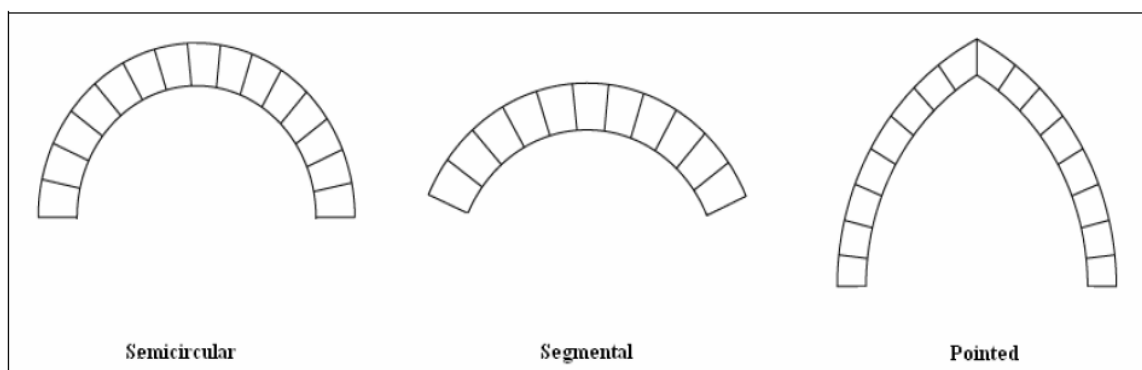


Figure 2.3 Some examples of arch forms (Ozer 2004)

To overcome the difficulties in determining an ideal shape for an arch, engineers and mathematicians have investigated the behaviors and shapes of arches over years in an effort to arrive at a rather simple formula for geometrical design of arches. Early attempts by mathematicians to arrive at a theoretical solution for arch geometrical design dates back to 17th century. Robert Hooke is credited with being the first who discovered that the ideal shape of a masonry arch in equilibrium is that of the inverted catenary curve. Figure 2.4 shows the “Hooke chain” which is drawn by a chain subjected to the same weight distribution (Morgan 1977, Roca et al. 2010). The voussoirs of the arch may be envisioned to be hanging from an imaginary chain, which represents the state of equilibrium. As the masonry must work in compression, the inverted “chain” must be contained within the arch (Heyman 1995).

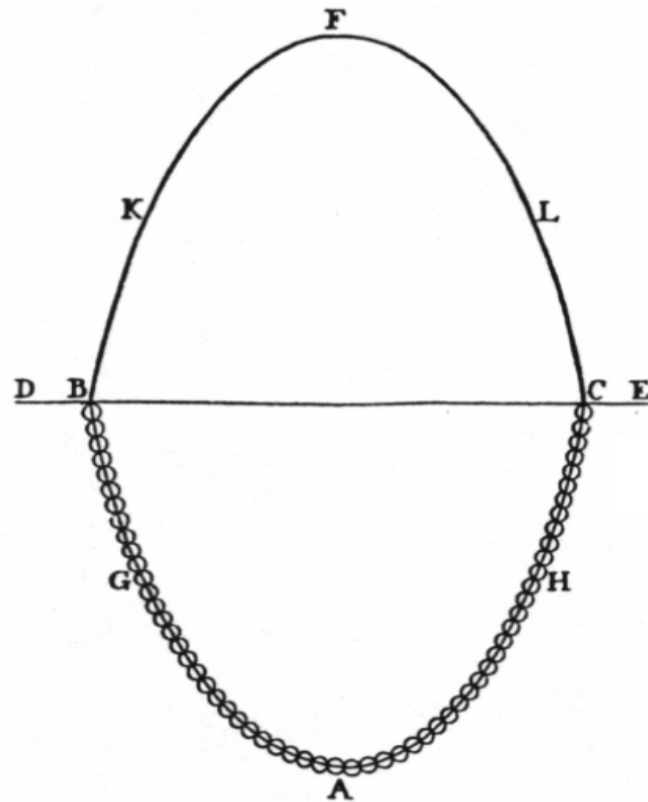


Figure 2.4 Hooke's hanging chain (Heyman 1995)

The main functions of an arch are carrying the load and transferring it to the piers or walls safely. The so called “arch action” is the main load-bearing principle for arched structures. It creates compressive stress internally and a pair of forces externally, which tries to push the supports apart. Generally, only compressive stresses occur under self-weight in the arched structure – and this is – through a virtual path, which is called the “thrust line”, located within its thickness.

The thrust line is a theoretical line, which represents the path of the resultants of the compressive forces along the structure. This line is a guide for engineers and architects to determine the correct arch shape. If the thrust line moves outside the middle third of cross section, which is called the central core, cracks occur due to tensile stresses. As long as the thrust line is inside the thickness, the arch safety is preserved. In

the old practice of design for the ideal arch shape, graphical methods were employed. The arch structure was drawn to scale. Then the arch was considered to be an ensemble of many rectangular blocks. By changing the shapes and locations of these blocks and with many trials, the engineer was able to come up with an ideal arch with the thrust line within the central core. Of course, the process had to follow certain constraints including the locations of the connection of the arch to the foundations, the span length and load points.

The superposition of the thrust line for a few arched structures is shown in Figure 2.5 (Gedik 2008, Ramage et al. 2008). Engineers have used the thrust line in many forms. Throughout the nineteenth century, they tended to ignore the element of uncertainty in an arch and discovered the best line through the structure. Gaudi, in the early 20th century went further and modeled an assumed thrust lines first, and then inclined the material around them so that the thrust was in the center of the structure. (Harvey and Moulder 2001).

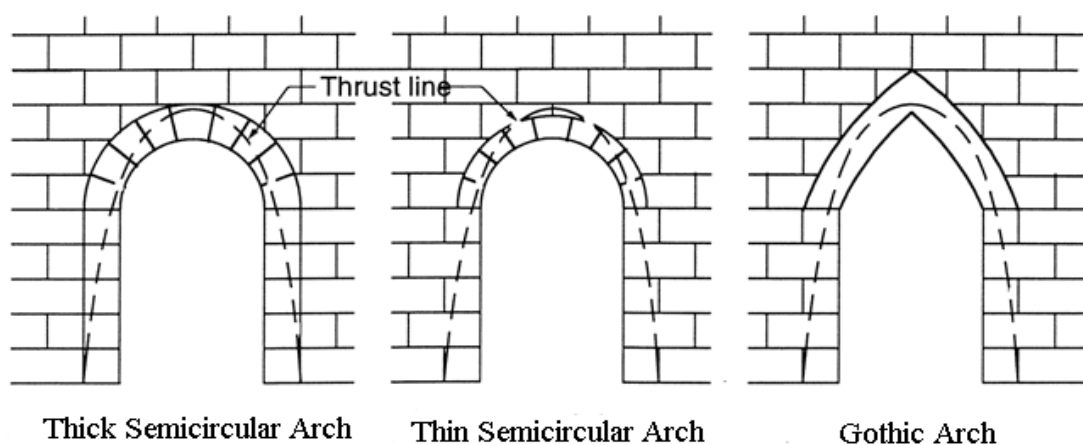


Figure 2.5 Thrust lines for some arched structures

Figure 2.5 especially depicts cases of parabolic curvatures in arches. Parabolic curvatures, when loaded with symmetric loads, have the ability of carrying axial forces

only. And as such, no bending moment occurs in the arches owing to its curvature properties. However, because of the interaction with other components, and the fact that the load is almost never symmetric, the bending moment will always be present. In addition to the bending moments, there are also horizontal thrusts in arches, especially in complex structures. All these conditions will impose tensile stresses in the cross sections of the arch structure. Since increasing the dead loads reduces the tensile stresses, cross-section dimensions of arches are often very large. This is especially true in historic masonry structures, where the contribution from the self-weight was recognized by engineers in maintaining the stability of arches (Gedik 2008).

A practical loading on arches in bridges is vertical uniform loading and hence the thrust line is often parabolic. The semicircular is therefore, not the best shape to use in a bridge. Nevertheless, semicircular arches were commonly used during the Roman period (300 BC to AD 365), probably due to the simplicity in setting out the shape rather than any notion of the thrust line configuration. The semicircular arches that survived evidently did so, because they were thick enough for the roughly parabolic thrust line to be contained within the arch (Sánchez 2007).

After choosing the shape of the arch, the most important step is determining the arch thickness. Many engineers and scientists have analyzed different arch shapes and their thicknesses in an effort to design an efficient system for carrying the applied loads. Hence many approaches have been proposed and various equations were established regarding the selection of the minimum thickness for arches. In 1669, Honoré Fabri, a French scientist, published a geometrical arch model and offered a set of equations for

arch structures. According to Fabri, the thickness of the arch e subject to the extrados radius R could be estimated (Kurrer 2008)

$$e_1 = 2R(3 - 2\sqrt{2}) = 0.343R$$

and the radius of the intrados r was given with

$$r = R(4\sqrt{2} - 5) = 0.657R$$

After Fabric's equations, in 1730 Pierre Couplet introduced a thickness value based on the following equation (see also Figure 2.6).

$$e_{u,Couplet} = 0.101.R$$

In 1982, Jacques Heyman suggested a minimum value for the arch thickness using the following equation.

$$e_{u,Heyman} = 0.106.R$$

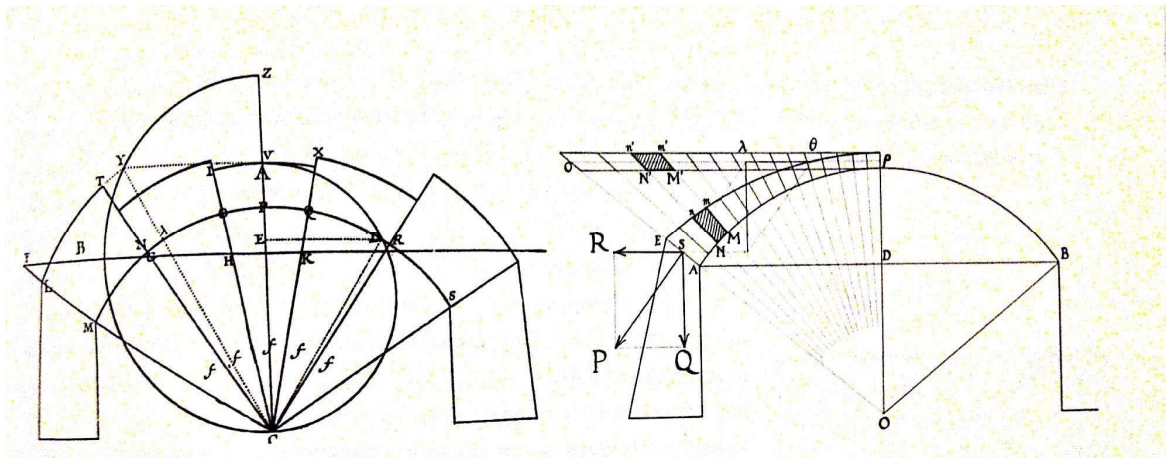


Figure 2.6 Couplet's determination of the position and size of the arch (Kurrer 2008)

According to Kurrer (2008), masonry arches that have thicknesses lower than Couplet thickness value will be unstable. In addition to these equations, empirical rules and equations have also been developed and suggested for arch thickness. Especially in

the 19th century, many such equations were published suggesting models for minimum arch thickness. These equations are listed in Table 2.1.

Table 2.1 Different empirical arch thickness formulas (Proske and Gerder 2009)

Dupuit for segmental arches	$e = 0.15 \cdot l^{0.5}$
Dupuit for semi-circular arches	$e = 0.20 \cdot l^{0.5}$
Rankine	$e = 0.191 \cdot R^{0.5}$
Gauteir for semi-circular arches	$e = 0.32 + 1/15l$
Perronet for semi-circular arches	$e = 0.325 + (1/24 - 1/144) \cdot l$
Lesguillier for semi-circular arches	$e = 0.10 + 0.20$
Dejardin for semi-circular arches	$e = 0.30 + 0.045 \cdot l$
Derjantin for circular arches	$e = 0.30 + 0.025 \cdot l$
Dejardin for elliptical arches	$e = 0.30 + 0.014 \cdot l$
Further equation	$e = 0.2 \cdot l$
German and Russian engineers for segmental arches	$e = 0.43 + 0.1 \cdot \rho$
Perronet	$e = 0.325 + 0.0694 \cdot \rho$
Perronet for semi-circular arches	$e = 0.325 + 0.035 \cdot l$
Lesguillier for segmental arches	$e = 0.10 + 0.20 \cdot l^{0.5}$
L'Eveille for segmental arches	$e = 0.33 + 0.033 \cdot l$
German and Russian engineers for semi-circular arches	$e = 0.43 + 0.05 \cdot l$
Gauthey semi-circular arches	$e = 0.33, l < 2 \text{ m}$ $e = 0.33 + 0.020833 \cdot l$
Gauthey semi-circular arches	$2 \text{ m} < l < 16 \text{ m}$ $e = 0.0416 \cdot l$
Gauthey semi-circular arches	$16 \text{ m} < l < 32 \text{ m}$ $e = 1.33 + 0.020833 \cdot (l - 32 \text{ m})$
Gauthey semi-circular arches	$l > 32 \text{ m}$
E.Roy for semi-circular arches	$e = 0.30 + 0.04 \cdot l$
Michon for semi-circular arches	$e = 0.40 + 0.04 \cdot l$

R – Radius of the circle passing through the crown joint and the intrados springing in metre,

l – Span in metre, e – Key stone thickness in metre, ρ – Curvature radius

for segmental arch bridges $\rho=1/2$, full circular arch bridges $\rho = \frac{l^2}{8 \cdot f} + \frac{f}{2}$, and elliptical arch bridges $\rho = \frac{l^2}{4 \cdot f}$

f – the ratio of the rise

2.2 Spandrels

With respect to engineering and architectural terminologies, spandrels are almost triangular spaces between one side of the outer curve of an arch, a wall and the ceiling or framework (OED 2011). In other words, the spandrel is a wall which is between the extrados of the arch and the roadway. Figure 2.7 depicts an arch bridge with spandrel walls.

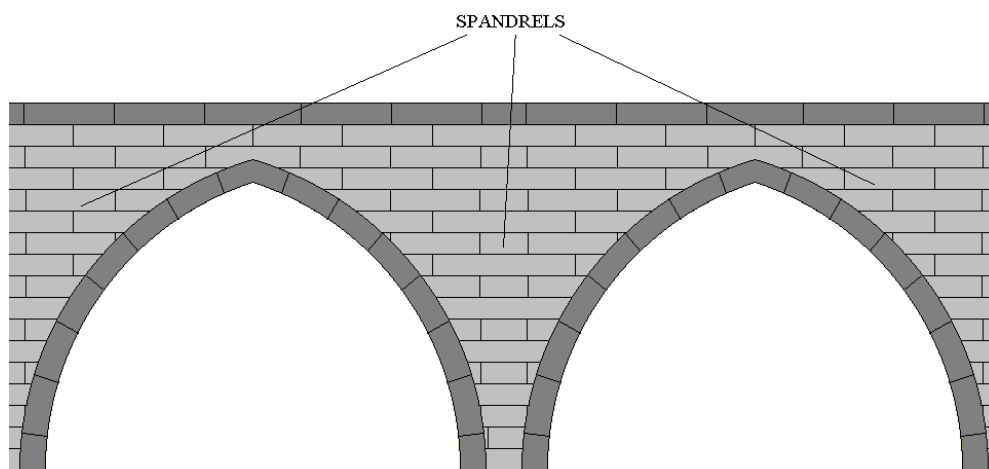


Figure 2.7 Spandrel walls in the masonry arch bridges

The primary functions of the spandrels walls are to increase stability. They act as retaining walls for the backfill material and will enhance the structural integrity of the bridge. Additionally, spandrel walls typically play a structural role in masonry bridges, transferring load from the deck slab to the supporting arch. In some cases, the spandrel walls have an arched geometry in plan, which boosts their capacity to resist the outwards pressure of the backfill by adding a longitudinal arching effect to gravity wall action (McKibbins et al. 2006).

In the simplest and possibly the most common case, the spandrel space is occupied by backfill materials. The material used to fill this space varies very

significantly and will depend on what was available locally at the time of construction. In general, the backfill material consisted of what was excavated (to build the foundations) mixed with rubble. As it is evident from bridges in use today, the rubble was primarily made up of randomly shaped stone; although well compacted and treated (to improve its strength). In most cases, after many years of compaction because of repeated applications of the loads in service, the backfill materials have gained a significant strength and possibly some degree of adhesion. In addition to this, the space near the haunches and the space above intermediate piers in multi-span bridges are backfilled with cementitious materials. Finally, when the arch and spandrels are completed, large-size stones are placed between the spandrel walls to form the roadway. This also has a positive effect on the stability of the structure (McKibbins et al. 2006, Ozer 2004).

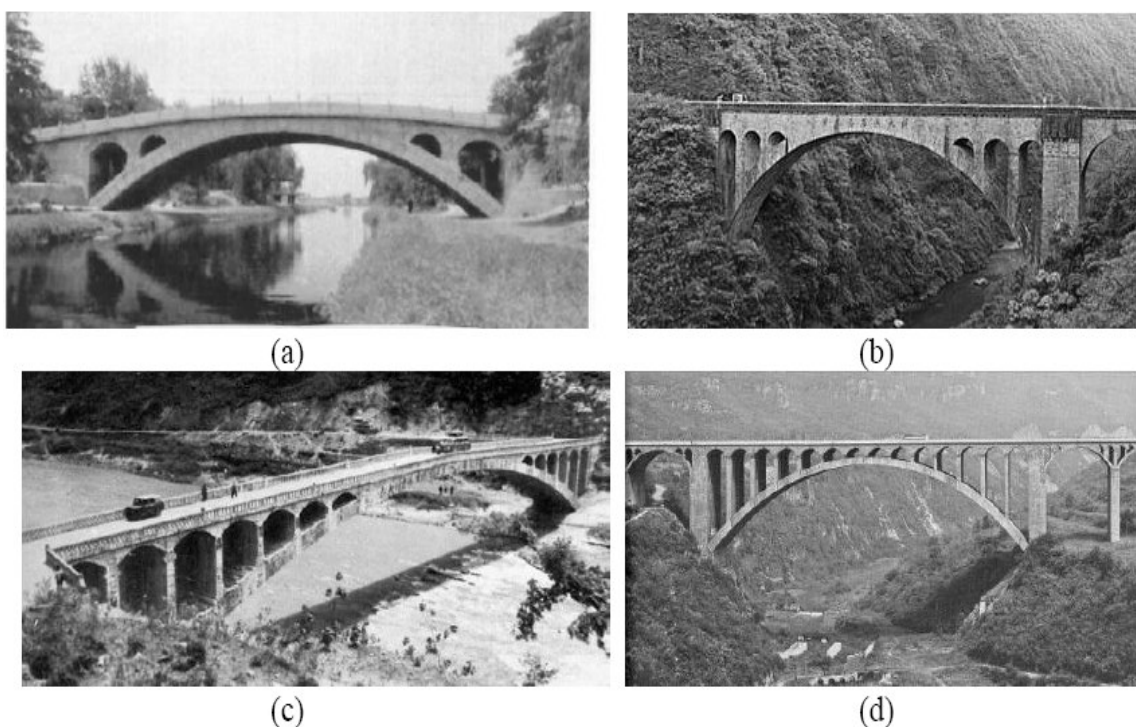


Figure 2.8 Some examples of open spandrel bridge in China, (a) Chawzhou Bridge, (b) Huanghugang Bridge, (c) Jiuxigou Bridge, (d) Danhe Bridge) (Wang et al. 2010)

In general, while the solid spandrels can appear in the traditional masonry arch bridges, sometimes the open spandrels can be seen in modern (steel and concrete) and masonry arch bridges. Especially, open spandrel masonry arch bridges (Figure 2.8) have been widely used since early 600 A.D. in China and the seventeenth century in Europe. However, no such structures have been constructed in the last one hundred years in the West while the practice of building such structures in China has continued through up to present day (Harding et al. 2010).

2.3 Piers and Abutments

Piers are wide columns which support the intermediate parts of multi span bridges and share the loads with abutments. Abutments are wide columns or walls which support and keep the parts on the land intact (Figure 2.9). While the piers may be placed on firm ground around the middle of a river, the abutments are placed at the ends of bridge (Khan 2010).

The piers have dual functions. One is carrying the vertical loads such as dead load and live load; and the other is resisting the horizontal loads such as wind loads, creep movements and water flow effects. Because of these, the piers must be designed safely to transmit the loads to the foundations and to the ground and also to resist any lateral loads due to wind or flow of the stream. The most common form for piers in streams is rectangular which has triangular or curved ends (Figure 2.10). The pointed ends below high water are known as starlings and are intended to reduce the disturbance to the stream flow and sometimes to act as ice breakers. Sometimes starlings are used only on the up stream end of the pier, but more commonly the horizontal section is made symmetrical (Spalding 1921).

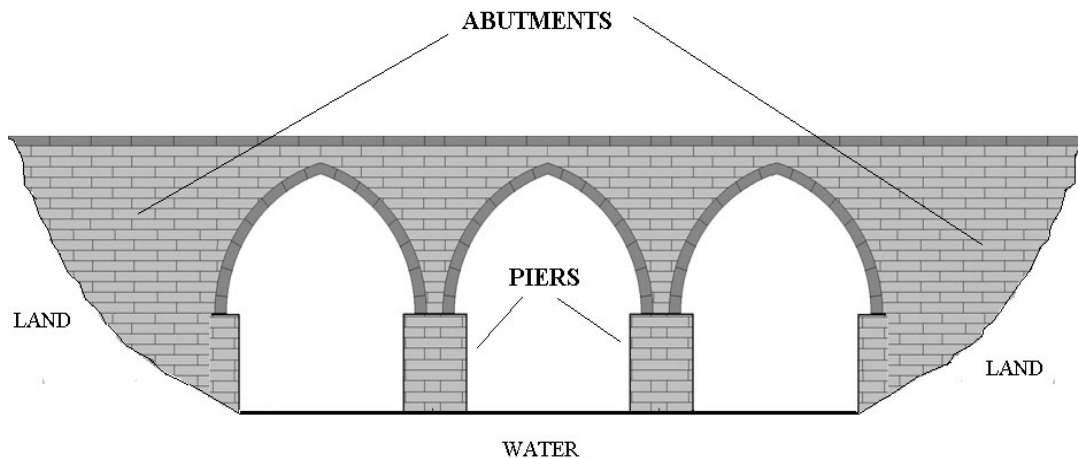


Figure 2.9 Abutments and Piers in the masonry arch bridges

Large masonry piers are generally built as hollow systems. As stated above, the masonry under the superstructure is considered to act as columns which transmit the vertical loads to the foundations; and the center part of the pier is regarded as bracing to stiffen the columns and carry the lateral loads. A part of the masonry at the center of pier may be extracted without appreciably reducing its strength, thus decreasing the weight upon the foundation and saving a considerable volume of masonry. Such an arrangement is shown in Figure 2.11 (Spalding 1921).

A bridge abutment is a structure that supports one end of a bridge span and at the same time supports the embankment that carries the vehicle or roadway. It carries the weight of ends of the bridge with its moving load and retains the embankment sustaining the roadway loading to the bridge. The requirements for stability of abutments are the same as those for a retaining wall.

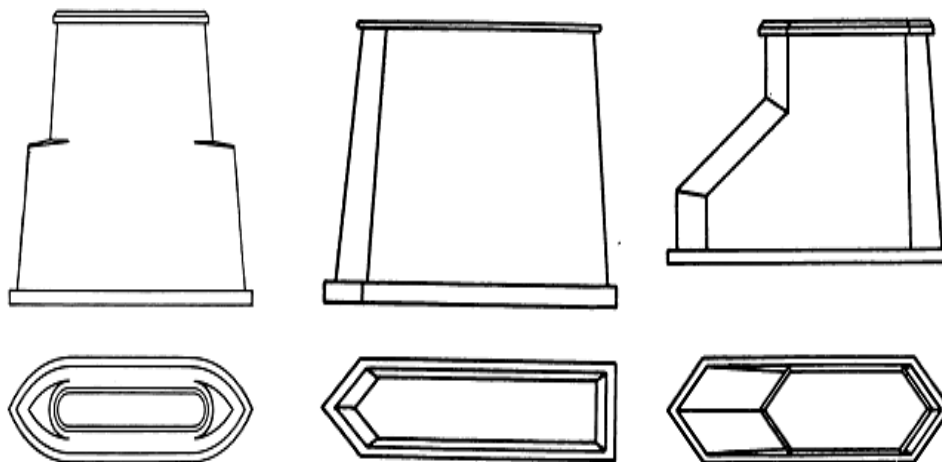


Figure 2.10 Some pier shapes (Spalding 1921).

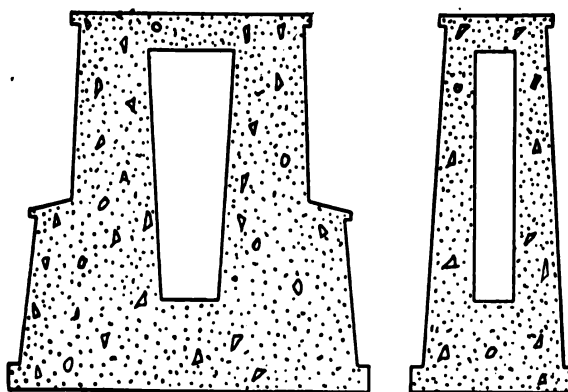


Figure 2.11 Hollow spaces in piers (Spalding 1921).

An abutment also usually protects the embankments from scour effects of the stream. Scour is especially accelerated with the speed of the flow and accumulation of debris. A bridge abutment not only must help reduce the scour effect, but also must be stable against overturning, sliding, and crushing the material on which the abutment rests. The abutments may be divided, according to the method used for supporting the side slopes, into straight or stub abutments, wing abutments, U abutments, and T abutments (Figure 2.12) (Spalding 1921, Ketchum 1919).

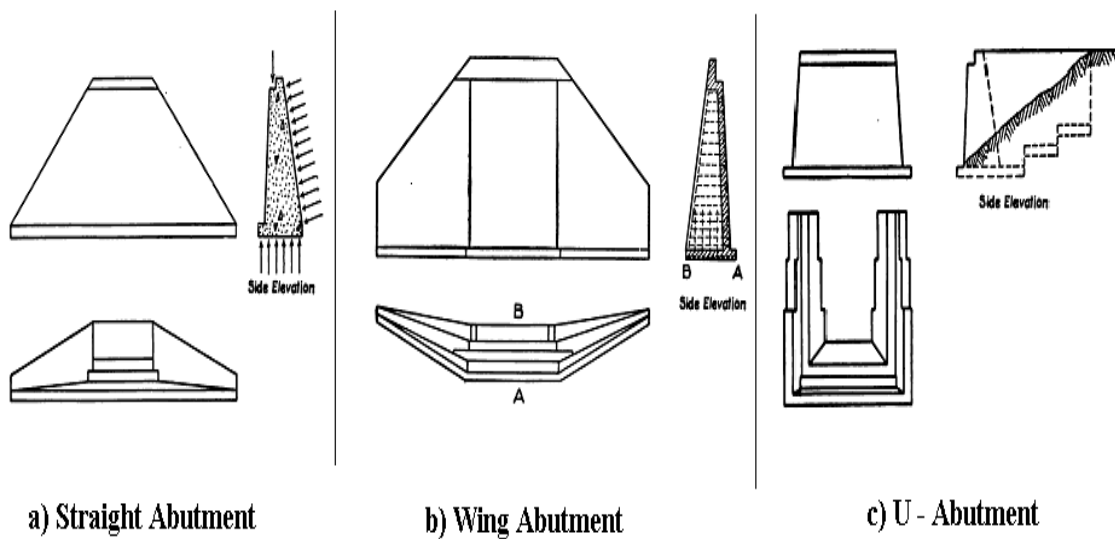


Figure 2.12 Some examples of abutment shapes (Spalding 1921).

2.4 Foundations

Technically, the foundation is the lowest part of a bridge that meets the ground. All loads such as dead load, live load, lateral load are transferred to the supporting soil via foundations. Also they help reduce the pressure/loading on a soil by spreading it over a larger area or transferring it to a stronger layer of soil (Anonymous 2011a). In older practice of stone arch bridge design, the foundations were taken as being the end parts of the arch. The graphical method for design also included the treatment of the thrust line into each foundation and within the foundation middle third of its cross section. Masonry bridge foundations have been built with different materials, workmanship, and construction techniques in different historical periods. However, it is always preferred to be constructed on strong soil in all forms. It can still be arranged in three different types - foundations that rest on: (1) rocky soils, (2) masonry floors, and (3) timber piles or rafts (KGM 2009).

a) Foundations on rocky soils

In this type of bridges, the foundation sits on rocky soils or the ends of cliffs. This type of foundations directly transmits the entire load to rock. Generally, these foundations can be seen in masonry bridges which are constructed to link two sides of a cliff (Figure 2.13, Figure 2.14).



Figure 2.13 The Buttes Chaumon Bridge in France



Figure 2.14 Malabadi Bridge in Turkey

b) Foundations on masonry floors

This type of foundations is one of the most existing types for masonry arch bridges. The piers and abutments sit on multiple layers of masonry foundations. Each layer is bigger than the layer on top of it. That is, the masonry bridge is gradually widening towards the ground (Figure 2.15). Generally, these foundations can be seen under the piers of multi-span bridges (Figure 2.16).

c) Foundations on timber piles or rafts

Timber piles have also been used for masonry arch bridges. Timber piles have successfully supported structures for more than thousands of years. The total weight of the bridge and its imposed loads divided by the permissible pressure of the soil gave a required area of spread greater than the area of the bridge site. Timber piles are ideal solutions for bridge foundations located at sites with weak soil properties (Figure 2.17).

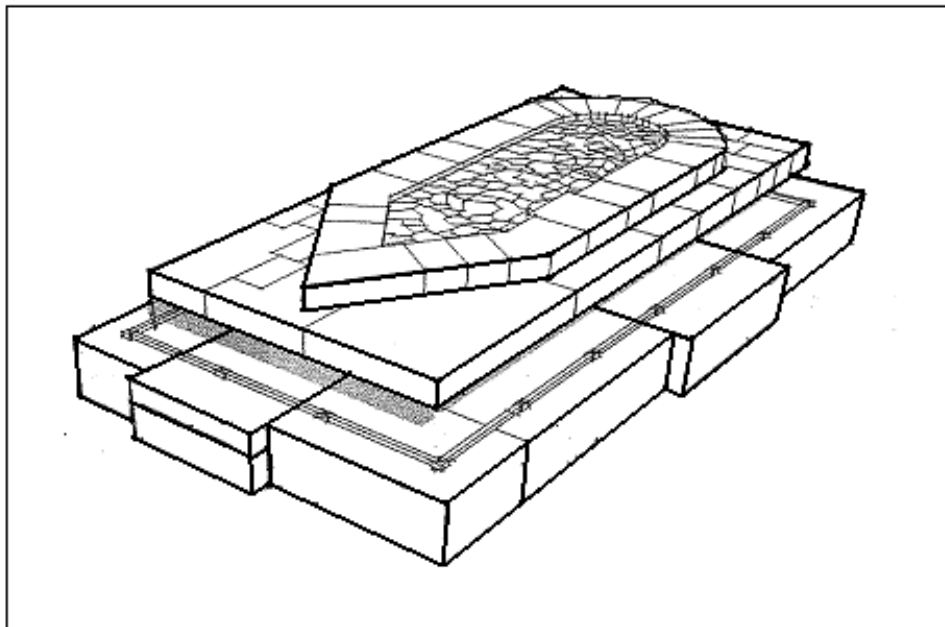


Figure 2.15 The foundation model of the Aspendos Bridge in Turkey (KGM 2009)

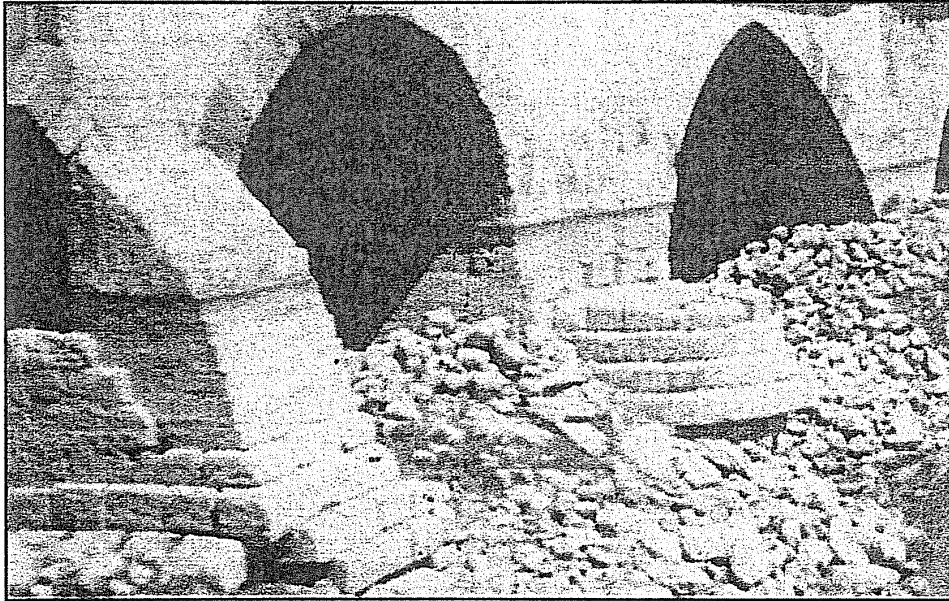


Figure 2.16 Multiplex foundations (the foundations are exposed due to the scour effect of streams) (KGM2009)

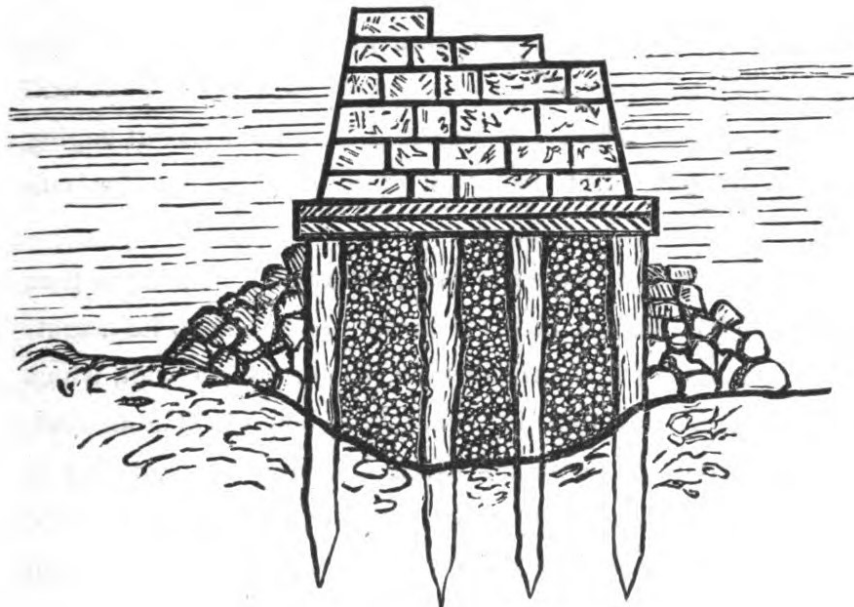


Figure 2.17 Timber piles in masonry bridge (Hasley 1883)

Timber has also been used as a shallow foundation for masonry bridges. Timber rafts are used when surface soils are sufficiently strong and rigid to support the loads (Figure 2.18). They are used to spread the loads from a bridge to the strong soil. Timber

rafts are generally unsuitable in weak or high compressible soils such as poorly compacted fill, peat, and alluvial deposits (Anonymous 2011b).

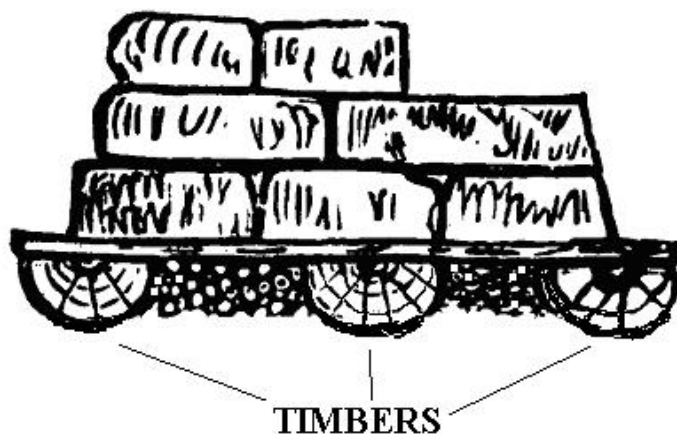


Figure 2.18 Timber raft foundation in masonry bridges (Hasley 1883)

2.5 Construction Materials

Initially, historic arch bridges were built with simple methods by making forms and shoring using materials such as turned down trees or one-piece rock segments. With the development of architecture and engineering, the construction method for masonry arch bridges underwent changes. In general, the significant changes in construction methods and materials for bridges occurred when builders started using, bricks, stone blocks and mortars (see Table 2.2).

Generally, while stones and bricks may be main construction materials, mortars and timbers may be secondary. This means that stones and bricks are load bearing materials but mortars and timbers are connective, load spreader and used as part of the integrity of the finished product. For the most part, mortars have been used for bond between blocks; while timber has been used for transmitting loads to strong soils as a

foundation component. In the following sections, the construction materials are discussed with their special features and properties.

Table 2.2 Construction materials for masonry bridge engineering

Material Type	Improvements over years
Stones	Natural stone was gradually replaced with stone blocks prepared for easy handling and bond with mortar
Bricks	Manufactured brick was introduced reducing labor time and cost
Mortars	Provided for strong bond between brick or stone blocks
Timbers	Shores and forms from trees were replaced with better sections and eventually with treated wood

2.5.1 Stones. Stones have been the most important and oldest construction material for masonry bridges for centuries. It has been used since the earliest times of civilizations in regions where stone was locally available. Masonry bridges have been built generally from stones that are potentially very solid, durable and strong. Also the strength of stone is higher than other construction materials; but there has been a tendency to rely on the quality of locally-available materials and the skill of masons. The quarrying, selecting, weathering and shaping of stone are very labor intensive and dependent on the employment of skilled and knowledgeable craftsmen. Stones may be classified according to their origin into genetic systems. This system divides three major groups. There are listed in Figure 2.19 (McKibbins et al. 2006).

Masonry structures that are built in the same period in history use same materials and the same masonry. Many stone types have been used as a main building material in

historical masonry structures for centuries. For example, sediment stones such as sandstones and limestones have been most commonly used in masonry arch bridges for centuries because of their malleability and softness. Although igneous stones are harder than sedimentary stones and not as malleable, they have also been used in early times for structures. Granite, for instance, was already used as a masonry building material by the Romans in the earliest centuries (Figure 2.20) (Proske and Gelder 2009).

MAJOR GROUP	SUB-GROUP	EXAMPLES
Igneous	Plutonic	Granite
	Volcanic	Basanite
	Matrix	Gabbro
Sedimentary	Clastic sediments	Sandstone
	Chemical sediment	Lime stone
	Biogenic sediment	Chert
	Residual stones	
Metamorphic		Mica Schist

Figure 2.19 Classification of stones (Proske and Gerder 2009)

Natural stones are generally rough and irregular in shape. Sometimes, there are great disparities in the size and shape of these stones. Thus, masonry was directed to form stones. The size and shape of stones depend on their strength and workability. While some stones could be hard and less workable by hand, others could be fragile and very easy to give a shape. Thus, ancient masons sometimes used the random rubble and irregular stones or sometimes they gave a shape to stones by various hand tools (Table

2.3) and procured regularly shaped stones from irregular and rubble stones. Modern technologies have greatly improved the efficiency of cutting stone and workmanship.

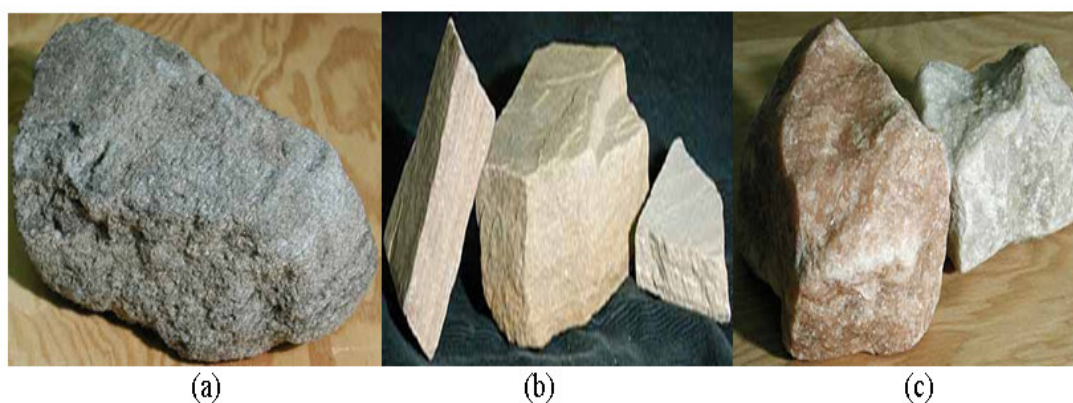


Figure 2.20 Some stone examples (a-Igneous, b-Sedimentary, c-Metamorphic)
(Anonymous 2011c)

Table 2.3 Stone types and cutting tools (Proske and Gelder 2009)

Name	Pointed	Flattened	Pilled	Charring	Wide charring
	1st action		2nd action		
Muster					
Tool					
Time	Until middle of the 11th century	Until beginning of the 12th century	End 12th until End 13th century	Middle 15th to end 17th century	From middle 17th century

2.5.2 Bricks. Bricks are one of the most common materials for masonry structures. Bricks have been widely used in masonry bridges and aqueducts for centuries. Earlier bricks were manufactured from mud, clay and shale. Because of this reason, bricks may be considered to be the first prefabricated building material. Bricks made from mud are the oldest discovered handmade bricks (discovered in Diyarbakir, Anatolia before 7500 B.C). Other examples of mud brick utilization have been encountered in the ancient

Egyptian and Babylonian civilizations. The Romans also preferred different type and different shape bricks for many architectural constructions such as buildings, aqueducts, domes and bridges (Figure 2.21). Generally, the Romans made sun dried and burnt bricks and later they developed mobile kilns for making bricks (Anonymous 2011d).

Bricks are cheap and valuable masonry materials. It may be produced with high strength, less weight and low water absorption. Although they are as strong as stones, they could be affected by humidity and temperature change. The quality of the bricks depends on the main material and correct production process. The best material for brick making is clay. The clay brick making process can be achieved through four main stages which are winning the clay, shaping the brick, drying the brick and firing the brick (Sowden 1990).



Figure 2.21 The Roman aqueducts in Nimes, France

After clay has been removed from the ground, it is separated from other materials such as soils, plants, sand powders and shaped by hand or machines. Generally, shaped bricks are dried under the sun and as the last step, dried bricks are fired with very high temperature in bricks kilns. They are produced in many different forms and types (Figure 2.22). Generally, we can outline four types of bricks as summarized in Table 2.4.

2.5.3 Mortars. Mortars are the bonding material between stones or bricks. It is an integral part of masonry structures and generally is used to fill the gaps between construction blocks (mortar joint) and to strengthen the structures. It also brings resistance to the masonry structures against air and water penetrations.

Table 2.4 Types of masonry bricks (Hendry and Khalaf 2001)

Type of Unit	Description
Solid	A brick which may have perforations not exceeding 25% of its volume or may have indentations (frogs) on one or both bed faces
Perforated	A brick which has a pattern of small holes through it comprising more than 25% of its volume
Cellular	A brick in which the holes comprising more than 20% of its volume are closed on one face
Hollow	A brick having large holes through it comprising more than 25% of its volume

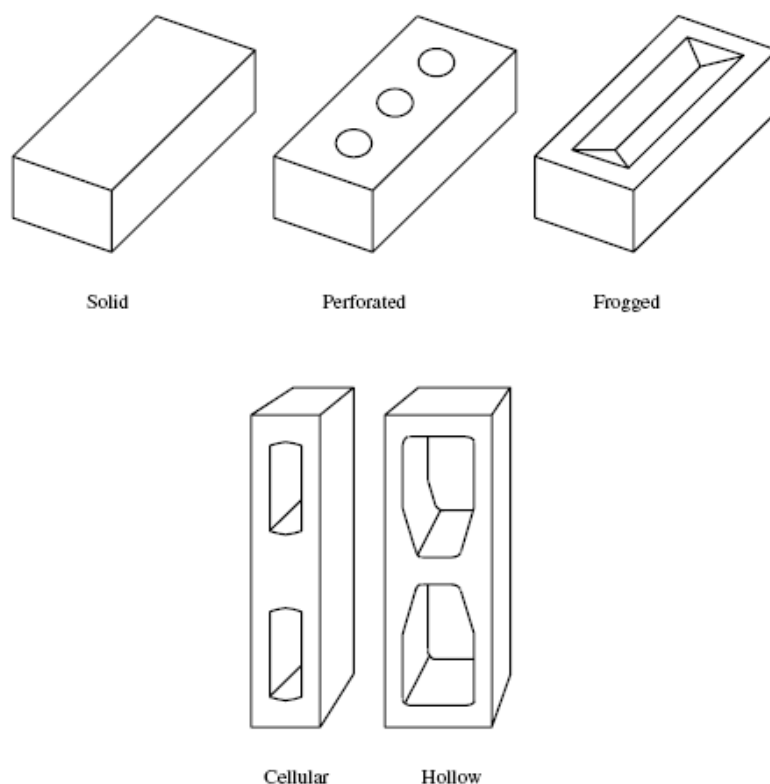


Figure 2.22 Common types of bricks (Hendry and Khalaf 2001)

Among the most important properties of mortars are workability, cohesiveness, resistance to external force and easy spreading. The volume of mortar depends on masonry types; but generally this amount is between 0 and 20 percent in the total volume of masonry. Despite its small volume, the mortar is very effective and important for masonry structures. When it is first prepared, mortar is in a plastic form and then it starts to stiffen rapidly (Figure 2.23). In the course of time, it reaches the hardest form (Sowden 1990, McKibbins et al. 2006, Hendry and Khalaf 2001).

Mortars are produced by mixing sand, lime, cements and water. In their traditional forms, mortars were produced by mud, clay and fat lime. The first examples for lime mortars were discovered around the Babylon; however, the Egyptians improved the mortars and used lime and gypsum mortars to build the pyramids. The historical masonry

bridges were generally built using lime mortars. However, the Romans developed the cement and it has been the dominant material for mortars. (Sánchez 2007).

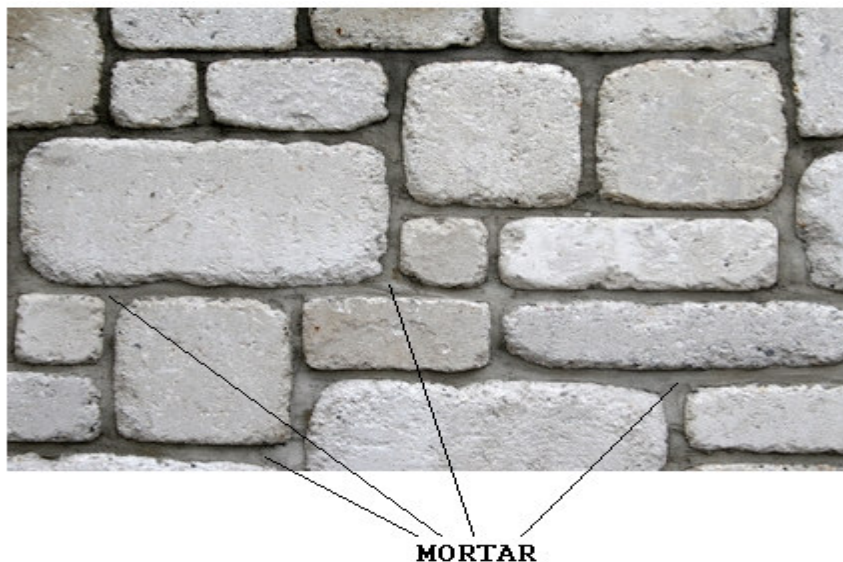


Figure 2.23 The hardest form of mortar after application for stone structure and its volume

The strength of the masonry structures depends on the mortar physical properties. Bond strength and binding characteristics of the mortar affect the building performance considerably. Nowadays, with the development of new building materials and chemicals, many chemicals and substances, which are organic and inorganic, are added to mortars in order to increase physical and mechanical properties. Especially, the modern mortars may include bitumen, brick/stone dust, natural cement and pigments. Because of these reasons, one may find many different mortar types and mixtures. Their performance and properties may depend on the properties of materials which form a particular mortar mixture. The most common mortar type for masonry structures is mixture of cement, sand, water and various chemicals added to control their properties (Gedik 2008).

2.5.4 Timber. Timber is one of the oldest known structural materials. It has been used as the main and helper material to masonry structures for thousands of years. Timber is encountered as a pile or raft foundation (Figure 2.24) and scaffolding for masonry bridges. In addition, masonry structures are sometimes supported by timber shoring. Although today the use of timber as a structural element is reduced in bridge structures, in terms of historical masonry bridge timber was one of the most important building materials.

Generally, timber materials could decay in the bridge foundation; besides, there may be damages and cracks from overloading, stroking and crushing. However, timber materials are easy to use and may be obtained from natural environmental and sustainable sources. In addition to these, it is cheaper than other structural materials. Timber materials have been formed from several tree species. The most commonly used kinds are oak, beech, walnut and chestnut tree. Contrary to stones, timbers resist to tensile and compression forces. Therefore, it may be used as a horizontal bearing member.

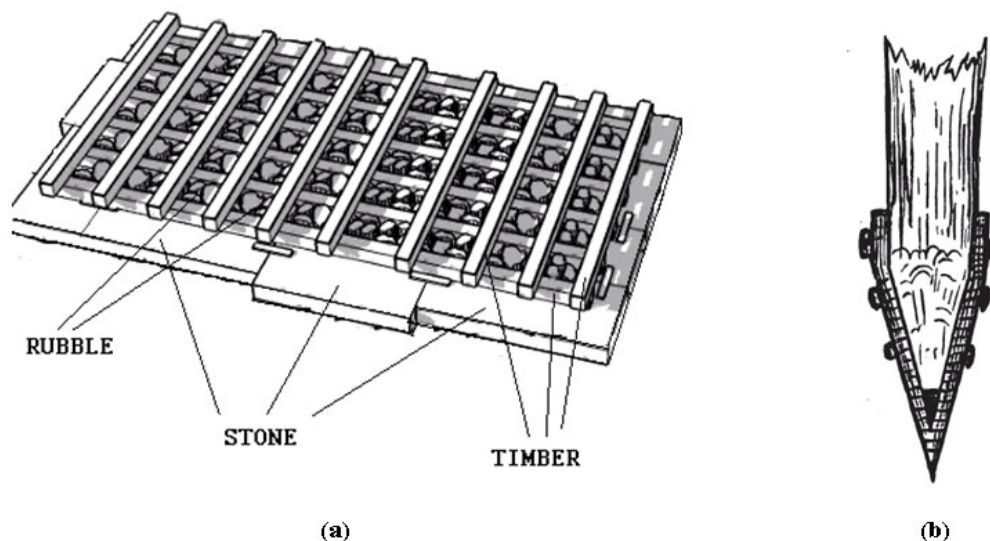


Figure 2.24 The timber raft foundation for masonry bridges (a) and the timber pile elevation drawing (b)

CHAPTER 3

STRUCTURAL BEHAVIORS OF MASONRY ARCH BRIDGES

This chapter reviews the structural behavior of masonry arch bridges and investigates their integrity. Essentially, understanding of structural behavior of masonry arch bridges offered to be a very complex issue to early masonry bridge builders. Since the end of 17th century, the structural behavior of the masonry arch has been broadly studied by engineers. However, engineers have not reached any consensus regarding the true behavior of this group of structures (Blasi and Foraboschi 1994). According to Wu (2010), “predictability of structural behavior of masonry arch bridges is still widely considered doubtful”. The purpose of this chapter is to identify loads on masonry arch bridges and classify causes of masonry bridge failures. This is through understanding the structural behavior of masonry arch bridges.

3.1 Loads on Masonry Arch Bridges

As it is known, ancient masonry arch bridges have been safely used as a transportation link to carry vehicles, trains, cars or pedestrians for years. Those in use today indicate their durability and strength in keeping up with the changes in the applied load types and intensity. In order to better understand the performance of these bridges and how they have been able to survive changes in the loading regime, an understanding of their load carrying capabilities and an estimation of the type and intensity of load on them would be needed. Major loads on masonry bridges are dead loads, live loads, lateral loads, and water and earth forces. The fact that many masonry bridges have been able to keep up with these loads and changes occurring to them is a testimony to the complexity

of their structural behaviors. The following section covers a description of various types of loads. This is followed by an overview of the overall performance of masonry bridges in carrying these loads.

3.1.1 Dead Loads. Dead loads consist of the weight of bridge components and the weight of permanently attached objects. Dead loads always remain on the bridge and affect the structure during its life. They also exist in the same position and constant magnitude. Because of these reasons, dead loads are sometimes called permanent loads or gravity loads. Dead loads often act vertically on the bridges and they cannot affect a lateral motion (Figure 3.1). Furthermore, dead loads are static loads and these loads provide for the stability of masonry arch bridges (McKibbins et al. 2006). Although the dead load is merely referred to as the structure's weight, superimposed loads are also classified as dead loads. Superimposed loads are generally placed on the superstructures and they are objects permanently attached to the bridges such as parapets, partitions, railings, utilities and other miscellaneous attachments (Tonias and Zhao 2007).

Structure's own weights and superimposed loads are often easy to compute; and they generally comprise of the construction material weight such as stone, brick, mortar, steel and timber structural members. According to the American Association of State Highway and Transportation Office (AASHTO) Standard Specification for Highway Bridges (2002) and AASHTO Load Resist Factor Design (LRFD) Bridge Design Specifications (2004), the unit weights of some materials are given in Figure 3.2.

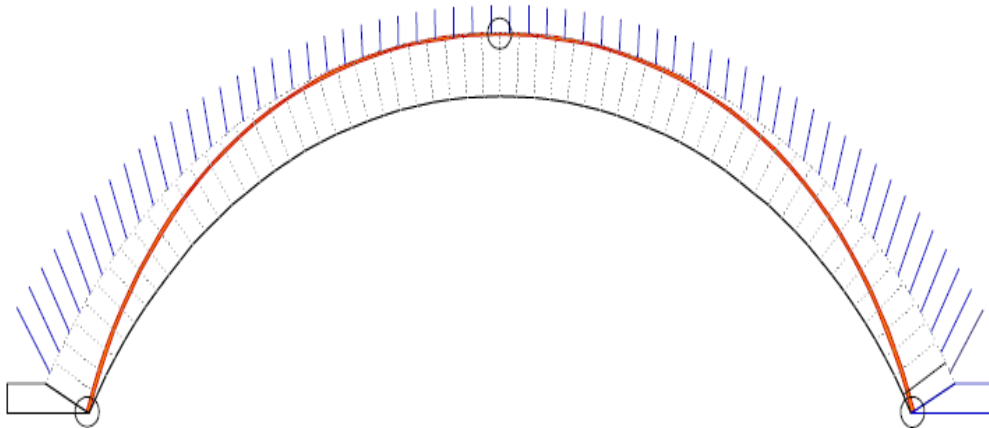


Figure 3.1 Effect of Dead Load (Unknown Reference)

MATERIAL		UNIT WEIGHT (lb/ft ³)
Aluminum Alloys		175
Steel		492
Stone Masonry		170
Wood	Hard	60
	Soft	50
Reinforced Concrete	Low Density	110
	Sand Low Density	120
	Normal	150
	HPC (10-16ksi)	155
Compacted Sand, Silt or Clay		120
Earth	Sand and Gravel, dry	100
	Sand and Gravel, wet	120
	Clay, damp	110
	Silt, mist, loose	78
Marble		156
Sandstone		137
Granite		153
Water		62

Figure 3.2 Unit weights of materials for computing dead load (Adapted from AASHTO 2002)

3.1.2 Live Load. Live loads consist of the weight of the moving loads such as vehicles, cars and pedestrians. They are transient and affect the structure for a short period of time. Their effect also creates a dynamic action on the bridge in the form of vibration. The vibration may especially be accelerated with the speed of the moving vehicle, structural stiffness, span length and road roughness. Mostly, live load effects on masonry bridges are poorly understood especially with changes that have occurred to the distribution and magnitude of the moving traffic over many years (Figure 3.3). While dead loads can be easily computed, live loads can only be approximately estimated during the life of the bridge because of their changing patterns and intensity.

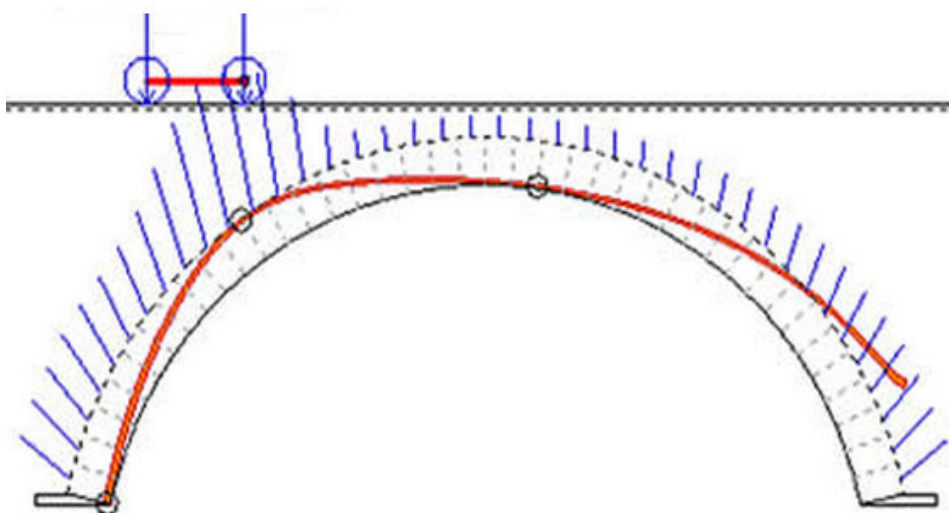


Figure 3.3 Effect of Live Load (Unknown Reference)

The American Association of State Highway and Transportation Officials (AASHTO) Specification specifies live loads due to vehicular traffic on highway bridges. Truck loading causes the heaviest effect on bridges. Therefore, in 1935, AASHTO published a loading scheme classified as H20-35 and H15-35 loading (Figure 3.4). This classification has undergone changes. For example, AASHTO improved H and HS class

trucks and introduced five new truck classes in 1944 (Table 3.1). Figure 3.5 shows AASHTO truck load it also shows H and HS design trucks.

Table 3.1 Gross vehicle weights (AASHTO 2002)

Trucks	Weights (lb)	Weights(kN)
H10-44	20,000	89
H15-44	30,000	133
H20-44	40,000	178
HS15-44	54,000	240
HS20-44	72,000	320

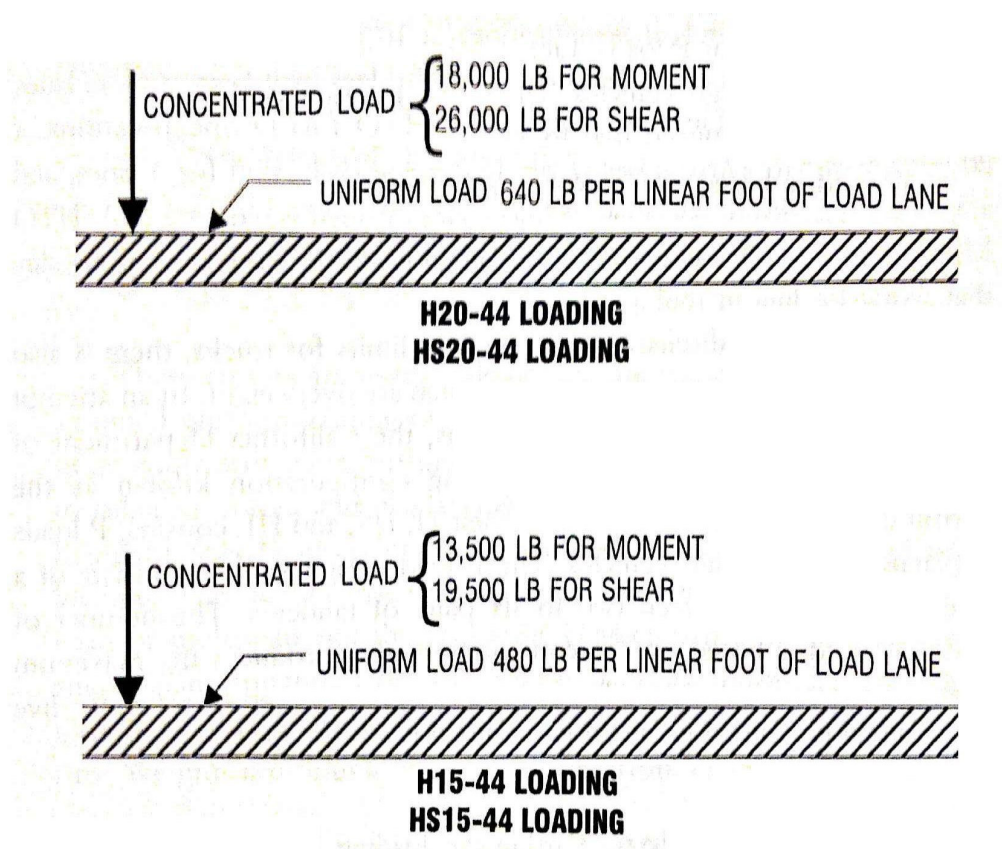


Figure 3.4 AASHTO Standard H and HS lane loadings

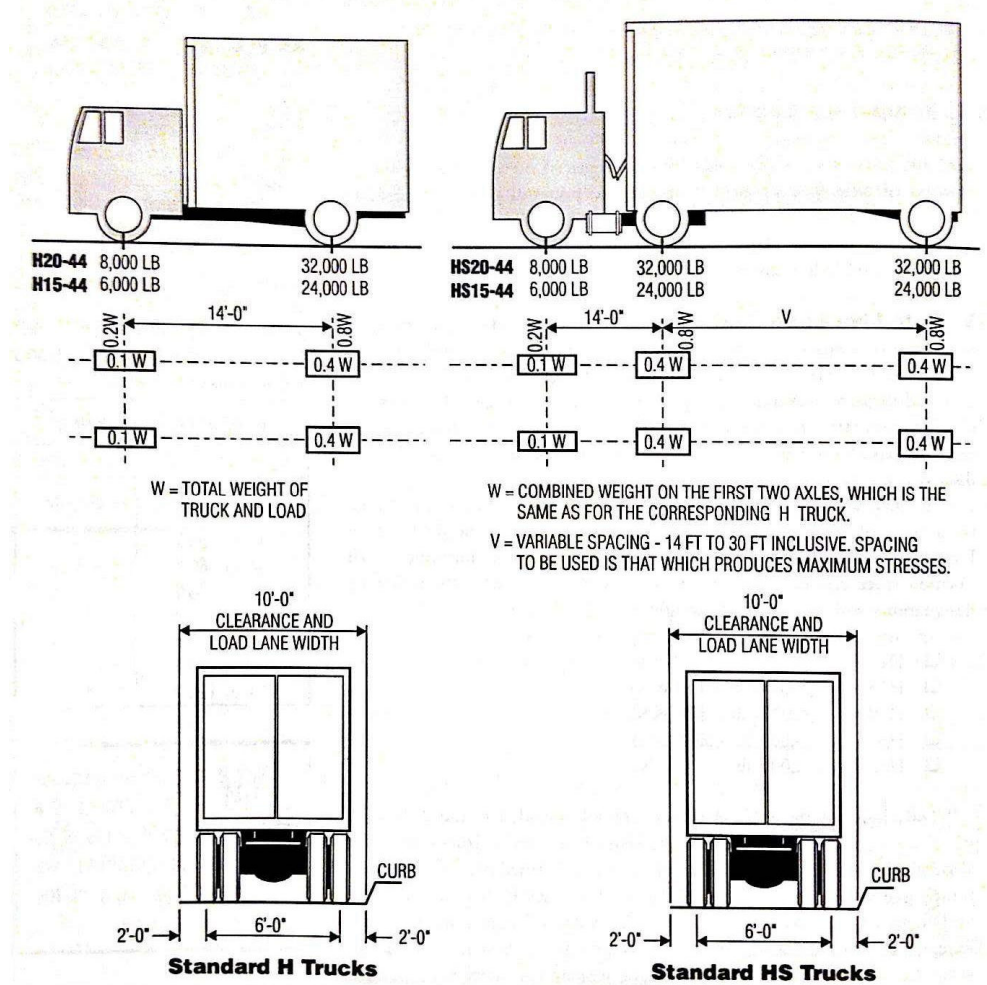


Figure 3.5 AASHTO Standard H and HS design trucks

3.1.3 Lateral Loads. Lateral loads are horizontal loads acting on the structures and are mostly caused by environmental events. Generally, lateral loads would be because of wind, earthquakes, temperature variations and the earth and water pressures.

The most common lateral load is from wind. Wind loads vary by intensity depending on the regions where the bridge is built. Its effect is accelerated as a result of the shape of the bridge and the moving traffic. Theoretically-speaking, wind loads constitute a dynamic force regime. However, the behavior of a bridge structure under

this type of dynamic load is very complicated since the load spectrum and intensity dramatically change with time. To simplify the process of wind load effect on a bridge structure, the wind load is often used as a static load; and the bridge is analyzed accordingly. Furthermore, wind can apply loads to structures from unexpected directions. Thus, a bridge designer must well estimate the dangers implied by wind loads.

An earthquake load is also a lateral load and dynamic in nature. An earthquake load is a function of the mass of the structure and the intensity of the ground acceleration. Since the nature of earthquakes is random, the timing of occurrence and the magnitude of the corresponding loads from earthquake is uncertain. And as such, the potential damaging effects from earthquakes may become more severe than those from the wind loads. Masonry bridges have large masses due to heavy construction materials such as stones, bricks and mortars. Thus, earthquake load significantly affects masonry bridges. The heavy mass increases the intensity of the force on the bridge. At the same time, most ancient masonry structures lack the structural ductility needed to perform well during earthquakes. As a result, the masonry bridges are vulnerable to earthquakes; and seismic effects have been among the most important reasons for collapse among masonry bridges. Earthquake loads are from ground shaking and formation of seismic waves, which usually have two major components -- horizontal and vertical. Recent research shows that the horizontal waves are more dangerous than the vertical waves on masonry structures; and many ancient and newer masonry structures have been destroyed due to horizontal waves (Meyer 2006).

3.2 Causes of Masonry Arch Bridges Failures

Masonry arch bridges have been exposed to many different external and internal effects throughout their lives. Although masonry arch bridges are very durable, some historical bridges in the world have been unfortunately deteriorated, damaged, collapsed or failed due to different effects (Table 3.2). Recently, many researchers have focused on these effects and have investigated basic failure reasons and failure mechanisms of masonry arch bridges (Chajes 2002; Ng and Fairfield 2004; Cavicchi and Gambarotta 2005; Betti et al 2007; Ural et al 2008; Drosopoulos et al. 2008; Felice 2009; Morer et al. 2011).

Table 3.2 The main causes of masonry arch bridge failures

-
1. Earthquakes
 2. Settlement Problems
 3. Flooding and Scours
 4. Overloading
 5. Failures of construction materials
 6. Demolition and Vandalizm
-

3.2.1 Earthquake failures. According to Ural et al. 2008, “the damages due to earthquakes have occurred especially on the mid-span of the main arches as cracking and the separation of the roadway. Stone and other such materials are strong in compression and somewhat so in shear, but cannot resist much force in tension so masonry arch bridges are designed to be constantly under compression. Furthermore lateral loads may

also be applied to the bridges in addition to vertical loads due to earthquake effects in seismic areas. Consequently, lateral displacements may also occur and cause damage.”

According to the reports on earthquake damages on masonry bridges, earthquake damages have been appeared in the spandrels (Figure 3.6) or the superstructures (Figure 3.7).



Figure 3.6 Collapse of spandrel of a masonry bridge during the Umbria-Marche earthquake of 1997



Figure 3.7 Damages occurred in superstructure of the Misis Bridge during the 1998 Adana-Ceyhan earthquake (Ural et al. 2008)

3.2.2 Settlement Problems. The main destabilization reasons which cause to damages, cracks or failures in the bridges are settlement problems (Figure 3.8) (KGM 2009).

Settlement problems generally cause fractures in the superstructure in masonry bridges (Figure 3.9). According to Ural et al. (2008), damages due to support settlements may be seen three major reasons:

- (1) Exceeding of bearing capacity
- (2) Some collapse of hollows just near the bottom of piers
- (3) Scours of bottom of piers (Figure 3.10).

These types of damages are very dangerous because they may cause fatal and destructive crashes and fractures. In addition, they cause differential movement of the bridge components. Therefore, these damages should be considered seriously and some precautions should be taken to avoid or to abate their effects.

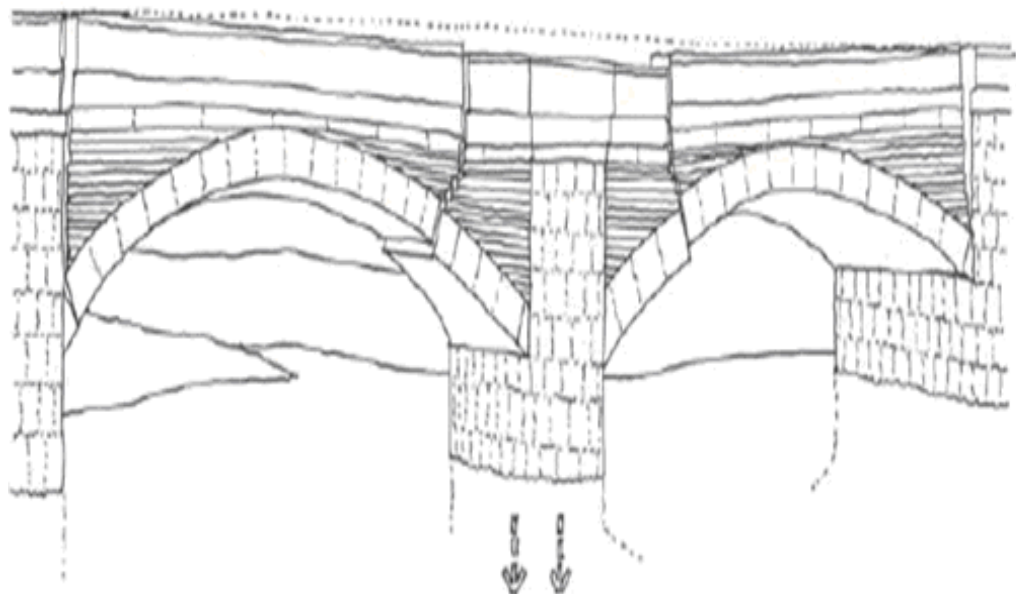


Figure 3.8 Settlement of pier and induced damages (Mathur et al. 2006)

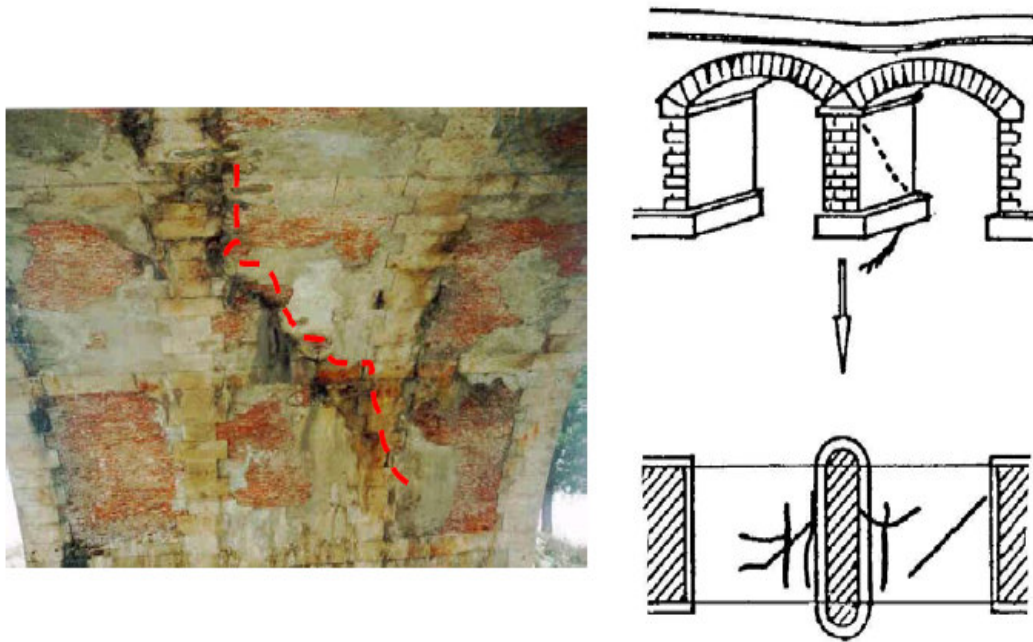


Figure 3.9 Differential settlement or transverse rotation on the longitudinal axis of a pier or abutment (Catalán and Álamo 2006)



Figure 3.10 Substructure failures due to settlement problems on the Mataraci Bridge (Ural et al. 2008)

3.2.3 Scours and Flooding. Scour is erosive to river bed and the bottom of bridges due to flowing water excavating and water power. It is one of the most important failure reasons of masonry bridges. Scour generally occurs due to the increase of river water velocity and flow rate under bridges. Therefore, scour is a natural problem (Figure 3.11). Scour causes failure of the bottom of piers compromising bridge stability. According to Ural et al (2008) “historical constructions have also badly suffered due to the floods. During the flood hazards, huge stones and trees come with water and crack to the bridge (Figure 3.12). Therefore, the bridge is subjected to these crashing effects in addition to hydrodynamic pressures”. Although damages because of scours and flooding generally happen due to natural events such as excessive precipitation, they can occur due to human intervention on river beds.

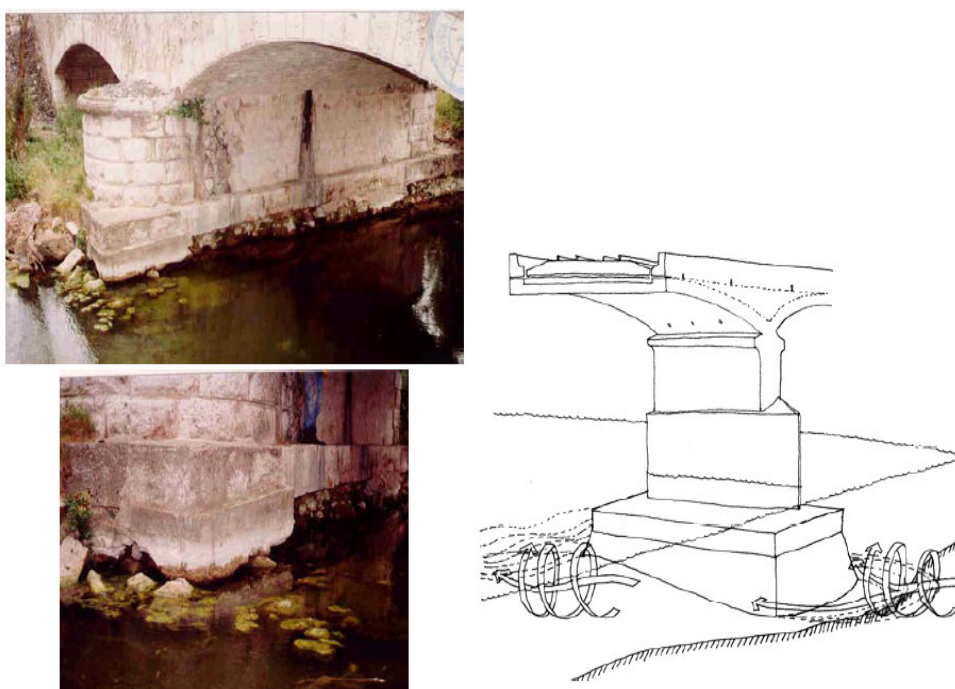


Figure 3.11 Local scour actions on a bridge foundation (Catalán and Álamo 2006)

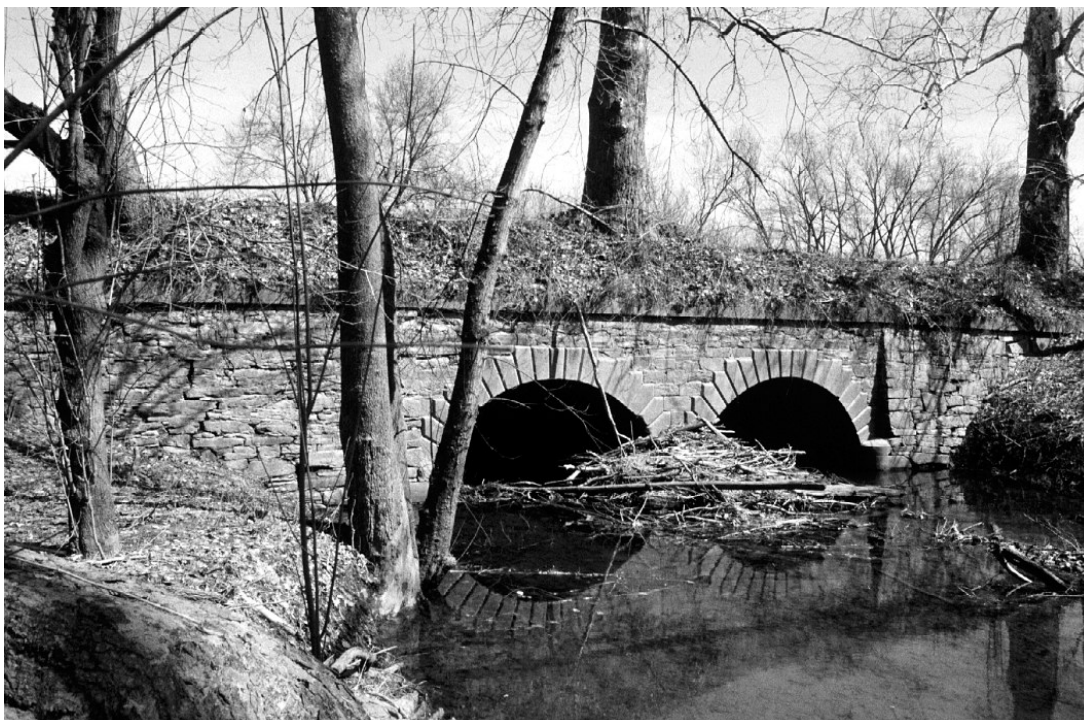


Figure 3.12 Trees come with flooding (Miller et al. 2000)

3.2.4 Overloading. Over the years, live loads on masonry bridges have changed; and many masonry bridges have exposed to the overloads such as heavy traffic or unusual loads (such as military hardware and traffic at the time of emergency). Overloads can also occur when special heavy vehicles are permitted to use the bridge (Figure 3.13). These overloads, if happen frequently, will contribute to the rapid deterioration and damage done to the bridge. Moreover, overloading of the arch triggers transversal cracks and settlements. These types of failures rarely occur and the incidences of overloading failures are very low and it is about 5% of all bridges (Proske and Gerder 2009).



Figure 3.13 An example of overload vehicle

3.2.5 Failures of construction materials. As highlighted in Chapter 2, a masonry arch bridge is made up of stones, bricks and mortars. Although stone and bricks blocks have high strength (in compression), mortars have low strength (Betti et al. 2007). During a masonry bridge's life, construction materials may deteriorate and lose their qualities due to environmental conditions and spalling or flaking. Potential failures because of material degradations should not be neglected because these degradations cause irreversible negative effects on masonry bridges. Ural et al. (2008) say that "if masonry materials have weak performance against such environmental conditions, they will deteriorate and cause bridge damages in the course of time. Small pieces occurred due to decomposition of stones during the cold winters and hot summers have been removed by intensive winds or vibrations (Figure 3.14)".



Figure 3.14 Deterioration of construction materials (Catalán and Álamo 2006)

3.2.6 Demolition and Vandalism. One of the most notable examples of these failures is Riga Railroad Bridge that was built in Latvia. It was attacked during the World War I; and two of its arches were demolished. These arches were later renovated in 1926 (Paeglitis and Paeglitis, 2009). Another example is Mostar Bridge in Bosnia and Herzegovina. It was blown up during the Bosnian War in 1993 and was completely demolished. This bridge was rebuilt by UNESCO in 2004; and it was opened to use on July 23, 2004 (Figure 3.15) (KGM 2009).



(a)

(b)

Figure 3.15 Mostar Bridge (a) in 1993, (b) in 2004 (KGM 2009)

3.3 Collapse mechanisms of masonry arch bridges

It is important to understand the collapse mechanisms of masonry arch bridges for the purpose of developing an appropriate plan for reinforcement and retrofitting. The collapse mechanism of an arch bridge depends on its structural behavior, which in turn depends on the arch thickness and geometry and materials. According to Audenaert and Beke (2010), a masonry arch can fail in three possible collapse mechanisms; a shear mechanism, a hinge mechanism and a combined shear-hinge mechanism.

3.3.1 Shear mechanisms. Shear mechanism depends on arch geometries and material properties. When the masonry bridge has a thick arch or a low rise-span ratio, shear mechanisms are likely to occur (Audenaert and Beke 2010) (Figure 3.16). Shear mechanism involves three sliding surfaces; therefore, it can be named as sliding mechanism, as well.

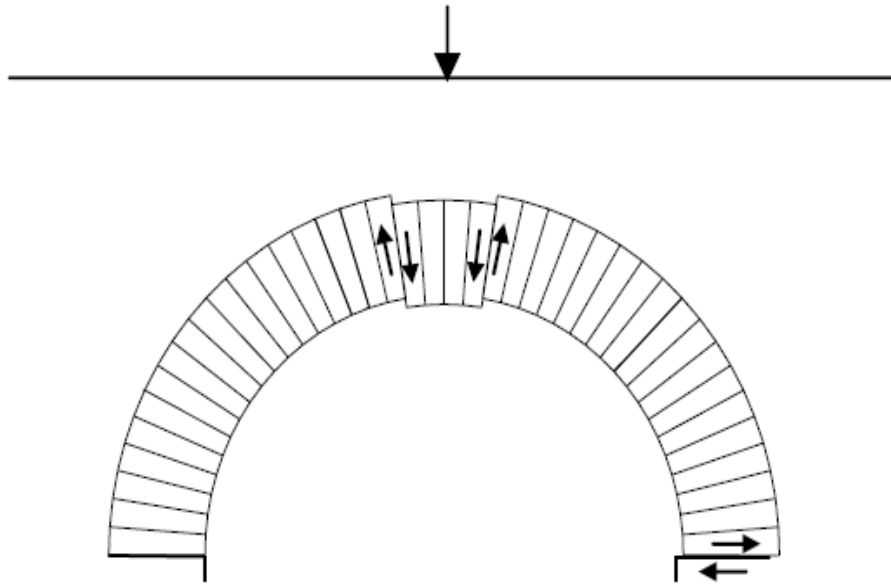


Figure 3.16 Shear mechanisms (Gilbert 2007)

3.3.2 Hinge mechanisms. Hinge mechanisms can possibly occur when the bridge has narrow arch rings and has a high rise-span ratio (Figure 3.17). This type of collapse mechanism predominates in masonry arch bridges. This mechanism was illustrated by Hendry's experiment in 1985 (Audenaert et al 2007) (Figure 3.18). According to Ozer (2004) "it will be seen that the thrust line reaches the surface (either the extrados or the intrados) at four locations. At each of these locations a hinge will form, and four hinges transform the stable arch structure into a mechanism of collapse". Thus, it can be also called as four hinges mechanism.

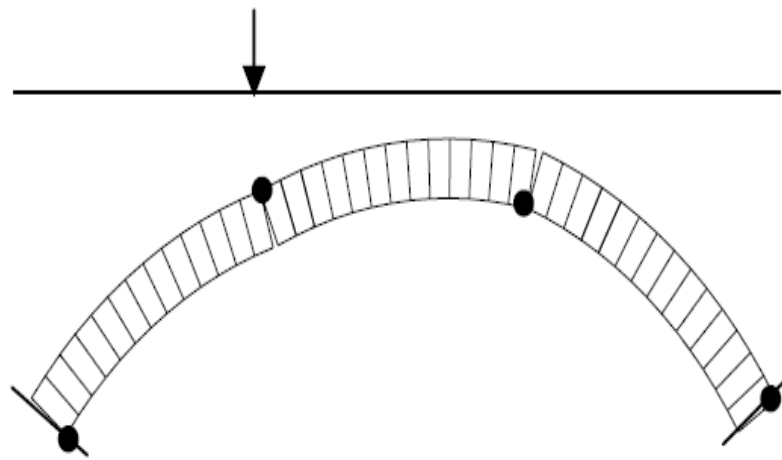


Figure 3.17 Hinge mechanisms (Gilbert 2007)



Figure 3.18 Hendry's experiment (Audenaert and Beke 2010)

3.3.2 Combined shear – hinge mechanisms. Combined shear-hinge mechanisms can be expected to appear when the arch bridge has a low rise-span ratio (Figure 3.19). It is the combination of shear mechanism and hinge mechanism (Audenaert and Beke 2010).

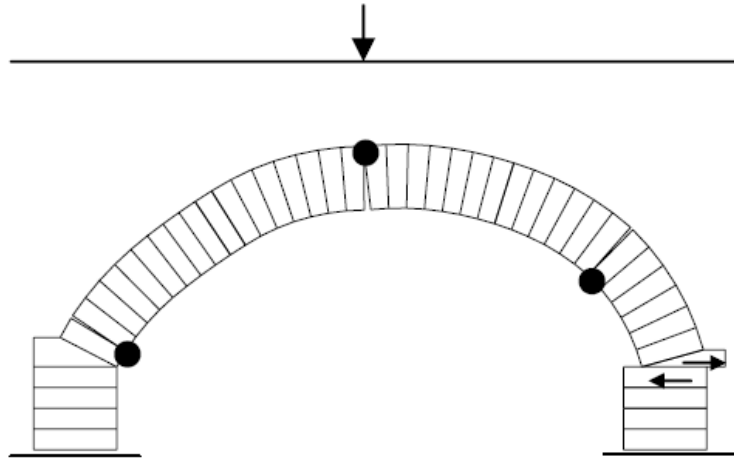


Figure 3.29 Combined shear – hinge mechanism (Gilbert 2007)

CHAPTER 4

SEISMIC RETROFITTING USING MICROPILES

Masonry bridges are regarded as the oldest examples of engineered structures in the world. The preservation of these structures is getting a great deal of attention in the structural engineering community. And as such, restoration, strengthening and reinforcement of historical masonry bridges have become a challenge for civil engineers. In general, and to most extent, engineers have relied on several traditional retrofitting techniques that could be implemented for historic bridges. However, traditional retrofitting techniques have been inadequate for improving seismic behavior and resistance of these structures. With current advancements in materials and construction techniques, new technologies that can be appealing to historical bridges are emerging. Among these techniques include underpinning using micropiles with the technique called “micropiling”. Today, micropiles are used for the structural and seismic retrofitting of bridges, mosques, churches and many other ancient cultural heritage and modern structures. This study mainly focuses on historical masonry bridges; and it consists of three major parts. The first part introduces seismic retrofitting using micropiles for historical bridges. The second part discusses advantages and disadvantages of micropiling compared to other underpinning methods, in terms of seismic performance. Finally, the third part presents examples of applications in different parts of the world.

4.1 Introductory Remarks

Historical masonry bridges are very complex structures with respect to their seismic behavior and seismic protection. Therefore, they require high levels of protection standards and advanced engineering knowledge about seismic design. As described

earlier, earthquake effects in masonry bridges generally depend on bridge types, construction materials and seismic behavior of bridge structures. It is well known that earthquakes can happen unexpectedly and without much prior warnings. Hence, many historical bridges are at risk in terms of seismic events; and they have mostly deficient in resisting seismic loads. Seismic retrofitting of masonry bridges has advanced significantly in recent years through understanding of structural behavior, developing advanced analysis methods and seismic design practices. In parallel to the developments of building technologies and seismic engineering, several seismic protections and underpinning methods have also been developed in order to improve the performance and protection of structures that are deficient in resisting seismic loads. Currently, many different underpinning methods exist with different workmanship techniques and equipments geared for applications in different types of structures. Specific to masonry restoration and retrofitting projects, there are four main underpinning methods. These are:

- (1) Traditional methods
- (2) Jet grouting methods
- (3) Compaction injection grouting methods
- (4) Micropiling methods (Cakir and Yetimoglu 2009).

Over the years, engineers have retrofitted structures to withstand earthquakes. When historical buildings in earthquake areas are studied carefully, the reminiscences of ancient seismic retrofits are encountered. These ancient cases of seismic protection have actually contributed to current retrofitting projects and understanding correct restoration methods for structures (Ahunbay 2009). According to the ninth article of Venice Charter (1964), “The process of restoration is a highly specialized operation. Its aim is to preserve

and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents. It must stop at the point where conjecture begins, and in this case moreover any extra work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp. The restoration in any case must be preceded and followed by an archaeological and historical study of the monument.” Furthermore, as it is also described in the tenth article of Venice Charter (1964), “Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience.” Hence, historical structures must be preserved using minimal and renewable intervention. Together with that, the most convenient underpinning techniques should be selected before intervening so that these structures can safely continue their intended function.

Micropiles were generally used for underpinning of existing foundations; however, recently, they have been frequently used for many different applications such as foundation support, soil settlement problems, deep excavations, adding new stories to buildings, slope stabilizations and bearing capacity problems. It has also been used for the seismic retrofitting of new and old structures. In the last few decades, the micropile technology has been significantly expanded because of its proven effectiveness as an attractive solution for the structural and seismic retrofitting of bridges, mosques, churches and many other ancient cultural heritage and modern structures in many earthquake-prone areas. The following section presents designing and seismic applications of micropiles. Furthermore, it discusses advantages and disadvantages of micropiles compared to other underpinning methods in terms of seismic performance.

4.2 Designing and Seismic Applications

Micropiles were implemented for the first time in Italy by Fernando Lizzi to retrofit the existing masonry structures and foundation systems in the early 1950's. Micropiles are small diameter piles and they are generally used in soil and foundation retrofits. Typically, they are under 25 cms (10 inches) in diameter, 7.5 or more meters (>24 feet) in length and 300-1000 kN (70-225 kips) in load-carrying capacity. However, these properties can be occasionally changed with application types and design requirements. Since micropiles are small-diameter piles, they are sometimes called mini piles, root piles, pin piles or needle piles. Micropiles are installed using the drill rigs which are generally hydraulic rotary machines. The successful construction steps for micropile application can be arranged under three major parts. They are drilling, placing reinforcing steel and grouting. These steps are consecutively implemented. That is, after the determination of the pile points, the drilling work is started with different type drilling machines and rigs. Then, small diameter steels are placed in these drilled holes and finally these steels are covered by grouting materials (Figure 2.1) (Kordahi 2004; Bruce et al. 1995).

Micropiles can be implemented to different sequence types and different connection forms. Although they could be vertically connected to the structure foundation, they could be connected in inclined forms around and below the foundations (Figure 4.2). By this, micropiles can become networks and they may behave like tree roots; thus, they may improve the soil-structure interaction behavior under seismic loads.

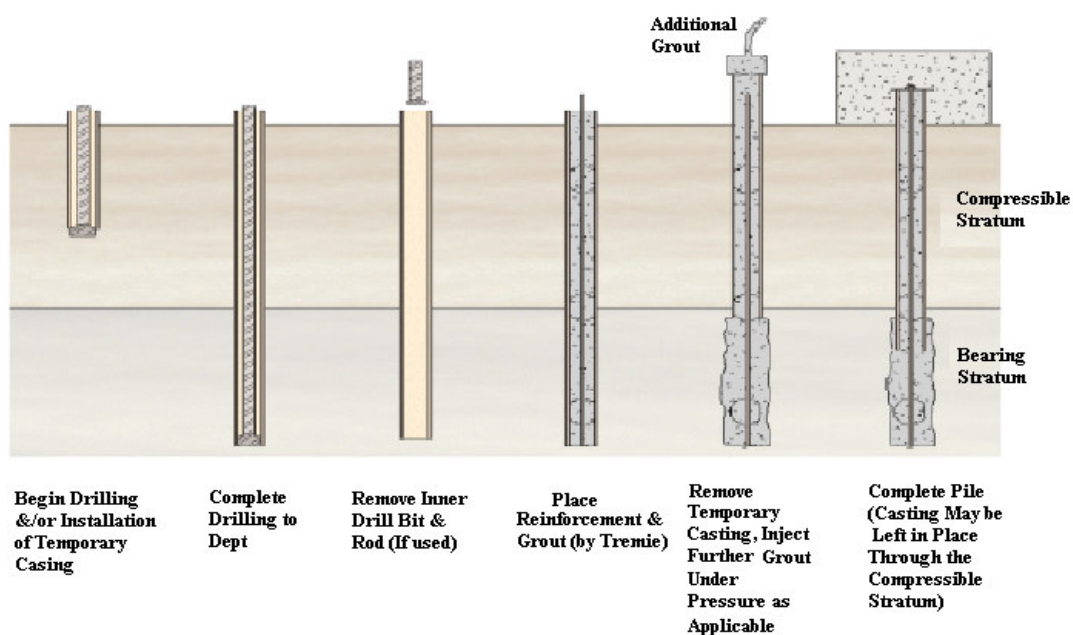


Figure 4.1 Schematics of pile main construction phases (Prezzi 2004)

Many studies have shown that the seismic performance of micropiles changes with micropile connection forms, sequences and directions. According to Sadek and Isam (2004), inclination of micropile will result in improve in micropile's performance in seismic load environments. As indicted by Sadek and Isam, any inclination improves the mobilization of the axial stiffness of micropiles and consequently leads to a reduction in the shearing forces and bending moments resulted from seismic loads. In terms of liquefaction, micropiles also provide attractive results. Generally, vertical micropiles don't reduce liquefaction during the earthquakes; whereas inclined micropiles reduce it (Bruce et al. 2005). However, studies reported by Bruce et al. (2005) show that "inclined piles should not be used for transmitting lateral loads to the soil, but if such piles are used, they must be safely designed to carry axial and bending loads."

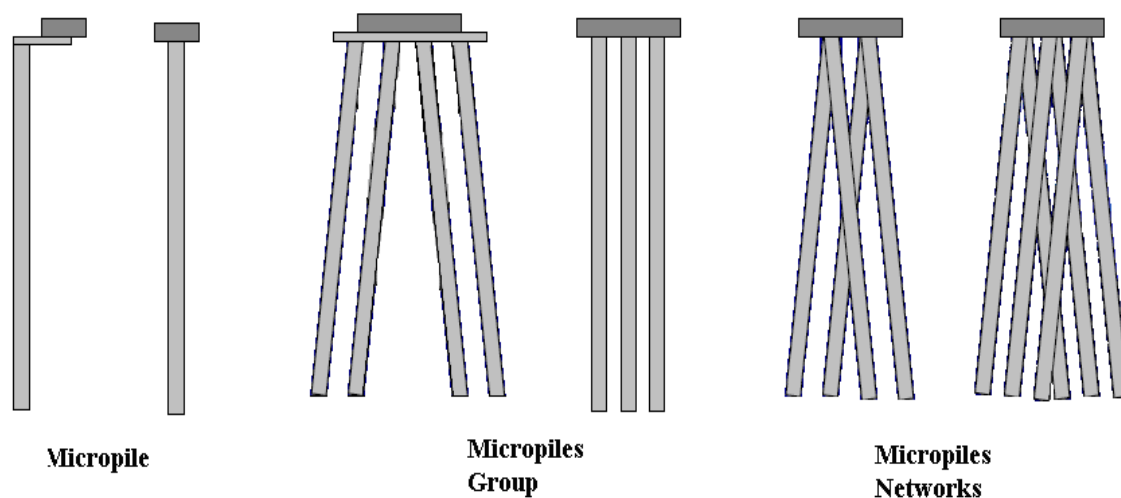


Figure 4.2 Some micropile application types (Frank 2006)

In another recent study, Sadek and Shahrour (2006) further mention that micropile systems have advantages over other methods in providing flexibility, ductility and capacity to withstand forces. Therefore, micropiles can be used as foundation support for new structures as well as for seismic retrofitting of older structures, which have suffered seismic damage. Research also proved that these systems increase seismic performance of masonry structures and minimize the foundation deflection because of its higher pullout and bearing capacity. (Babu et al 2004; Misra et al. 2004; Leon et al. 2004; Han and Ye 2006; Misra et al 2007).

Compared with the benefits of micropiles, as indicated above, the traditional methods are insufficient for seismic retrofitting and protection. Although these methods may offer an economical solution for underpinning, they often lead to settlement in the foundation because of their heavy mass. For these reasons, applications of traditional methods have decreased gradually for historical structures. Other methods, known as the compaction injection grouting, may not be preferred for soft clay soils; because they have caused extra pore water pressure in the soil and have led to excessive soil settlement in

the long run. Furthermore, when these methods are applied for settled and lopsided structures, there may be structural damage in the superstructures due to uncontrolled injections. Consequently, the soil profile and soil properties have to be particularly defined before the compaction injection applications and correct grouting materials with convenient injection parameters are chosen. The method known as the jet grouting may be a good solution for seismic retrofitting and protection. However, this method is very expensive for historical structures; because it requires special equipments and workmanship. Furthermore, it is difficult to produce long columns with this system because generally jet grout columns are shorter than five meters. Nevertheless, jet grouting can be applied for almost all types of soil and they can be produced for a lower price (Cakir and Yetimoglu 2009).

By using innovative engineering, micropiling can be effective and provide an economical solution for all applications whether small and large. Micropiles have been successfully implemented in restricted working spaces, and sensitive structures; however, they are unsuitable or unstable soils (such as slopes). Because of its proven capabilities, micropiling represents an advanced underpinning technique in retrofit problems of historical bridges. By means of high flexibility and ductility, they behave well under seismic loads. However, according to Marek and Muhunthan (2005) although there have been many advancements in the field of micropile technology; its seismic behavior is still a little obscure.

4.3 Case Studies

This section discusses different micropile applications in masonry bridges. Many applications using this method have been reported for different purposes. Figure 4.3

presents different examples of micropile applications in the world. Among various applications, the list specifically provides two examples of the seismic implementation of micropiles in New York, United States and Venice, Italy respectively.

Bridge Name	Location	Purpose of Application
The 145th Street Bridge	New York, USA	Seismic Retrofitting
The Pierre Bridge	Bordeaux, France	Foundation Reinforcement
The Vila Fria Bridge	Felgueiras, Portugal	Seismic Protection
The Ponteceso Bridge	Galicia, Spain	Widening and Strengthening
The Sandro Gallo Bridge	Venice, Italy	Widening
The Three Arches Bridge	Venice, Italy	Static and Seismic Retrofitting
The Broadmeadow Viaduct	Dublin, Ireland	Stabilization
The Northwich Viaduct	London, England	Settlement Problem
The Tarano Bridge	Alessandria, Italy	Foundation Strengthening

Figure 4.3 Different types of micropile applications for some masonry bridges

The first application example is the 145th Street Bridge in New York. The 145th Street Bridge was completed in 1905 across the Harlem River to connect Manhattan and the Bronx. Its center span is 91.5 meters (300 feet) and the total length is 481.5 meters (1,580 feet). It is a movable bridge; and its substructure was built with steel trusses and its two piers were constructed by masonry stone. In 1998 the bridge was examined in terms of its resistance to earthquakes by the New York City Department of Transportations (NYCDOT). NYCDOT considered two earthquake levels for the

investigation. Consequently, the bridge piers were strengthened with 20 micropiles which were of 6.35 cms diameters and Grade 75 (520 Mpa) steel bars (Figure 4.4)

In the micropiling application phases, first, the piers were drilled from base to top and thus boreholes appeared. After that, the steel micropiles were placed in these holes and finally they were grouted by concrete. The results of the micropile reinforcement showed that the micropiles can increase seismic performance and they can significantly reduce vertical displacement to the bridge piers (Wang and Abrahams 2006).

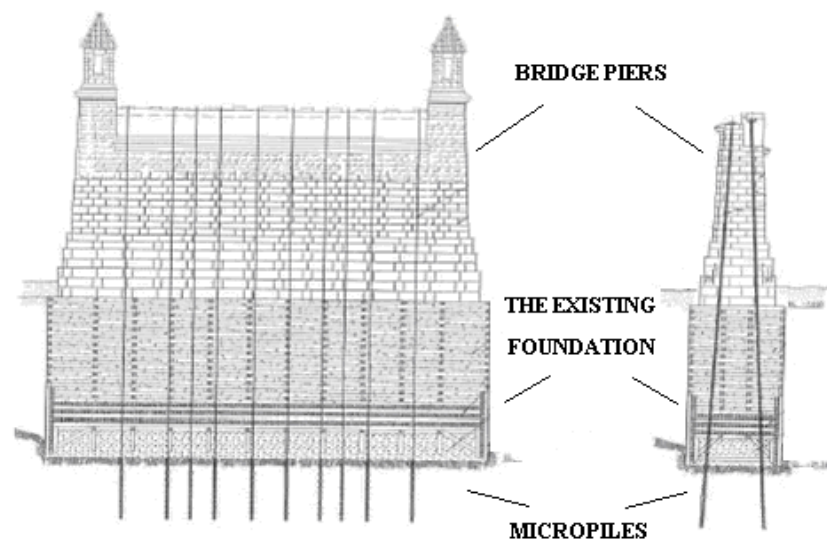


Figure 4.4 Elevation views of the micropiles as strengthening reinforcement (Wang and Abrahams 2006)

The second application example cited in the table for seismic retrofitting is the Three Arches Bridge in Italy. The Three Arches Bridge was built in 1688 on the Rio di Cannaregio Canal in Venice, Italy. It was designed as three arches form by Antonio Tiralli. Its central arch span is 15 meters (49 feet) and the end arches spans are 8 meters (26.2 feet) each and the total bridge length is almost 40 meters (131 feet). This bridge is a very important historical bridge because it is a single example of a bridge with three arches in Venice. The bridge parapets were added to the first restoration in 1794; and

these parapets created extra loads on the bridge. In the course of time, the bridge was damaged by the boat and gondola traffic. Scours also caused soil erosion and differential movements. In 1960, Fernando Lizzi and his team prepared a restoration project and the bridge was restored with micropile networks (Figure 3.5).

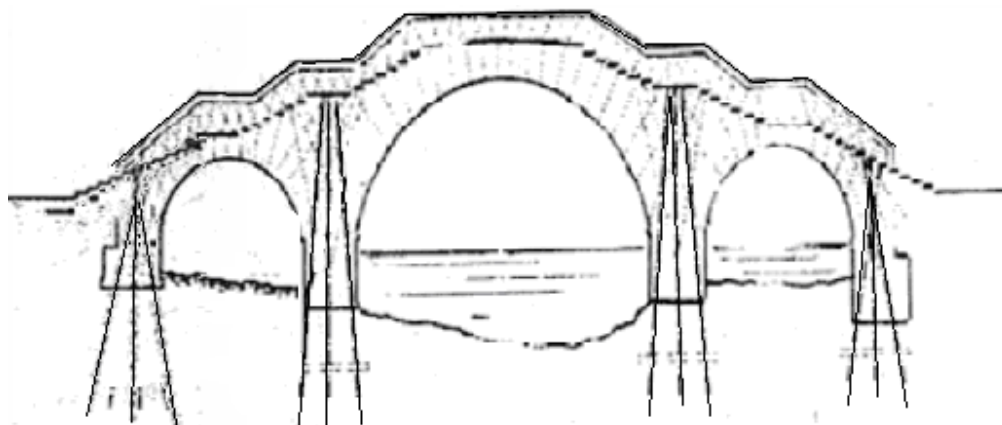


Figure 3.5. Micropile retrofit scheme of the Three Arches Bridge (Mason and Bruce 2001)

The bridge was successfully retrofitted by a micropile network in 1960. In the application phases, first, the bridge was drilled by rotary drill rig on the bridge from the piers top to the substratum and then the micropiles were located and grouted. As a result of this retrofitting project, the There Arches Bridge was strengthened with minimum damage received during reinforcement when using micropiles (Mason and Bruce 2001).

4.4 Concluding Remarks

Recently, earthquakes have shown that many historical and modern structures are inadequate in terms of seismic performance; and they have to be retrofitted at the earliest. It is known that masonry bridges are one of the oldest examples of engineered structures in the world; and they have to continue their service safely. As Venice Charter (1964) mentioned, “the 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.” In this study, the micropiling method which has proven its reliability is discussed for seismic retrofitting and protection of historical masonry bridges. The seismic application principles are summarized and some examples of micropile applications are presented. Furthermore, two specific application examples of seismic retrofit are presented.

In summary, when seismic retrofit plans are considered for a structure:

1. Historical background and performance of the structure has to be examined and its past performance evaluated.
2. Underpinning techniques offer a proven method for the protection of the historical bridges. Therefore, this method will need to be considered as a means of providing an effective alternative in the structure’s retrofit plan.
3. Before implementing the underpinning, the correct equipment and workmanship must be considered.
4. Underpinning application has to be implemented with the minimum damage to and maximum protection for historical structures.
5. The entire restoration steps should be implemented according to the international protection committees such as ICOMOS and UNESCO.

CHAPTER 5

CONCLUSIONS AND SUGGESTIONS

5.1 Summary

Masonry arch bridges are one of the most important structures in terms of their age, intended uses, heritage value and structural properties. As changes occur in the loads applied on these structures, their preservations against man-made or natural hazards impose a challenge to bridge engineers.

This study focuses on an overview of the types, functions, loading condition, and a study of structural integrity and mechanism of failure of masonry arch bridges. In addition, considering seismic forces to be a major cause of collapse of these structures, the study also covers implementation of effective methods for seismic retrofit using micropiles.

Among major findings of this study are the following:

1. Many historic masonry arch bridge continue to offer services and historical values; and as such, it is important to understand their structural behavior and collapse mechanism when developing a plan for their preservation and retrofit.
2. Among various causes of failure, seismic forces are considered as a major reason for collapse of masonry arch bridges.
3. New restoration and retrofitting methods should be preferred where traditional methods are insufficient; and as such, a proven technique using underpinning with micropiles offers a reliable approach for strengthening and retrofit of these bridges

5.2 Recommendations for Future Studies

The following list suggests proposed future studies regarding masonry arch bridges.

1. Conduct a comprehensive structural analysis using finite element methods to better understand the mechanism of failure of masonry arch bridges especially under the dynamic effect of earthquakes.
2. Conduct additional studies on the behavior of materials and failure causes from other sources such as increased dynamic traffic load effect, cumulative damage and crack formation, etc.
3. Conduct a survey of methods used for reinforcing masonry in ancient bridges for prolonging the life of bridges and their serviceability.

BIBLIOGRAPHY

- AASHTO (2002). "Standard Specification for Highway Bridges", *American Association of State Highway and Transportation Office*, 17th Edition, Washington, D.C., USA
- AASHTO LRFD (2004). "Bridge Design Specifications", *American Association of State Highway and Transportation Office*, Washington, D.C., USA
- Ahunbay, Z., (2009). "Anıtlar, Depremler ve Onarımlar", Proceedings of Symposium with International Participation on Strengthening and Preserving Historical Buildings and Cultural Heritage – 2, p. 55–56, 15-16-17 October 2009, Diyarbakir, Turkey
- Anonymous (2011a). <http://www.seslisozluk.com/?word=foundation>, 04/16/2011
- Anonymous (2011b). http://www.timberengineeringeurope.com/art_found.html, 04/16/2011
- Anonymous (2011c). <http://showcase.scottsdalecc.edu/geology/rocks/>, 04/24/2011
- Anonymous (2011d). <http://www.artistopia.com/brick>, 04/24/2011
- Audenaert, A. & Beke, J., (2010). "Applicability analysis of 2D-models for masonry arch bridge assessment ring: archie-M and the elasto-plastic model", *WSEAS transactions on applied and theoretical mechanics*. 2010, 5, 4, p. 221-230
- Audenaert, A., Peremans, H. & Reniers, G., (2007). "An Analytical model to determine the ultimate load on masonry arch bridges." *Journal of engineering mathematics*, 59(3): 323-336
- Babu, G.L.S., Murthy, B.S., Murthy, D.S.N. & Nataraj, M.S., (2004). "Bearing Capacity Improvement Using Micropiles: A Case Study", *GeoSupport 2004: Drilled Shafts, Micropiling, Deep Mixing, Remedial Methods, and Specialty Foundation Systems*
- Betti, M., Drosopoulos, G.A. & Stavroulakis, G.E., (2007), "On the collapse analysis of single span masonry/stone arch bridges with fill interaction", 5th International Conference on Arch Bridges, September 12-14, 2007, Madeira , Portugal
- Blasi, C. & Foraboschi, P. (1994). "Analytical approach to collapse mechanisms of circular masonry arch." *Journal of Structural Eng.*, 120 (8), 2288 –2309
- Boyd, T.D., (1978). "The Arch and the Vault in Greek Architecture", *American Journal of Archaeology* 82 (1): 83–100 (91)

- Bruce, D.A., DiMillio, A.F. & Juran, I. (1995). "Introduction to Micropiles: An International Perspective", *Foundation Upgrading and Repair for Infrastructure Improvement*, Published by ASCE, Newyork, USA
- Bruce, D.A., Cadden, A.W. & Sabatini, P.J., (2005). "Practical Advice for Foundation Design – Micropiles for Structural Support", *Geotechnical Special Publications* 130-142 & GRI-18; Proceedings of the Geo-Frontiers 2005 Congress, January 24.26, 2005, Austin, Texas
- Cakir, F. & Yetimoglu T., (2009). "Repair and Underpinning of Historical Building Foundation", Proceedings of Symposium with International Participation on Strengthening and Preserving Historical Buildings and Cultural Heritage – 2, p. 269–279, October 15-16-17, 2009, Diyarbakir, Turkey
- Catalán, R.O.G. & Álamo, J.A.M.C., (2006). "Catalogue of Damages for Masonry Arch Bridges", *Final Draft, Improving Assessment, Optimization of Maintenance and Development of Database for Masonry Arch Bridges*, Paris, France
- Cavicchi, A. & Gambarotta, L., (2005). "Collapse analysis of masonry bridges taking into account arch–fill interaction", *Engineering Structures* 27 (2005), 605–615
- Chajes, M., (2002). "Load Rating of Arch Bridges", *Delaware Center for Transportation*, University of Delaware, Newark, Delaware, USA
- Chen, W., F. & Duan L., (2000). "Bridge Engineering Handbooks", CRC Press, Florida, USA
- Drosopoulos, G.A., Stavroulakis, G.E. & Massalas, C.V., (2008). "Influence of the geometry and the abutments movement on the collapse of stone arch bridges", *Construction and Building Materials* 22 (2008), 200–210
- Felice, G.D., (2009). "Assessment of the load-carrying capacity of multi-span masonry arch bridges using fibre beam elements", *Engineering Structures* 31 (2009), 1634-1647
- Frank, R., (2006). "The French National Project on Micropiles", 14th Prague Geotechnical Lecture, 22nd May 2006, Prague, The Czech Republic
- Gedik, Y.H., (2008). "Analysis Repair and Strengthening of Historical Masonry Structures; Case Study: Mehmet Aga Mosque", M. Sc. Thesis, Istanbul Technical University, Istanbul, Turkey
- Gilbert, M., (2007). "Limit analysis applied to masonry arch bridges: state-of-the-art and recent developments", 5th International Conference on Arch Bridges, Madeira, pp 13-28

- HAER, (2001). "Pennsylvania Railroad, Rockville Bridge", *Historic American Engineering Record*. No. PA-524
- Harding, J.E., Parke, G.A.R. & Ryall, C., (2010). "Bridge Management 3, Inspection, Maintenance, Assessment and Repair", Taylor and Francis Press, USA
- Harvey, B., & Maunder, E., (2001). "Thrust line analysis of complex masonry structures using spreadsheets", *Historical Constructions*, P.B. Lourenço, P. Roca (Eds.), Guimarães, Portugal
- Han, J. & Ye, S-L., (2006). "A Field Study on the Behavior of a Foundation Underpinned By Micropiles", *Canadian Geotechnical Journal*, 43:30-42, 10.1139/t05-087
- Hasley, J., (1883). "Railway Masonry and Bridge Foundations", The Railway Age Publishing Co., Chicago, USA
- Hendry, A.W. & Khalaf, F.M., (2001). "Masonry Wall Construction", Taylor & Francis Group, London, England
- Heyman, J., (1995). "The Stone Skeleton. Structural Engineering of Masonry Architecture", Cambridge University Press, Cambridge, England
- Heyman, J., (1998). "The assessment of strength of masonry arches", in A. Sinopoli (ed.), *Arch Bridges*, Balkema, Rotterdam 1998, pp. 95-98
- Ketchum, M.S., (1919). "Structural Engineers' Handbook", Mc Graw Hill Book Company, London, England
- KGM, (2009), "Tarihi Kopruler (Historical Bridges)", *Republic of Turkey General Directorate of Highways*, Ankara, Turkey
- Khan, M.A., (2010). "Bridge and Highway Structure Rehabilitation and Repair", Mc Graw Hill Press, Newyork, USA
- Kordahi, R.Z., (2004). "Underpinning Strategies for Building with Deep Foundations", The Massachusetts Institute of Technology, MSc Thesis, Massachusetts, USA
- Kurrer, K.E., (2008). "The history of the theory of structures: from arch analysis to computational mechanics", Ernst & Sohn, Berlin, GERMANY
- Marek, A.R. & Muhunthan, B., (2005). "FHWA Supported Structures Research Seismic Behavior of Micropiles", *Research Report, Washington State Transportation Center (TRAC)*, Washington, USA
- Mason, J.A. & Bruce, D.A., (2001). "Lizzi's Structural System Retrofit with the

Reticulated Internal Reinforcement Method (IRM)", *Transportation Research Record* 1772, Paper No. 01-2861

- Mathur, M., Kumar, S. & Singh, K., (2006). "Assessment and retrofitting of arch bridges", from www.wiki.ircen.gov.in/doku/lib/exe/fetch.php?media=622:2arch_bridge.pdf
- Meyer, P.K., (2006). "The impact of high frequency/low energy seismic waves on unreinforced masonry", M.Sc Thesis, Massachusetts Institute of Technology, Cambridge, USA
- McKibbins, L.D., Melborne, C., Sawar, N. & Gallard, C.S., (2006). "Masonry Arch Bridges: Condition Appraisal and Remedial Treatment", CIRIA Press, London, England
- Miller, A.B., Clark, K.M. & Grimes, M.C., (2000). "A Survey of Masonry and Concrete Arch Bridges in Virginia", *Final Report, Virginia Transportation Research Council*, Charlottesville, Virginia, USA
- Misra, A., Chen, C.H., Oberoi, R. & Kleiber, A., (2004). "Simplified Analysis Method for Micropile Pullout Behavior", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE/October 2004
- Misra, A., Roberts, L.A., Oberoi, R. & Chen, C.H., (2007). "Uncertainty Analysis of Micropile Pullout Based upon Load Test Results", *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE/August 2007
- Morer, P., Arteaga, I.D., Armesto, J. & Arias, P., (2011). "Comparative structural analyses of masonry bridges: An application to the Cernadela Bridge", *Journal of Cultural Heritage xxx* (2011) xxx-xxx (Article in Press).
- Morgan, W., (1970). "The Elements of Structure an Introduction to the Principles of Building and Structural Engineering", Published by Pitman, New York, USA
- Ng, K.H., (1999). "Analysis of Masonry Arch Bridges" Ph.D. Thesis, Napier University, Edinburgh, Scotland
- Ng, K.H. & Fairfield, C.A., (2004). "Modifying the mechanism method of masonry arch bridge analysis", *Construction and Building Materials* 18 (2004) 91-97
- OED (2011). Oxford English Dictionary, from <http://www.oed.com>
- Ozer, S., (2006). "The Analysis of Structural Elements in Traditional Masonry Buildings", M.Sc. Thesis, Erciyes University, Kayseri, Turkey
- Ozer, O., (2004). "Assessment of Masonry Arch Bridges by Mechanism Method", M.Sc.

Thesis, Middle East Technical University, Ankara, Turkey

- Peaglitis, A. & Peaglitis, A., (2009). “Restoration of masonry arch bridge over Venta River in Kuldiga”, International Baltic Road Conference, August 2009, Riga, Latvia
- Prezzi, M., (2004). “Use Of Micropiles for Foundations of Transportation Structures”, *Research Study, Joint Transportation Research Program*, Purdue University, USA
- Proske, D. & Gerder, P.V., (2009). “Safety of Historical Stone Arch Bridges”, Springer Press, Berlin, Germany
- Ramage, M.H., Ochsendorf J., A., Block, P. & Rich P., (2008). “Advanced Geometry, Rudimentary Construction: Structural form finding for unreinforced thin-shell masonry vaults”, Advances in Architectural Geometry Conference Program, Venice, Austria
- Roca, P., Cervera, M., Gariup, G. & Pela, L., (2010). “Structural Analysis of Masonry Historical Constructions: Classical and Advanced Approaches”, *Arch Compute Methods Eng.* 17 (2010), 299–325
- Rota M., Pecker A., Bolognini D. & Pinho R. (2005). “A methodology for seismic vulnerability of masonry arch bridge walls,” *Journal of Earthquake Engineering*, Vol. 9, Special Issue 2, pp. 331-353
- Sadek, M. & Isam, S., (2004). “Three-dimensional finite element analysis of the seismic behavior of inclined micropiles”, *Soil Dynamics and Earthquake Engineering*, 24 (2004), 473– 485
- Sadek, M. & Shahrour, I., (2006). “Influence of the head and tip connection on the seismic performance of micropiles”, *Soil Dynamics and Earthquake Engineering*, 26 (2006), 461–468
- Sánchez, I.B., (2007). Strengthening of arched masonry structures with composite materials, Ph.D. Dissertation, University of Minho, Julho, Portugal
- Sen, B., (2003). “Modeling and Analysis of the Historical Masonry Structures”, M.Sc. Thesis, Bogazici University, Istanbul, Turkey
- Sevim, B., Bayraktar A., Altunisik A.C., Atamturktur S. & Birinci F., (2011). “Assessment of nonlinear seismic performance of a restored historical arch bridge using ambient vibrations”, *Nonlinear Dynamics*, 63 (2011): 755–770
- Spalding, F.P., (1921). “Masonry Structures”, John Wiley & Sons, London, England

- Sowden, A.M., (1990). "The Maintenance of Brick and Stone Masonry Structures", E.&F.N. Spon, New York, USA
- Tonias, D.E. & Zhao, J.J., (2007). "Bridge Engineering: Design, Rehabilitation, and Maintenance of Modern Highway Bridges", Second Edition, McGraw-Hill Companies, Inc., New York, USA
- Ural, A., Oruç, Ş., Doğangün, A. & Tuluk Ö İ, (2008). "Turkish historical arch bridges and their deteriorations and failures", *Engineering Failure Analysis*, 15, 43–53.
- Wang, B., Tang, S. & ShangGuan, X., (2010). "The heritage and development of the stone arch bridges in China", 6th International Conference on Arch Bridges, Fuzhou, China
- Wang, J.N. & Abrahams, M.J., (2006). "Seismic Retrofit of Unreinforced Stone Masonry Bridge Piers and Discrete Element Analysis", 22nd US - Japan Bridge Engineering Workshop, October 23-25, 2006, Seattle, Washington, USA
- Wu, X., (2010). "Load Rating of Existing Masonry Arch Bridges in USA", 6th International Conference on Arch Bridges, October 11-13, 2010, Fuzhou, China
- Venice Charter (1964). *IInd International Congress of Architects and Technicians of Historic Monuments*, Venice, Italy