

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**CABLE-NET FACADES WITH NOVEL GLASS NODES:
DEVELOPMENT, DESIGN, AND TESTING**



M.Sc. THESIS

Esra Yağdır ÇELİKER

Department of Architecture

Environmental Control and Construction Technologies Program

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**ÖZGÜN CAM DÜĞÜM NOKTALARINA SAHİP KABLO-AĞ CEPHELERİN
GELİŞTİRİLMESİ, TASARIMI VE TESTİ**

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EKİM 2018

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Date of Submission : 13 September 2018
Date of Defense : 9 October 2018





To my dear mother,



FOREWORD

My dear family, I always feel your support and love every moment of my academic and personal life. My dear father, you are the bravest person that I've ever seen, thank you for teaching to me what courage is. My dear mother, you are not only the woman that gave a birth to me but also, you are my best friend and profound mentor. Thank you for teaching to me how being a strong woman. Dear Deren Ünal, you are the most compassionate person in my life, thank you for making me smile whatever happens. Dear Venüs Ünal, thank you for helping me about re-exploring the life's hidden surprises.

I would like to give a special thanks to;

My advisor Oğuz Cem ÇELİK for profound and continuous support and mentorship during my thesis studies,

My jury members Aslıhan ÜNLÜ TAVİL and Volkan GÜR for contribution to my thesis with worthful criticisms,

My first year professor Sait Ali KÖKNAR for illuminating comments and interdisciplinary approaches about architectural design studies that integrated with building technology fields.

All members of Metal Yapi Company and especially; Bülent ÖZGÜL, Selami GÜREL, İlknur AKIN, Mehmet Fatih KABAN, Emrah ERENLER, Burak BABATUTMAZ, and Ali Can KARAYANI for all supports during the design processes of the study,

All members of Facade Testing Institute (FTI) and especially; Murat SEYHAN, Öner ARSLAN, Emre ARSLAN, Nilay BULUT, Sinan BAYRAKTAR and all testing technicians for all supports in order to execute tests of Glass Node,

Dostcam Company which never hesitated to provide the required glass elements for manufacturing the Glass Node,

Alcam Company for all experimental manufacturing processes which enabled the study to be accomplished,

All member of Sika Turkey and especially; Tolga ŞENTÜRK and Koray ÖZDER for sustained helps during the experimental bonding procedures of the specimen.

Also, I would like to thank Efecan TİRELİOĞLU, the person that show me what friendship really is. Olga ÖZTEL, I know you are always going to be beside me by your heart. Ayşe Dede, Cavidan BAYRAKTAR, Ilgın AVCI, Pelin ARIBAŞ; you are the most cheerful people in my life, thank you for making the all moments that we spent unforgettable. Ceren ÖN, thank you for all childhood memories that keep me happy and accepting to be my thesis English editor.

October 2018

Esra Yağdır ÇELİKER
(Architect & Civil Engineer)



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ABBREVIATIONS

AISC	: American Institute of Steel Construction
ANG	: Annealed Glass
ASCE	: American Society of Civil Engineers
ASD	: Allowable Strength Design
ASTM	: American Society of Testing and Materials
BS	: British Standards
DIN	: Institute of German Norms
EN	: European Norm
FEM	: Finite Element Method
FTG	: Fully Tempered Glass
FTI	: Facade Testing Institute
HSG	: Heat Strengthened Glass
IGU	: Insulated Glass Unit
LC	: Load Combination
TS	: Turkish Standards
POM	: Ployoxymethylene
PVB	: Polyvinyl Butyral



SYMBOLS

ρ	: Density
α	: Linear expansion of Soda lime Silicate Glasses
σ	: Stress
A_g	: Effective Net Area
E	: Elasticity Modulus
F_a	: Target Force
F_{3t}	: Triple of Target Force
F_u	: Ultimate Tensile Strength
F_{gn}	: Average Breaking Load of Glass Node
H	: Horizontal Reaction Force
L	: Short Span of Structure
N_d	: Deflection Reduction Factor
N_f	: Fitting Reduction Factor
P_a	: Tensile Rupture
P_d	: Allowable Strength
P_n	: Nominal Compression Stress
q	: Distributed load
R_a	: Required Strength
R_n	: Nominal Strength
S_a	: Allowable Strength
S_{max}	: Maximum Reaction Force
V	: Vertical Reaction Force
δ_{lim}	: Deflection Limit
δ_{max}	: Maximum Deflection
ϵ	: Strain
μ	: Maximum Deflection
ω	: Safety Factor



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CABLE-NET FACADES WITH NOVEL GLASS NODES: DEVELOPMENT, DESIGN AND TESTING

SUMMARY

This study focuses on designing an innovative Glass Node for cable-net glass facade structures. The realization process of the Glass Node was done by establishing conceptual relationships between architecture and facade structures, conducting a literature review on previous studies that include technological and philosophical aspects, analyzing design principles of cable-net facade systems, and developing a point fixing component for cable-net facade. Literature review in this research consists of architectural discourses, which are generated by the philosophers and researchers, as well as it includes the development of facade technologies, and its relations with architectural design. In the context of this review, the history of lightweight structures, which are essentially based on Frei Otto's design approach of cable structures, classification of structural glass facades and cable-net facade component analyses according to related standards are also briefly displayed. As a result of the literature review, a research method is developed, which is de-recomposition of the elements of the target component in order to analyze and design an innovative point-fixing component.

After the literature review, design of the cable-net facade was performed in four stages which are architectural design of cable-net facade, structural design of cable-net structure, steel frame and insulated glass unit (IGU). The cable-net facade was designed as 5,136 m x 8,812 m which consists of 20 insulated glass units (IGU), $\Phi 14$ mm steel wire ropes, anchors, the Glass Node as point fixing components, sealants, and steel frame. After architectural design stage, the cable-net structure was designed, based on the Allowable Stress Design (ASD), ASCE19-16, AISC360-10 and ASCE 7-10. According to the analysis results, the maximum reaction force and deflection were observed at the combination of positive wind load, positive temperature load, dead loads, and prestress load of the designed cable-net. While the maximum reaction force at the pin support is 43,29 kN near the middle axes of structure, the maximum deflection is calculated to be 97,95 mm, observed at the fixing point located at midpoint of structure. If the structure is tested for strength and deflection limits according to related standards (59,95 N and 11,36 mm), it can be seen that the cable-net facade ensures the strength and deflection limits. After the cable-net facade design, a steel frame prototype testing was designed by using SAP2000 according to ASD and AISC360-10. As a result, the steel frame consists of 260x260x12 mm steel box profile beams with 100x100x10 mm steel braces and 260x260x12 mm box profile steel columns. Furthermore, as a final component, insulated glass units were analyzed at SJ Mepla Software. The maximum strength and deflection were determined to be 33,34 MPa and 9,20 mm respectively which also ensures the strength limit (80 MPa) and deflection limit (10 mm) of IGU.

Afterwards, the design of the cable-net facade, architectural and structural design, prototyping and testing process of the Glass Node is executed.

Design of the Glass Node was performed in two main steps; the architectural design and the structural design. The architectural design and dimensioning process were carried out according to the cable-net facade that was previously designed. The Glass Node was configured as a 170x170x10 mm prism-shaped steel/glass composite component. Moreover, it consists of 2 layers of laminated and tempered glass cap (TG103-1), 1 layer cross shaped stainless steel core (SS104), 4 layers tempered and laminated glass, (TG103-3), 2 layers tempered and laminated glass in two types (TG103-3 and TG103-4), two types of stainless steel bedding element (SS101 and SS103), 4 units stainless steel roll pins (SS102), 6 units M12 countersunk bolts (SS105) and POM bedding elements (PM101-1, PM 101-2, PM 101-3, PM 101-4, PM 101-5, PM 101-6). In accordance with the architectural design, the stainless steel and glass elements are bonded to each other via Sentryglass lamination and SikaFast-3131 methacrylate based adhesive¹.

Following the architectural design, structural analysis of the Glass Node was performed by using the Solidworks Software. During the structural design process, effective loads of the Glass Node were determined to be 2,4 kN wind load and 1,65 kN dead load of IGU. Furthermore, the analysis was conducted by making the model of the Glass Node as three separated parts which are the cap of Glass Node (TG103-1), the stainless steel cross shaped core (SS104) and the glass-stainless steel composites. From analysis; the most critical component was determined as the cap of the Glass Node of which the maximum stress is 29 MPa. This is less than the limit strength of a tempered glass (80 MPa) and it can be seen that all elements of the Glass Node ensure the design strength limits. Nevertheless, structural performance of the bonding materials was to be determined by way of testing. Therefore, a prototyping process and a manufacturing process were executed and afterwards, primarily bonding testing was performed in order to determine adequate bonding materials.

Prototyping process of the Glass Node was executed in two steps; design prototyping and engineering prototyping². The design prototyping was carried on by creating a 3D model of the Glass Node and printing all the elements via 3D printers. Afterwards, the 3D-printed Glass Node was assembled, and connections were evaluated in terms of their applicability. As a result, some revisions were added to the architectural design of the Glass Node, such as extra bedding materials, in order to prevent interaction between metal-glass elements. Afterwards, the process was carried out by manufacturing the Glass Node with real materials. Except the bonding of 2 units TG 103-3 and SS104, all the components were bonded via Sentryglass lamination material. However, 3 different adhesive materials (Sentryglass, Sikasil SG500 and SikaFast-3131) were used for bonding for TG103-3 and SS104.

After the bonding procedure, primarily tension test process was performed in order to determine the adequate adhesive for bonding of SS104 and 2 units TG103-3. Preliminary test procedure was executed according to DIN18008-3 and additionally the target strength values of Glass Facade were determined to be 2,4 kN (yield strength, F_a) and 7,2 kN (ultimate strength, F_t). All the test procedures were performed by using a tension test machine located at the Facade Testing Institute Laboratories at Çatalca, Istanbul and the results were video recorded. According to the test results, the most adequate adhesive is determined as SikaFast-3131 of which the yield (F_a) and ultimate strength (F_u) are respectively 10,36 kN and 11,54 kN. However, Sentryglass

¹ Elements are bonded as; TG103-1 and SS101, TG103-3 and SS103, 2 units TG103-2 and SS104.

² As it is mentioned previously, engineering prototyping is executed by computational analysis of the Glass Node via Solidworks Software.

(lamination sheet) and Sikasil SG-500 (structural silicone) could not reach the target strength values. Hence, SikaFast-3131 was used for the main test procedure of the Glass Node. When the test results are analyzed according to the failure type, it is seen that all samples fail due to bolt stripping. Therefore, M10 bolts were replaced by M12 bolts in order to reach higher tension strengths.

After revising the bolt types, the main test procedure was also executed according to DIN18008-3. 5 samples are tested, and the test data are recorded by using a software for test tension machine and a video camera. The test was performed in a stabilized environment of 30 °C and 80% humidity. According to the test results, the average ultimate breaking strength and maximum displacement were measured to be 19,22 kN and 10,22 mm, respectively. Moreover, while the maximum ultimate breaking strength (21,04 kN) and maximum displacement (12,68 mm) were observing Sample 5 and Sample 1 respectively. The minimum ultimate breaking strength (16,30 kN) were observed for Sample 2 and minimum displacement were determined to be (7,93 mm) for Sample 2 and Sample 3. Furthermore, average ductility ratio of test samples is calculated to be 1,33. The maximum and minimum ductility ratios were determined to be 1,59 for Sample 4 and 1,0 for Sample 2 respectively. As a conclusion, the strength of the Glass Node is 8 times greater than F_a (2,4 kN) and approximately 2,7 times greater than F_u (7,2 kN). Furthermore, when the failure types of the samples are analyzed; while Sample 1,2,3 and 5 fail by breakage of exterior cap of Glass Node (SS103-1), Sample 4 fails because of bolt stripping.

According to the test results, Glass Node ensures the design limits determined according to international standards and it could be assumed as an innovative cable-net facade component which can be integrated to full scaled cable-net facades. The same results show that the strength of the Glass Node is 8 times greater than F_a value and 2,7 times greater than F_u value, which means that the design of the Glass Node can be optimized in terms of architectural and structural design.

In conclusion, the study fulfills the objectives of the research by means of increasing transparency ratio of cable-net facade systems by %17 percent with satisfactory structural performance.



ÖZGÜN CAM DÜĞÜM NOKTALARINA SAHİP KABLO-AĞ CEPHELERİN GELİŞTİRİLMESİ, TASARIMI VE TESTİ

ÖZET

Çalışma mimarlık teknolojisi ve mimarlık felsefesi konularını baz alarak rüzgâr yükleri etkisi altında bir kablo-net cephe tasarımı ve bu cepheler için özgün bir birleşim elemanı tasarlama, geliştirme, üretme ve test etme süreçlerine odaklanmıştır. Çalışmanın amacı, kapsamı ve beklenen çıktılar 1. Bölüm’de açıklanırken, çalışmanın niteliğini arttıracak öğeler, kavramsal bağlamda cephenin mimari bir “söylem” haline gelme durumu ve hafif strüktürel sistemlerin kısa tarihi 2. Bölümde tartışılmış, 3. Bölüm strüktürel cam cephelerden biri olan kablo-ağ cephelerin teknik analizi üzerine yoğunlaşmıştır. 4. Bölümde ise ileriki çalışmalar için Çatalca’da bulunan Facade Testing Institute (FTI)’da sonradan gerçek boyutta inşa edilmesi planlanan, bir kablo-ağ cephe tasarlanmış ve etkin yükler altındaki davranışları hesaplanmıştır. 5. Bölüm’de kablo-ağ cam cephe için tasarlanmış olan “Cam Tutamaç”ın mimari tasarımı, dijital strüktürel analizleri, prototip geliştirme süreçleri, gerçek malzemelerle “Cam Tutamaç”ın üretimi ve 2 fazdan oluşan test süreci anlatılmıştır. 6. Bölüm olan sonuç bölümünde ise tüm çalışmanın çıktıları, olumlu ve olumsuz yönleri açıklanmıştır.

Çalışmanın ana amaçları cephe tasarımının mimari tasarımdaki rolünü anlamak, kablo-net cephelerin strüktürel tasarımına hakim olmak, kablo-net cephelerin transparanlık (saydamlık) yüzdesini arttırabilecek bir komponent tasarımı gerçekleştirmek, kablo-net cephelerin tektoniğini kavramak, cam-metal kompozitler hakkında özlü bilgi vermek ve bunu komponent tasarımına yansıtarak etkin yüklere karşı yeterli dayanıma sahip olan bir “Cam Tutamaç” tasarlamak, geliştirmek, üretmek ve dayanım testlerini gerçekleştirmek olarak tanımlanabilir. Bu bağlamda tezin ileriki bölümlerinde literatür araştırmaları yapılmış ve araştırmalar sonucunda ortaya çıkan bulgular tasarım süreçlerine yansıtılmıştır.

Literatür araştırması cephede transparanlık ve bunun iç-dış ile ilişkisinin kurgulanmasını, bu kurguda kablo-net cephenin bir ara mekân olarak potansiyellerinin belirlenmesini, bir kablo-net cephenin tekrar kurgulanması üzerine geliştirilen kavramsal bir komponent tasarımı metodolojisini, mimari akımların cephe tasarımına olan etkilerini ve Frie Otto odağında hafif strüktürlerin kısa tarihini kapsamaktadır. Ayrıca kavramsal tasarım ve yapı teknolojisi arasındaki ilişkiler çapraz okumalar ile güçlendirilmiş, mimarlık felsefesi ve yapı teknolojisi arasındaki yadsınamaz ilişkiler cephe ve komponent tasarımı üzerinden tekrar kurgulanmıştır. Bu kurgu özellikle bir sistemi, yapıyı ya da bir yapı bileşenini elementlerine ve ya da iç boyutlarına ayırarak (dekompozisyon) element bazında bir sistemin potansiyellerini araştırmak üzerine odaklanmıştır. Bu potansiyeller hem fenomolojik bağlamı hem de teknolojik gelişmeleri ve bu gelişmeleri sistemlere ya da yapı bileşenlerine entegre etmeyi içinde barındırmaktadır.

Kablo-net cepheler fenomolojik olarak ele alındığında transparanlık yüzdesi diğer cephelerden oldukça yüksek bir yapı elemanı sunmaktadır. Bu transparanlık yalnızca fiziksel olarak değil alt anlamlarıyla da yapı elemanını mimari olarak diğer cephelere göre daha farklı değerlendirmeye olanak sağlar. Transparanlık katmanlar arası ilişkilerin muğlaklaştığı iç-dış arasındaki ilişkilerin tekrar kurgulandığı bir sistemi temsil etmeye başlar. Bu nitelikli mimari ilişkileri içinde barındıran mimari öğeyi (cepheyi) detay tasarımı özelinde ele alıp teknolojiyi kullanarak geliştirmek hem mimari kavramsal tasarıma hem de yapı teknolojilerine katkı sağlayan bir süreci tanımlamaktadır. Bu bağlamda dekompoze edilmiş olan sistemler, farklı yapısal detaylar, farklı ve yenilikçi malzemeler ile tekrar tekrar bir araya getirilerek (rekompoze edilerek) tasarlanabilir ve bu tasarı yapı teknolojileri gerçekleştirilebilir hale gelir. Tüm bunların yanı sıra, modern mimarlık tarihi bu kavramsal yaklaşımların mimarlık pratiğindeki karşılıklarını kavramada oldukça önemli bir rehberdir. Modernizmle birlikte cephenin özgürlüğü mottosu yükselmiş, cephe taşıyıcı sistemden bağımsız hale gelerek kendi mimari artikülasyonlarını türetmeye başlamıştır. Ardından gelen postmodernizm ise modernizmin aksine cepheyi imgeleri temsil eden bir araç olarak ele almış ve gerektiğinde geleneksel yapı malzemeleri ve sistemlerinin kullanılabildiği bir araç olarak görmeye başlar. Ardından gelen dekonstrüktivizm ise cephe ve form ilişkisi üzerine odaklanarak, formları ve bu formlar üzerinde oluşan algıları yerinden etmeye odaklanmaktadır. Dekonstrüktivizm ile algıların tekrar kurgulanması aynı zamanda form, taşıyıcılık ve detay tasarımı konularını da etkileyerek, cephe tasarımında farklı bakış açılarıyla tasarlama süreçlerini hızlandırmıştır. Son ve en önemli sayılabilecek mimari akım olarak high-tech örnek gösterilebilir. Bu akım ile birlikte artık taşıyıcı sistem kavramsal tasarımın bir ögesi haline gelecek, saklanan, üzeri kapatılan bir yapı bileşeni olmaktan çıkmaya başlayacaktır. Bu noktada yapılan tez çalışması, özellikle high-tech ile güçlü bağlar kurmaktadır. Kablo-ağ cephenin taşıyıcı sistem tasarımıyla mimari bir öğe olarak var olma durumu, kurgulanan strüktür-mimarlık ilişkisinin ne kadar nitelikli olabileceğini göstermektedir. Bu bağlamda hali hazırda var olan kablo-net cephe sistemlerinin taşıyıcı komponentlerinin mimari estetik kaygısı güderek yeniden tasarlanması hem yapı teknolojisine hem de kavramsal tasarıma oldukça önemli katkılar sağlayacaktır. Hafif strüktürel tasarımın kısa tarihine bakıldığında da strüktürün mimari bir öğe haline gelme durumu oldukça sık ortaya çıkar. Shukov ve Le Recolais'ın çağdaşı Frei Otto hem mimari hem de strüktürel tasarımlarını üstlendiği yapılarıyla gergili sistem tasarımı hakkında oldukça detaylı bir rehber görevi görmektedir. Bu sebeple, çalışmanın teknik analizleri ve tasarım süreçleri de Otto'un tasarım prensipleri baz alınarak sürdürülmüştür.

3.Bölüm ile birlikte strüktürel cam cephelerin sınıflandırılması ve strüktürel cam cephelerde olan kablo-net cephelerin tasarım prensipleri ve yapısal bileşenleri detaylı olarak incelenmiştir. Kablo-net cepheler binaların ana taşıyıcı sistemlerine gerektiğinde ikincil bir taşıyıcı sistem kurgulanarak entegre edilen, ana taşıyıcıları paslanmaz çelik halatlar olan, cam paneller ve bu cam panelleri halatlara bağlayan genellikle paslanmaz çelikten üretilen tutamaçlara sahip özgün, transparanlık oranı oldukça yüksek bir cephe sistemidir. Bu cephe sisteminin mimari ve strüktürel detay tasarımlarını anlamak amacıyla cephe bileşenleri bazında detaylı bir literatür araştırması yapılmış ve bileşenleri oluşturan malzemelerin mekanik özellikleri ulusal ve uluslararası standartlarda yararlanılarak derlenmiştir. Araştırmalar sonucunda özellikle paslanmaz çelik halatların mekanik özellikleri ve türlerine göre cam malzemenin strüktürel potansiyelleri belirlenmiştir.

4. bölümde, 2. ve 3. Bölüm’de yapılan araştırmalar ışığında Facade Testing Institute (FTI)’da bulunan 7,009 m x 11,986 m boyutlarında betonarme test standına entegre edilecek şekilde 5,136 m x 8,812 m boyutlarında bir kablo-ağ cephe tasarlanmıştır. Tasarlanan cephe 20 adet 1 m x 2m yalıtımlı cam paneller, $\Phi 14$ mm çelik halatlar, sabit ve ayarlanabilir kablo bağlantı aparatları, cam panelleri kablolarla noktasal olarak bağlayan 12 adet “Cam Tutamaç”, strüktürel ve dolgu silikonlarından oluşmaktadır. Ayrıca kablo-net strüktürü ana betonarme taşıyıcıya bağlayan çelik bir iskelet sistem tasarlanmış ve cephe tasarımına entegre edilmiştir. Mimari tasarımı tamamlanan kablo-ağ cephenin strüktürel dayanım analizleri, kablo-ağ, çelik iskelet ve yalıtımlı cam paneller için 3 ayrı fazda gerçekleştirilmiştir. Kablo-ağ cephenin strüktürel analizi Emniyet Gerilmelerine Göre Tasarım (ASD) prensipleri doğrultusunda ASCE-19-16 ve AISC 360-10 standartlarına göre SAP2000 programında yapılmıştır. Analizden önce cepheye etki eden yükler belirlenmiş ve ASCE7-10’a göre yük kombinasyonları kurgulanmıştır. Konusu geçen standartlar çerçevesinde limit dayanım ve deplasman değerleri³ 59,95 kN ve 110,36 mm (L/50) olarak belirlenmiştir. Ayrıca Sisteme etkileyen yükler, pozitif ve negatif rüzgâr yükü (W ; $\pm 8 \times 10^{-7}$ kN/m²), negatif ve pozitif sıcaklık (T ; ± 30 °C), iki yönde etkilenen deprem yükleri (EQX ve EQY), sistemin ölü yükü (D), cam panellerin ölü yükü (SDL ; $+6 \times 10^{-7}$ kN/m²) ve son olarak strüktürün stabilitesini sağlayan ön germe kuvvetidir (PR , -35 kN). Buradaki en önemli nokta ön germe kuvvetinin optimizasyonudur. Sisteme etkiletecek olan ön germe kuvveti seçilen kablonun gerilme-şekildeğiştirme oranına (strain) bağlıdır. Bu nedenle, optimizasyon bu oranın değişimine göre yapılmıştır. Sonuç olarak en elverişsiz kombinasyon pozitif rüzgâr, pozitif sıcaklık, ölü yükler ve ön germe kuvvetinin olduğu LC04 kombinasyonu olarak belirlenmiştir. LC04 etkisindeki sabit mesnet ile bağlanmış cephede gözlemlenen maksimum tepki kuvveti 43,29 kN olarak cephenin orta aksında bulunan mesnet noktalarında görülmüştür. Bunun yanı sıra maksimum deplasman da 97,95 mm ile cephenin orta noktasında bulunan düğüm noktasında oluşmuştur. Analiz sonuçlarına bakıldığında; maksimum tepki kuvveti ve deplasman değerleri optimizasyon sonucunda limit değerlerin altında kalmayı başarmıştır. Kablo-ağ strüktürün analizi sonucunda elde edilen tepki kuvvetleri kullanılarak betonarme test standı ile cepheyi birbirine bağlayan çelik iskelet sistemin boyutlandırılması gerçekleştirilmiştir. Tasarım ve boyutlandırma kablo-ağ strüktürde olduğu gibi Emniyet Gerilmelerine Göre Tasarım (ASD) ve AISC 360-10’a göre yapılmıştır. Yapılan analiz ve tasarım sonucunda 260 mm x 260 mm x 12 mm kirişler ve bu kirişleri ikili olarak birbirine bağlayan 100 mm x 100 mm x 10 mm ebatlarında çaprazlar kullanılmıştır. Ayrıca kolonlar da 260 mm x 260 mm x 12 mm olarak boyutlandırılmıştır. Çelik iskeletin tasarımı sonrasında cephede kullanılacak olan cam panellerin DIN18008’e göre etkin rüzgâr yükleri altındaki davranışı SJ Mepla yazılımı kullanılarak analiz edilmiştir. Analiz sonuçlarına göre maksimum gerilme camların tutamaçlar ile sabitlendiği noktalarda 33,34 MPa olarak gözlemlenirken, maksimum deplasman ise 9,20 mm’dir. Cam panelin limit dayanım ve deplasman değerleri ise sırasıyla 80 MPa ve 10 mm’dir. Bu limit değerler göz önüne alındığında cam panelin ilgili standartları karşıladığı belirlenmiştir. Kablo-ağ cam cephenin tüm tasarım ve strüktürel analizleri tamamlanması ile birlikte bu cepheye etkileyen yükler göz önüne alınarak özgün bir “Cam Tutamaç” tasarlanarak prototip geliştirme, gerçek malzemeler ile üretimi, ön ve ana dayanım testlerinin yapılması işlemleri sırasıyla uygulanmıştır.

³ L, cephenin kısa açıklığıdır.

Cam Tutamaç tasarımı ön mimari tasarım, final mimari tasarım ve strüktürel analiz olarak üç ana faz olarak gerçekleştirilmiştir. Öncü mimari tasarım kablo-net cephenin boyutları göz önüne alınarak 3 boyutlu olarak modellenmesi ve kavramsal tasarımını kapsar. Ardından uygulama detayında mimari çizimler ile Cam Tutamacın mimari tasarımı tamamlanmıştır. Yapılan tasarım cam-metal kompozit bir yapıda olup 170 mm x 170 mm x 170 mm boyutlarında prizmatik formdadır. Ayrıca Cam Tutamacı meydana getiren elementlerin; en dışta 2 katmanlı temperli lamine camdan oluşmuş ortasında havşa delikli bir kapak (TG103-1), haç şeklinde paslanmaz çelik bir gövde (SS104) ve bu gövdeye yapıştırılan iki adet 4 katmanlı lamine temperli cam modülü (TG103-2), yivli iki adet çubuğun haç şeklinde kaynaklanması ile oluşturulan paslanmaz çelik kablo yatağı (SS103) ve bu kablo yatağına lamine edilmiş 2 katman temperli cam (TG103-3), yivli bir adet paslanmaz çelik kablo yatağı (SS101) ve bu yatağa lamine edilmiş 2 katman temperli lamine cam (TG103-4) olduğu görülür. Tanımlanan katmanlar 4 adet içine dış açılmış paslanmaz çelik pim ve bu pimleri birbirine bağlayan M12 bulonlar ile birbirine bağlanmıştır. Ön kapak ise SS104 paslanmaz çelik gövdeye yine M12 bulon ile monte edilmiştir. Mekanik bağlantıların güvenli bir şekilde yük aktarması ve metal-cam arasındaki olası etkileşimi önlemek adına POM ve alüminyum malzemeden üretilmiş conta ve tamponlar tasarlanmıştır. Final mimari tasarım Cam Tutamacın strüktürel analizi ve öncü deneyler sonucunda tamamlanmıştır.

Cam Tutamacın strüktürel analizi Solidworks yazılımı ile yapılmıştır. Analizde kullanılacak etkin yükler kablo-net cepheye etkiyen rüzgâr yükü (2,4 kN) ve cam panellerin ölü yükü (1,65 kN) baz alınarak hesaplanmıştır. Cam Tutamaç ön kapak, paslanmaz çelik gövde ve kabloları stabil hale getiren paslanmaz çelik-cam kompozit elemanlar olarak 3 ayrı fazda modellenmiş ve etkin yüklere göre analiz edilmiştir. Analiz sonuçlarına göre Cam Tutamaçta gözlenen maksimum gerilmeler; ön kapakta (TG103-1) 29 MPa, paslanmaz çelik gövdede 4 MPa ve paslanmaz çelik-metal kompozitlerde 5 MPa olarak belirlenmiştir. Elemanların limit dayanımları ise ilgili standartlara göre sırasıyla 80 Mpa, 195,45 MPa ve 80 MPa'dır. Bu değerlere göre tüm elemanların limit dayanımların altında kaldığı ve en elverişsiz elemanın ön kapak (SS103-1) olduğu sonucu görülmüştür. Ancak, dijital strüktürel analiz sonuçlarına ek olarak prototipleme süreci sonrasında metal-cam birleşimini sağlayan yapıştırıcıların strüktürel dayanımlarının deneysel olarak tespit edilmesi gerekmektedir.

Cam Tutamaç'ın prototipleme süreci tasarımsal prototipleme ve mühendislik bağlamında prototipleme olarak iki ana fazda ilerletilmiştir. Tasarımsal prototiplemenin son adımı olarak dijital olarak 3 boyutlu modeli oluşturulmuş Cam Tutamaç, 3 boyutlu baskı makineleri ile gerçek boyutunda polimer esaslı bir malzeme olan poliamidten basılmış ve mimari detayları ile ilgili gereken kontroller yapılmıştır. Kontroller ışığında metal-cam etkileşimini önleyecek POM tamponlara ekler yapılmış ve tasarım revize edilmiştir. Tüm revizyonlardan sonra gerçek boyutlarda ve gerçek malzemeler kullanarak Cam Tutamaç'ın üretim sürecine geçilmiştir. Cam Tutamaç genel olarak strüktürel yapıştırma yöntemleri ile üretilen bir yapıya sahiptir. Bu bağlamda cam-metal birleşimleri, SS104 ve 2 adet TG103-2'nin yapıştırılma prosesi dışında Sentryglass laminasyon malzemesi ile yapılmıştır. Laminasyon süreci özellikle cam-metal birleşimleri için oldukça dikkat gerektiren ve ilgili uygulama rehberleri eşliğinde yürütülen bir çalışmadır. Laminasyondan beklenen en büyük performans yüzeylere kabarcık oluşmadan yapışmanın sağlanmasıdır. Bu bağlamda otoklav derece ve süreleri deneysel olarak belirlenmiş ve kabarcıksız bir yapışma tüm elemanlar için sağlanmıştır. Ancak SS104 ve 2 adet TG103-3 ün birbirine yapışma süreci için üç farklı yapıştırma malzemesi seçilerek uygulanmıştır. Bu malzemeler; Sentryglass

laminsasyon malzemesi, Sikasil SG500 strüktürel silikon ve metakrilat bazlı bir yapıştırıcı olan SikaFast-3131'dir. 3 ayrı malzeme ile yapıştırılmış 3 ayrı Cam Tutamaç numunesi için SS104 ün 2 adet TG103-1'e yapışmasını sağlayacak en uygun malzemeyi belirlemek amacıyla bir ön test uygulanmıştır.

Ön test DIN18008-3'e göre kurgulanmış ve hedef dayanım değerleri 2,4 kN (akma dayanımı, F_a) ve 7,2 kN (kopma dayanımı, F_u) olarak belirlenmiştir. Facade Test Institute (FTI) 'da bulunan çekme cihazında yapılmış ve tüm süreçler kamera ile kayıt altına alınmıştır. Test sonuçlarına göre en iyi dayanıma sahip olan yapıştırıcı 10,36 kN F_a ve 11,54 kN F_u değerleriyle SikaFast-3131 olmuştur. Bu sonucun yanı sıra, Sikasil SG500'ün akma değeri 4,60 kN ve kopma değeri 6,84 kN olarak, Sentryglass'ın akma değeri 1,1 kN ve kopma değeri 4,48 kN olarak ölçülmüştür. Dayanım değerlerine ek olarak Cam Tutamaç'ın göçme modlarına bakıldığında; SikaFast-3131 ile yapıştırılmış numunede ön kapakta bulunan bulonun kayması ile göçme, diğer numunelerde ise yapıştırıcının kopması ile göçme gözlemlenmiştir. Bu nedenle, ilk aşamada M10 olarak tasarlanmış olan bulon çapları alüminyum contalar kullanılarak M12 olarak değiştirilmiş ve böylece Cam Tutamaç'ın mimari tasarımı tamamlanmıştır. Tüm bu süreçlerin ardından SikaFast-3131 ana deneylerde kullanılmak üzere hazırlanacak numunelere uygulanmıştır.

Ana deneyler 5 adet numune üzerine uygulanmış, tüm deney süreçleri kamera ile kayıt altına alınmış, deney dataları ve bu datalar sonucunda oluşan kuvvet-yerdeğiştirme grafikleri de çekme test cihazının yazılımı sayesinde elde edilmiştir. Tüm bunlara ek olarak ortam koşullarına bakıldığında, sıcaklığın 30 °C ve ortam neminin %80 olduğu belirlenmiştir. Ana deney sonuçlara göre Cam Tutamaç'ın ortalama kopma dayanımı 19,22 kN, ortalama maksimum yer değıştirmesi ise 10,22 mm olarak belirlenmiştir. Ayrıca maksimum kopma dayanımı ve yer değıştirme değerleri 21,04 kN ve 12,68 mm olarak Numune 1'de gözlemlenirken, minimum kopma dayanımı ve yer değıştirme 16,30 kN (Numune 2) ve 7,93 (Numune 2 ve 3) mm olarak belirlenmiştir. Numunelerin süneklik oranlarına bakıldığında ortalama sünekliğin 1,33 olduğu, maksimum sünekliğin 1,59 değeri ile Numune 4'te ve minimum süneklik değeri 1,00 olarak Numune 2'de olduğu görülmektedir. Bu bağlamda Numune 2'nin sünek olmayan bir davranış ile göçme moduna direk olarak geçtiği görülmektedir. Dayanım ve yer değıştirme değerlerine ek olarak Numune 1,2,3 ve 5 ön kapağın kırılması ile göçme haline geçerken, Numune 4'te bulon kayması şeklinde göçme meydana gelmiştir. Hiçbir numunede yapıştırıcı kaynaklı bir göçme gözlemlenmemiştir.

Yukarıda açıklanan tüm süreçler göz önüne alındığında Cam Tutamaç DIN18008-3'e göre belirlenen hedef dayanımların oldukça üzerinde bir strüktürel performansa sahip olduğu sonucu ortaya çıkmaktadır. Bununla birlikte, Cam Tutamaç'ın ortalama dayanımı 2,4 kN olan F_a değeri 7,7 kat, 7,2 kN olan kopma değeri 2,6 kat büyüktür. Bu bağlamda ileriki çalışmalar için Cam Tutamaç'ın optimizasyonu üzerine çalışmak oldukça yararlı olacaktır. Ayrıca tüm üretim süreçleri göz önüne alındığında; Cam Tutamaç'ın gerçek boyutlarda tasarlanmış ve inşa edilecek bir kablo-net cepheye rahatlıkla entegre olabilecek, cephenin transparanlığını %17 oranında arttırabilecek bir cam düğüm noktası komponenti olduğu açıkça görülmektedir.



1. INTRODUCTION

1.1 Motivation

Cable-net glass envelope systems are worthwhile building systems for designing innovative and modern constructions all over the world. An envelope as an interlayer element between outer and inner spaces, which is based on concept of transparency, can be defined as a profound movement for architectural technology and design theory fields simultaneously. In this context, transparency can be re-evaluated in terms of structural engineering disciplines regarding architectural sensibility. At that point, investigating the limits of transparency is a quite interesting research field in order to understand potentials of light-weight structural glass envelopes such as cable-net facades.

Cable-net facades are envelope systems which fulfill the high displacement limit conditions against effective wind loads. Load bearing system of cable-net facades is provided by pre-tensioned steel cables. Furthermore, there are several types of joint elements that enable to support the structural system. Therefore, this study focuses on two related subjects mentioned above; investigating behavior of cable net facades under effective wind loads and designing innovative point-fixing components.

Innovation of joint elements of cable-net facades can be a quite essential move in order to maximize transparency of building skins. Therefore, designing a cable-net facade in order to develop innovative point fixing components can be regarded as an essential design strategy. Moreover, investigating structural potential of transparent materials such as glass can also enable to develop an innovative point fixing component. With that aspect, point fixing components of cable-net facades can be configured as transparent as possible in order to emphasize the transparency concept integrated to architectural articulation of cable-net facades. In order to realize the conceptual ideas mentioned above, after designing a cable-net facade, a novel “Glass Node” is developed and tested here in following the available international and national regulations and standards in this study.

1.2 Purpose

The study focuses on mainly three subjects; investigation of the relationship between architectural configuration of cable-net facades and their structural potentials, tectonics of cable-net facades and innovative component design. The main aim of focusing on these three subjects is to develop a cable-net facade system which enables to reach maximum possible transparency with their innovative point fixing components. Moreover, in order to achieve that, there are several determined sub-aims a listed below;

- Understanding the role of facade design in architectural design,
- Understanding the structural design of cable-net facade with a literature review study,
- Developing architectural detailing of adequate cable-net facade design,
- Understanding and analyzing tectonics of cable-net facade,
- Investigating innovative structural materials in order to integrate them with Glass Node design,
- Creating a composite, transparent, structurally sound Glass Node component for cable-net facades,
- Understanding prototyping and manufacturing process of glass-metal composites and executing the process,
- Executing experimental process in order to realize conceptual design of Glass Node.

All sub-aims mentioned above provide understanding and developing the main aim which is to design Glass Node for cable-net glass facade.

1.3 Scope

The study includes literature review about cable-net facade tectonics, architectural movements related to facade technologies, realization of conceptual theories with regard to conceptual facade design, transparency and its effects, lightweight structural design history and its effects to cable-net facade technology. Moreover, the study also mentioned facade design and its spatial configurations with regard to the relationship

between interior and exterior spaces. Besides the literature review, the study consists of architectural and structural design of a prototype cable-net facade specimen in accordance with an existing reinforced concrete (RC) test setup placed at the FTI laboratories, both architectural and structural design of a Glass Node are performing following prototyping and testing processes. Note that testing part of this work includes the Glass Node specimen with various manufacturing properties. Although design of the whole facade components is conducted, system-wise testing has been excluded and left for a future potential experimental work.

1.4 Objectives

Main objective of study is to design an applicable innovative cable-net facade component which is approved by an experimental process in accordance with international standards and regulations. Moreover, besides designing, prototyping and testing the Glass Node, establishing a strong relationship between architectural and structural designs is one of the substantial objectives of this work. When investigation and realization of the ideas; all sub-meaning of creating a structure, can emerge. This is the non-negligible criteria that all architectural and structural designers should consider in order to produce qualified architectural configurations. Therefore, the study always takes a position in between architecture and structural design disciplines.

In addition to the objectives mentioned below, the study also emphasizes the importance of interdisciplinary study approaches for the development of a structural component. Therefore, the study can be considered as a guideline for future investigators that intending to study on interdisciplinary research.



2. RE-CONFIGURATION OF CABLE-NET FACADES

Cable-net facades are generated by several literal and phenomenal components which determine characteristics of a building facade and its surroundings. With that aspect, cable-net facades can be analyzed in terms of conceptual theories and architectural tectonics. While conceptual theories focus on sense of creation and sub-meanings of the architectural articulations, investigating the tectonics of the facade systems enables to understand the relationships of components that enable to realize conceptual designs. Moreover, tectonic researches help to generate an innovative component design which is directly related to building technology research field. At that point, integration of conceptual design theories into building technology studies can enable to re-configure cable-net facades. In this chapter, cable-net facades are analyzed in the context of the intersection of design theories and tectonics in terms of facade design.

2.1 Cable- Net Facade Tectonics

Tectonics in architecture is defined as “science of art of construction, both in relation to use and artistic design”(Maulden, 1986). The definition enables artistic value of architectural design to be comprehended. Understanding the tectonics of architectural production depends on analyzing the design parameters and dimensions. According to Maulden, the analysis reveals the transformation of the physical elements into metaphysical concepts (Maulden, 1986). For instance, load-bearing components of a building also embody the effect of light, transparency, void, sense and movement besides its main function. This embodiment creates abstract atmosphere of architectural creation. At that point, tectonic studies provide understanding the coalescing of the atmosphere which pioneers experimental architectural research. With those aspects explained above, can be also integrated into design process of cable-net facade design.

Cable-net facades differ from traditional claddings in terms of their structural system elements, containing artistic design values besides their load-bearing function.

Therefore, using tectonics to re-configure innovative structural glass envelopes can be regarded as an essential design approach.

Tectonics in architecture establish mutual relations with other disciplines such as philosophy. Deleuze and Guattari also mention tectonics in architecture in an abstract way in their articles. They approach architecture by dissolving it to parameters and dimensions in order to comprehend sub-meanings of the architectural articulations. Deleuze discussed parameters and dimensions of architecture through redefining body. Body can be anything such as building, body of human or a component (Ballantyne, 2007). According to Deleuze body can be dissolved as longitudes and latitudes which correspond to unformed elements and sensory acquisitions (Deleuze, 1988). This dissolution helps to understand the dynamics of physical and sensory parameters of body. After dissolution, longitudes and latitudes can be re-composed in many various possibilities. The process of re-composition can be defined as generating of form which is part of the body. Ballantyne also mentioned the creation of form; “A precondition for finding form is to be without form, to suspend the condition of having form so that a new possibility can emerge” (2007). With this discourse, cable-net facades can be re-defined by way of decomposition and re-composition method. Thus, form is evolved from formlessness. With that formlessness, infinite possibilities of emerges and innovative designs can derive themselves in a loop. Hence, this approach is also quite adequate to investigate new technologies and design novel facade components.

2.2 Transparency, Structure, and Architectural Movements

Realization of the conceptual theories grow with architectural movements. With Modernism Movement, innovative materials revealed, and new structural components were designed as a part of building envelope (Sönmez, 2011). By means of combination of new materials, modernism helps to perceive “envelope” as a designable component of building. Le Corbusier and Pierre Jenet also emphasized the freedom of facade as one of the five design parameters in architecture (Conrads, 1971). Freedom facade discourse not only defines separation of inner and outer structural systems but also emphasizes the innovative usage of glass elements. Thus, transparency concept becomes quite substantial parameter of building envelopes. According to Rowe and Slutzky, transparency concept inholds phenomenological and

literal meanings (Rowe & Slutzky, 1963). These meanings are also the parameters that enable to enrich building envelope design. Literal and phenomenological meanings of transparency help to comprehend the relation between material, form and essence of envelope (Rowe & Slutzky, 1963). This approach has some similarities with Deleuze and Guattari's de-composition of architecture theory which is also explained previously. However, Rowe and Slutzky establish a relationship between analytical cubism and transparency by analyzing Le Corbusier's "Villa Stein" and Leger's "Three Faces" (Rowe & Slutzky, 1963). As seen at Figure 2.1 Leger's refers to merely phenomenological meanings of transparency while Le Corbusier's contains both.

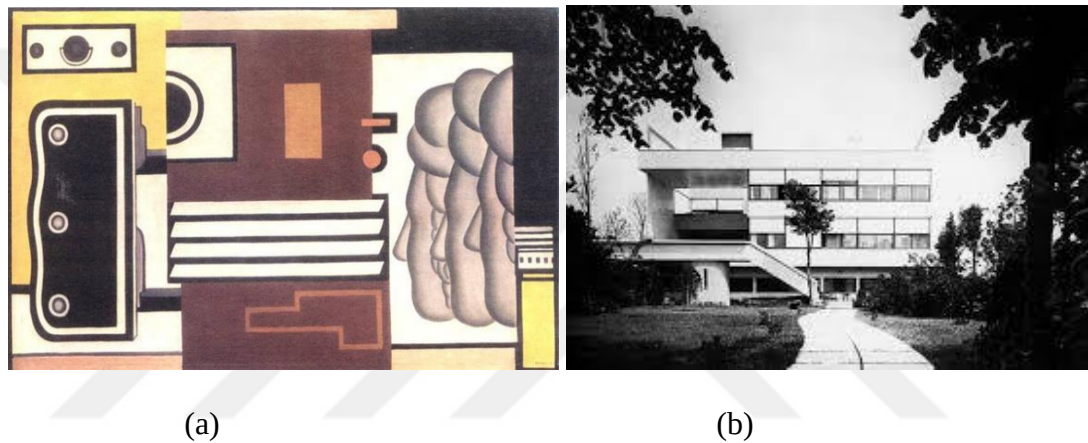


Figure 2.1 : Transparency: (a) Villa Stein by Le Corbusier (Url-1), (b) Three Faces by Leger (Url-1).

Contrary to Modernism, Ancient and Renaissance Architecture evaluated the envelope that was an expression of inner organization of building (Violette-Le-Duc, 1858). But, modernism movement has opened the way for structural independency to building envelope by using secondary structural elements. Thus, building envelope was separated from a mass of building. Nonetheless, modernism was not intended to refer to any specific idea or historical reference by using building envelope, on the contrary; modernism focuses on understanding of potentials of new materials and makes the components functional. On the other hand, postmodern architecture uses building envelope as a separated component which gives historical references (Schumacher, 2010). Unlike modernism, postmodern architects do not hesitate to use traditional construction methods and materials to express the conceptual imaginary (Figure 2.2).



(a)

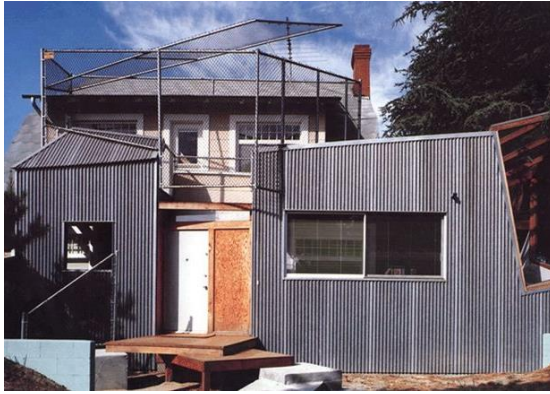


(b)

Figure 2.2 : Postmodernism: (a) Harold Washington Library, 1991 by Hammond, Beeby Babka (Url-2), (b) Resorts World, 2012 by Graves, (Url-3).

Despite contradiction between modernism and postmodernism, these two architectural movements have pioneered correlation of technological developments and design theories. With this correlation, new movements and manifestos such as Deconstructivism and Structural Expressionism were revealed (Düzgün & Polatoğlu, 2016).

Deconstructivism arises with discourses by Derrida. Derrida focuses on dissolving architectural elements in order to open the way to new practice in architecture (Vitale, 2010). New practice in architecture can appear as finding new forms, designing new structural components and analyzing the phenomenological meanings of architectural productions. Furthermore, realization of Deconstructivism in architecture occurs by distorting and dislocating of architectural components (Hoteit, 2015). As seen in Figure 2.3, Gehry's design articulates the distortion and the dislocation of building envelope. Furthermore, Prix's design focusing on distortion of a transparent rectangular prism (Figure 2.3). Unlike Gehry's, Prix's dissolution is more abstract in terms of deconstruction. Besides, Prix also uses glass units to make inner organization readable from outside. As seen in Prix's design, deconstructivism uses the transparency in order to express conceptual configurations. Thus, transparency of facade enriches artistic values of building. Dislocation and distortion glass envelopes are possible due to technological improvements. Technology gives opportunity to realize literal and phenomenological transparency.



(a)



(b)

Figure 2.3 : Deconstructivism (a) Gehry House, 1978 by Frank Gehry, Santa Monica CA, USA (Url-4). (b) UFA Palast, 1998 by Prix, Dresden Germany (Url-5).

With respect to extraordinary form construction, Deconstructivism pioneers to design innovative structural component indirectly. On the other hand, Structural Expressionism (High-Tech Architecture) enables to develop structural glass envelopes in an effective way. Structural expressionism uses steel and glass as a main material of architectural design in order to reveal artistic value of structural components (Davies, 1988). Thus, the structure of the building does not need to be hidden via exterior cladding or plasters. This approach refers to Modernism according to usage of load bearing systems. On the other hand, there is a difference between Modernism and Structural Expressionism. While Modernism focused on merely functionalities of structural components, Structural Expressionism symbolizes the technology by way of using structural components and service systems as an artistic element of architecture (Davies, 1988). Thus, structure and service systems exposed themselves as a sense of architecture.

In Figure 2.4, Calatrava uses light-weight structural components such as tensioned cables, steel and glass. Calatrava considers the functionality and aestheticism of structural components in his architectural configurations. Structure realizes building envelope by itself. This approach reflects multidisciplinary studies between architecture and civil engineering.



Figure 2.4 : Campo Volantin Bridge, 1997, Bilbao, Spain 1997 by Calatrava (Url-6).

Evolution of architectural movements leads to improvement of innovative structural glass facades and its components by using building technology integrating design theories. Thus, at the intersection of architecture and civil engineering, re-configuration of structural glass envelope can be realized. Using lightweight steel structure and glass in different variations is enabled by effect of Structural Expressionism and Modernism. Moreover, Deconstructivism also supports the idea of dissolution of structure which enables to create new possibilities of building envelope design. Structural glass envelopes are sort of architectural expression of art and design. Especially, structural glass envelopes which is designed with the aim of using minimum load-bearing component is one of the considerable types of glass envelope systems. One of the most innovative types of structural glass envelope is Cable-Net Glass Facades which are suspended by stainless steel cables.

As seen in Figure 2.5, Cable-net facade is point fixed and carried by stainless-steel cables. The light weight load-bearing elements of the structure reflects the idea of pushing the limits of the structure. Therefore, analyzing the dynamics of the structure of cable-net facades and developing innovative components regarding transparency are quite substantial research subjects for building technology studies.



Figure 2.5 : Cable-net facade (Url-7).

2.2.1 Relation Between Structure of Facade and Its Spatial Configuration

Understanding the relation of structural design and spatial configuration is a remarkable subject in contemporary architectural studies. With Industrial Evolution, modern technologies began to be used to develop innovative design and construction methods (Sezer, 2017). One of the substantial parts of these developments emerges at intersection of structural and architectural design. According to Clark and Pause (2012), components of structure enable to express architectural concepts such as frequency, pattern, simplicity, regularity, randomness and complexity which define space, create units, articulate circulation, suggest movement or develop composition and modulations. Thus, Clark and Pause emphasize non-negligible role of structural components related to spatial configuration. Moreover, Le Corbusier also stated the importance of relation between spatial configuration and structure; “Light creates ambiance and feel of a place, as well as the expression of structure” (Brooker, 2012). In this context, building envelope can be perceived as a part of spatial configuration.

Building envelope can be defined as an interface creating new correlation between the body of building and its surroundings through using innovative structural designs. For

instance, using light-weight load bearing systems and wider glass units changes the topology of the building envelopes dramatically. Maximizing the transparency of building envelope also enables to create connection between inner and outer spaces in various combinations. Transparency of the glass reveals the literal and phenomenological dimensions -which are mentioned previously- of building envelope. In this context, building envelope has a structure that does not separate the interior and the exterior from each other. On the contrary, it creates in-between spaces that support derivatives of spatial configurations by way of expression of the structure. Frei Otto, architect and civil engineer also mentioned the relation between derivation/re-creation of spaces by structural design. According to Otto, structural components determines the architecture (Aldinger, 2016). With this aspect the structure of the facade can be defined as a system that acts like “interlayer” which determines the form of building skin. Furthermore, structural gestures in building skins also enable to balance between urban and architectural configurations using inner and outer spaces. One of these configurations can be seen at Cable-Net Facade of Yapı Kredi Cultural Center which is shown at Figure 2.6.



Figure 2.6 : Yapı Kredi Cultural Center, 2017 by Teğet Architecture & Metal Yapi (Url-8).

Cable-Net Facade of Yapı Kredi Cultural Center enables express architectural configuration to urban dramatically. According to project report; “The content of the building becomes visible to the city as much as the city is visible from the building. It is an inside-out building which sustains a dialogue with the city” (Kütükçüoğlu & Uçar, 2017). The dialog is created by using phenomenological and literal transparency

by means of innovative building technologies. The facade reflects inner to outer by way of transparent cable-net. Thus, the interlayer becomes a connection component more than a separator for its surroundings. This effect of structure can be perceived as an innovative path for re-definition and re-creation of building skins by using structural elements as a part of spatial composition. Moreover, according to Hasol in the process of building design, the building envelope's orientation at urban scale and detail scale is a quite considerable subject to recapture architectural imagery by means of structure-related facade design (2011). Recapturing the architectural imaginary is a quite considerable subject that must be regarded by both architects and structural engineers. Philosophical foundations of the project are created during the conceptual design which can be realized by structural engineering technologies. As a result, developing innovative technologies contribute to architectural imaginary directly. Cable-net facades differ from other building envelope systems by means of creating a unique architectural experience. The facade carried by delicate steel cables creates an in-between space which generates new architectural possibilities. Therefore, minimizing the load-bearing components improves the spatial configuration in a unique way. Space is re-defined via interaction between transparency and structure of building envelope. Furthermore, in between space created by cable-net facade is defined as an interaction with urban dramatically. Interdisciplinary studies between architecture and structural engineering provide such an experience by using the relationship between transparency and structure. As a result, cable-net facades are advanced structural glass envelopes in terms of its spatial configuration that is created by itself.

2.4. Evolution of Lightweight Structures and Their Relationship with Cable-Net Facades

Structure and architectural design are engaged with various design aspects in history. The role of structure in architectural design evolved with technological improvements and design trends simultaneously. According to MacDonald, structure can be evaluated as an ornamented component of building, an ornament of building, expression of architecture or form generator (2001). Even secondary roles of structures change in time, initial performance of the structure is to be adequate load bearing capacity in most economical way. Therefore, studies about developing the performance of lightweight load bearing components have been carried on for a long time. Collaboration of structural engineers and architects, lightweight structures enable

to generate extraordinary architectural configurations such as “Structural Glass Facade Technology”. One of the most dematerialized Structural Glass Facades is “Cable-Nets” which is developed by inspiration from design principles of lightweight structures. Therefore, historical review of lightweight structures is carried on in order to understand design approaches and potential features for facade technologies.

Lightweight structures have been constructed in decades. One of the primitive examples of lightweight structures are yurts used by nomads in Asia. Ancient yurts comprise complex grid shells which can be assembled, disassembled and reassembled easily (Aldinger, 2016). As seen in Figure 2.7, yurts consist of thin wooden structural component and their coverings.

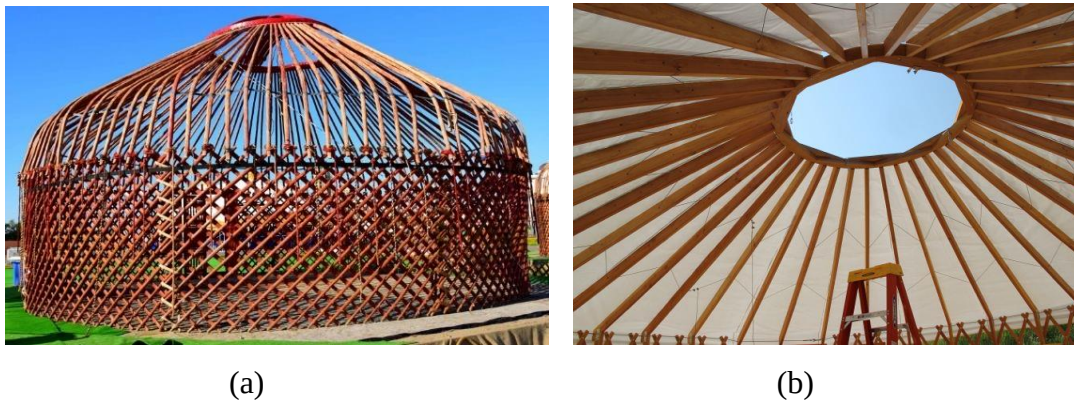


Figure 2.7 : Primitive lightweight structures: (a) Structure of yurt (Url-9), (b) Roof structure of yurts with covering (Url-10).

Yurts are primitive examples of grid shell structures and design principles are inspiring for contemporary structures. In addition to yurt’s lightweight structure, many researchers and inventors such as Da Vinci and Galileo, studied on eliminating the load bearing components in their studies. However, bending moment of the traditional materials is quite limited for large spans and thinner sections. Therefore, lightweight structures became distinguished with the invention of cast iron and steel production. In the 18th century mass production of cast iron could manufactured in England (Cowan, 1966). Afterwards, in 1781 the first iron structure (Iron Bridge) was designed over River Severn, Coalbrokedale at England by Abraham Darby (Giedion, 1962). As seen in Figure 2.8, the structure of Iron Bridge which has pioneered lightweight structural design was designed as delicate sections as a future trend in terms of minimizing the load bearing components.

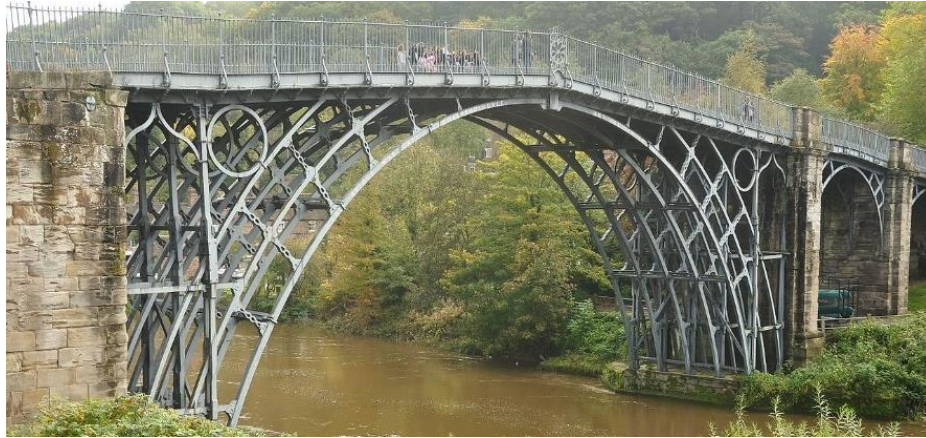


Figure 2.8 : Iron Bridge, 1781 by Darby, (Url-11).

Darby's bridge design also focuses on the importance of architectural and structural design integration. Structural components express the architectural imaginary and aesthetic values of the construction. In 1851, Architect Robert Paxton designed the Crystal Palace with cast iron and glass component (Sezer, 2017). This building is a milestone in terms of usage of iron and glass material in such a big scaled structure in terms of demonstration of the effect of Industrial Revolution in Architecture (MacDonald, 2001). As seen in Figure 2.9, the Crystal Palace's transparency and lightweight structure lead to reconfigure envelope of architectural volumes.



Figure 2.9 : Crystal Palace by Robert Paxton, 1851, (Url-12).

With developments in iron and steel manufacturing, the first lightweight hyperbolic latticed structure was designed by engineer and inventor Vladimir G. Shukov in 1896 (Beckh, 2014). Shukov's designs are quite inspiring about creating new structural technologies due to the experimental studies about minimizing the structural component and exploring new forms of structure. His studies and design methods are

accepted as the first scientific movement in terms of light weight structural design methodology (Beckh, 2014). Shukov designed many towers and doubled curved roofs in his professional carrier. In 1918, 350 m high Shabolovka Tower was designed but constructed as 150 m high due to economic reasons (English, 2005). As seen in Figure 2.10, 350 m high Shabolovka Tower is a quite innovative design in terms of form finding with minimum material compared to 324 m high Eiffel Tower.

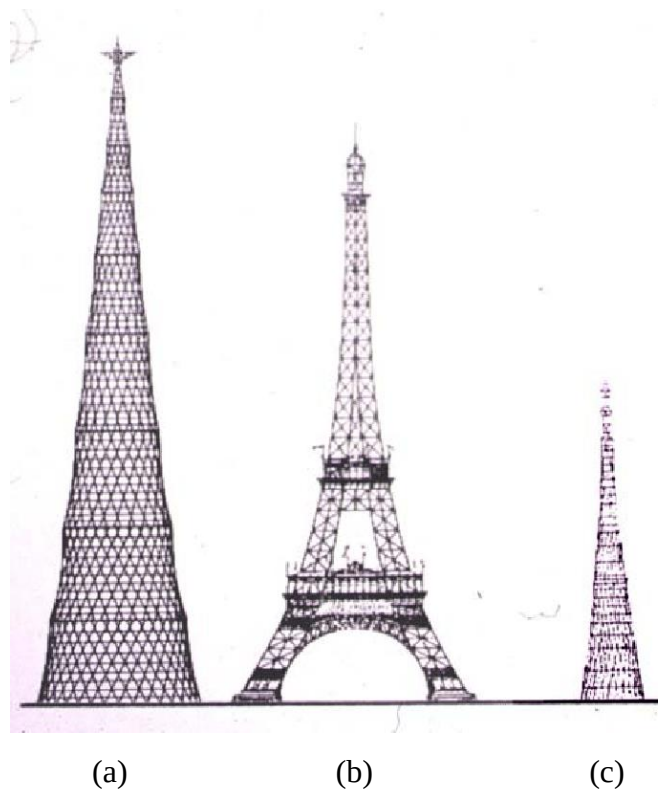


Figure 2.10 : Lattice structures: (a) Shabolovka Tower as designed in 1918, (b) Eiffel Tower as built in 1889, (c) Shabolovka Tower as built 1919, (English, 2005).

Shukov designs influenced many engineers and architects about designing extraordinary structures with minimum material. Dematerializing the structures evolved in time through integration of new structural components such as steel wire ropes. With using steel wire ropes in construction industry, tensile structures emerged. Thus, innovative and extraordinary form finding experiments became possible.

2.2.2 Evolution of tensile structures

Structural systems are classified in order to their behavior according to effective loads as post and beam, semi form-active and form-active structural systems (Engel, 2004). Tensile structures are the form-active systems that allow the structure to be flexible by

way of pretensioned steel wire ropes and minimal rigid steel components. Therefore, developments about steel cable technology have a significant role in designing tensile structures in time. After the invention of wire rope made by hemp by German Engineer Wilhelm Albert in 1834 (“Cable,” 2018), the first steel wire rope was manufactured by German Engineer John Augustus Roebling (Sayenga, 2016). Structural design of tensile systems was arisen by means of mass production of steel wire ropes. The first tensile structure was Oval Pavilion designed by Shukov for Nizhyn Novgorod Fair in 1896. As seen in figure 2.11, Shukov’s Oval Pavilion was stabilized by rigid lightweight steel structure and tension cable-nets determined the form of structure.

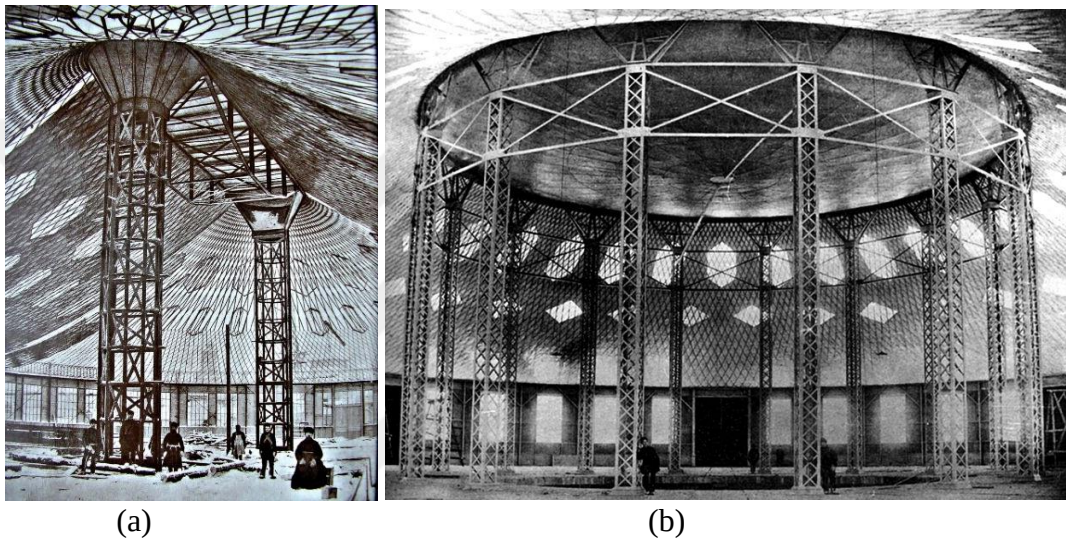


Figure 2.11 : Oval Pavilion: (a) Under construction, 1895, (Url-13), (b) After construction, 1896, (Url-14).

Moreover, experimental studies about tensile structures were also carried out by French Engineer Robert Le Ricolais, who was inspired by Shukov’s studies (English, 2005). As seen in Figure 2.12 Ricolais design; Funicular Polygon of Revolution consists of aluminum cables and struts.



Figure 2.12 : Funicular Polygon of Revolution by Robert Le Ricolais, 1961, (Url-15).

According to Ricolais, creating a structure with artistic value can be realized by creating the holes inside itself (McCleary, 1996). With that statement, Ricolais explains the design approach of lightweight structure studies and the origin of the forms that he created. Most importantly, Ricolais explains the motivation about lightweight structure studies carried out as; “To research what? Research of what? Zero weight, infinite span.” (McCleary, 1996).

Experimental models and numerical researches lead to develop lightweight and tensile structures as mentioned below. Frei Otto is one of the engineers that studied on conceptual and numerical analysis realized by creating experimental tensile structure test models. With that movement, tensile structures evolution and development accelerated.

2.2.2.1 Frei Otto’s design approach

German architect and engineer Frei Otto is known by innovative design approach about tensile structures. Otto developed their design method during Second World War era. Otto studied on minimizing the structural elements of the architectural volumes. One of the reasons for this experimental approach was economic conditions of war. Most importantly, Otto’s professional background was supporting the studies that he carried on. In early ages, Otto focused on aircraft engineering which enabled to understand design principles of lightweight structures (Roland, 1972). After light

weight structures arose, Otto focused on integration of tensile elements (steel wire ropes) into conventional structural systems. In order to understand precise behavior of tensile structures, Otto developed his own design method (Figure 2.13).

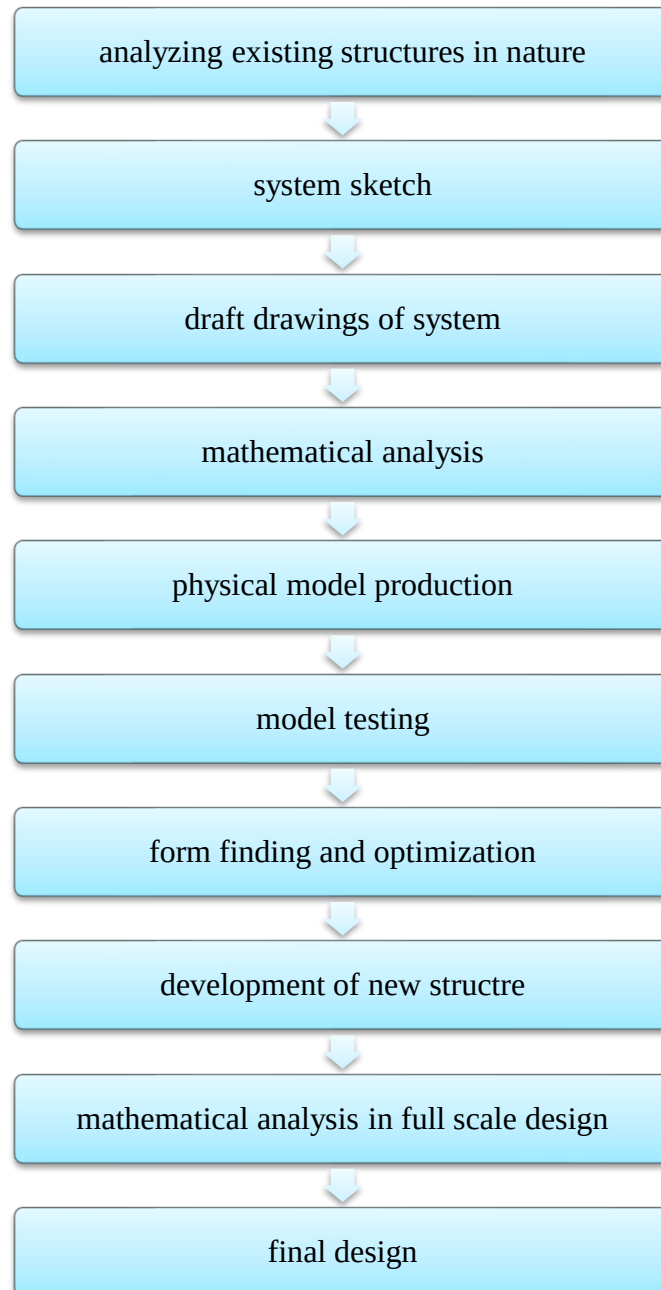


Figure 2.13 : Frei Otto Design Approach (Roland, 1972).

Otto's design approach emerges a correlation between aesthetics and mathematical analysis simultaneously. To do that, Otto and his team focused on analyzing existing structure in nature in order to create design tools (Aldinger, 2016). However, Otto's approach is not biomimicry directly. Otto's inspiration may come up by natural forms,

but he simplifies them in order to represent as mathematical functions which enable innovative structures emerging in contemporary architecture. As seen in Figure 2.14 (a), Frei Otto analyzes the structures in nature by focusing on load bearing components such as skeleton of mammals, spider nets and branching principles of a tree. Moreover, in contemporary research studies are carried on also by focusing on load bearing principles of nature such as nest structures (Figure 2.14 (b)).

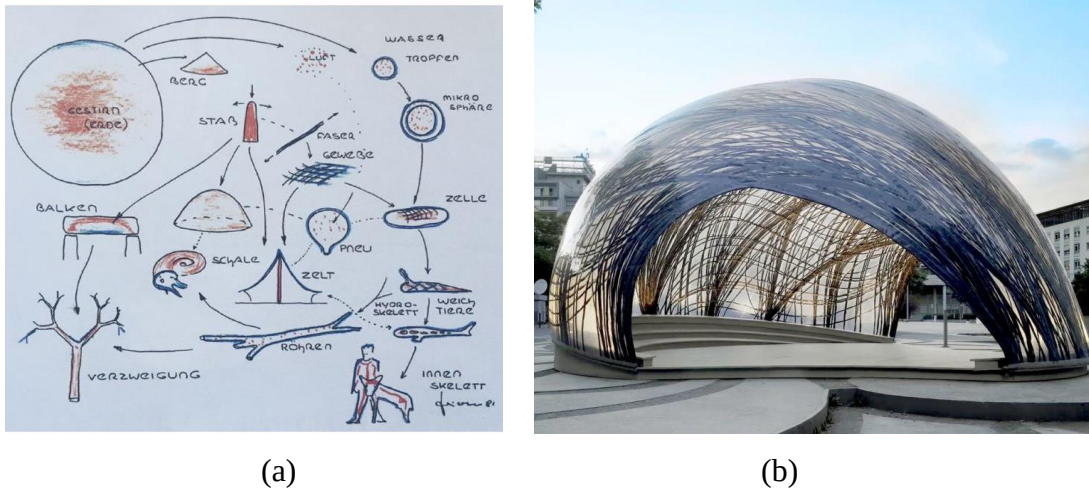
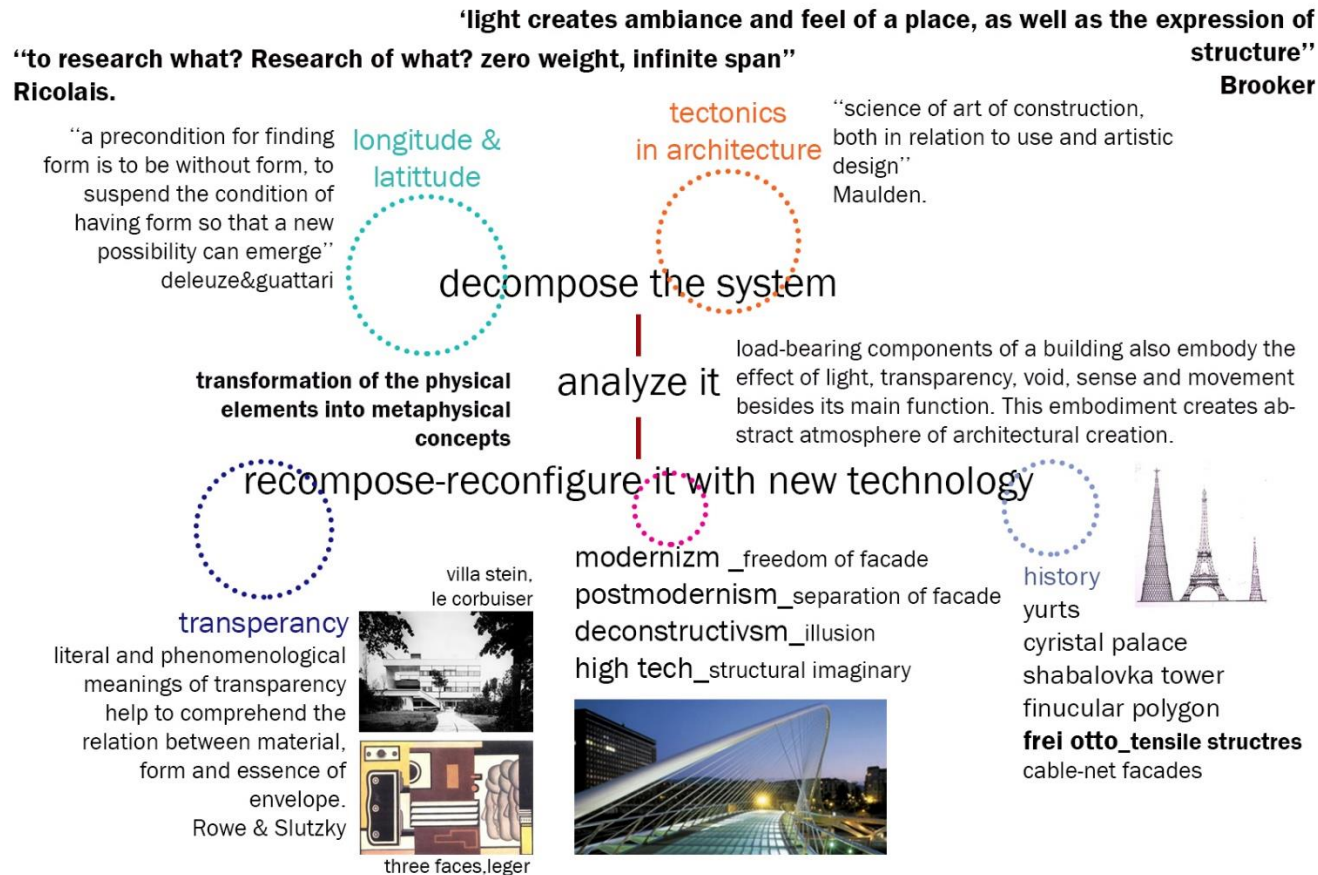


Figure 2.14 : (a) Frei Otto's conceptual sketch, (Aldinger, 2016). (b) Pavilion inspired by nests, (Url-16).

After analyzing existing structures, Otto starts to design with conceptual freehand sketches and draft drawings of the structural system and making physical models. Afterwards, he continues his study preliminary mathematical analysis of the system. Studying with models is milestone in form finding process and understanding the effect of loads on structure system. Test results of the models lead to develop numerical analysis which is basis of complex geometries in contemporary structures. Otto's one of the most known designs is Cable-Net Roof of Munich Olympic Stadium built in 1975 (Aldinger, 2016). As seen in Figure 2.15, Otto also used his methodology for Cable-Net Roof of Munich Olympic Stadium. Primary sketches and test models of the structure include form finding studies by using engineering design principles. Otto's scaled model enables to comprehend not only architectural configuration but also structural performance of the cable-net roof of stadium under effective loads.

Figure 2.16 : Methodology of re-configuration of cable-net facades.



3. TECHNICAL EVALUATION OF CABLE-NET FACADES

Structural glass envelopes are defined as dematerialized building skin with using light weight load bearing components in order to enrich transparency (M. R. Patterson, 2008). Cable-net facades are a type of structural glass facades which consist of glass panels, tensioned cables and point fixing components. The development of cable-net facade technology is based on integration of tensile structure design principles mainly created by Frei Otto. Otto's design methodology and mathematical theories lead to integrate pretensioned cable components into glazing technologies. This development provides developing structural systems to gain maximum transparency in building envelope.

Besides structural system innovations, technological developments in glass manufacturing also pioneered structural glass technologies. However, the invention of tempered and laminated glass provides much more transparency in building facades, load bearing elements such as aluminum mullions decrease the percentage of transparency in building envelopes. Therefore, dematerialization concept is dramatically essential for increasing transparency level through using minimal loadbearing components such as point fixings and steel wire ropes. Moreover, using glass component as a structural load bearing element is also another approach in order to maximize transparency.

Cable-net facades as structural glass envelope have the lightest load-bearing system in today's technology in terms of dematerialization concept. Therefore, understanding the design principles of cable-net facades and developing its structural system is a quite considerable research area in order to disclose new possibilities for future facade design. In this chapter, the study focuses on basic design principles of cable-net facade systems regarding classification of structural glass envelopes. Moreover, this section also includes evaluation of the standards and regulations related to cable-net facade design in context of structural components.

3.1 Classification of Structural Glass Facades (M. Patterson, 2015)

Structural Glass Envelopes are classified according to their load bearing components by summarizing the Patterson studies.

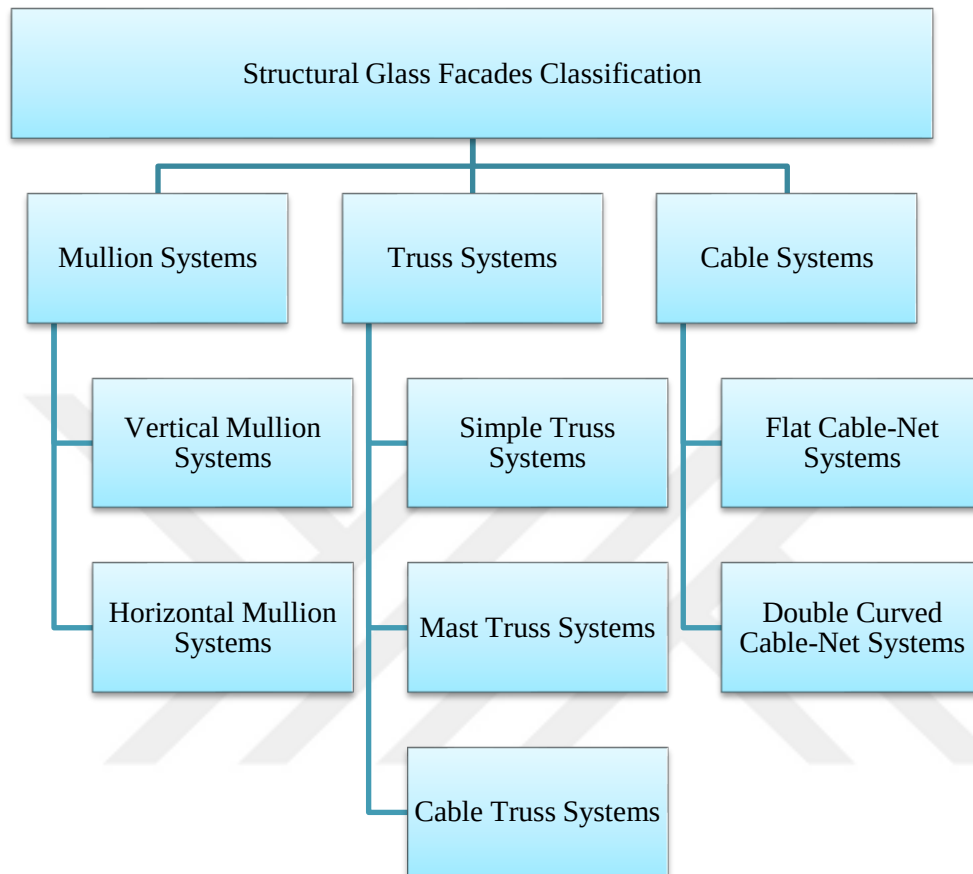
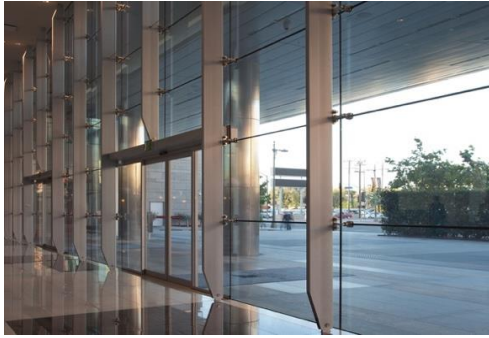


Figure 3.1 : Structural glass facades classification, (M. Patterson, 2015).

As seen in Figure 3.1, Structural Glass Facades are classified according to their main load bearing component. The aim of this classification is to understand the role of load bearing elements and form active structures. Moreover, under these structural systems sub-systems which specified the structural system of the facade in detail are included.

3.1.1 Mullion systems

Main load bearing element of mullion systems is vertical or horizontal mullions which are made by different structural materials such as aluminum or steel. Workmanship of the system is more complex than conventional curtain wall facade system. The first experiments about gaining more transparency in building facades began with adapting the mullions to building envelope. Therefore, mullion systems are the first development to reach maximum transparency in facade technologies (Figure 3.2).



(a)

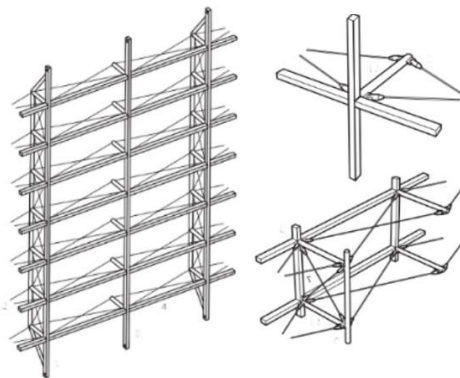


(b)

Figure 3.2 : Mullion Systems: (a) Vertical Mullion Systems, (Url-17), (b)Horizontal Mullion Systems (Url-17).

3.1.2 Truss systems

Truss systems consist of light-weight load bearing components applied hierarchically. According to classification mentioned below, truss systems can be subdivided into three systems which are simple truss, mast truss and cable truss. In this section truss systems are analyzed systematically to gain more acknowledgement about light-weight structural facade design. Simple truss systems are initial systems which consist of light weight rigid elements and tension cables using together. As seen in Figure 3.3, simple truss systems use the cables as a stability element between vertical and horizontal steel load bearing elements.



(a)



(b)

Figure 3.3 : Simple truss system (a) System sketch of simple truss, (M. Patterson, 2015), (b) Walter E. Chicago Convention Center, (Url-17).

Facade of Walter E. Chicago Convention Center was also constructed as simple truss system (Figure 3.3 (b)). The most conspicuous part of simple truss system is that it includes dense structural components which express the architectural articulation.

Moreover, structural components emphasize the conceptual design principles via functional detailing. Thus, the density of structural components and special connection detailing enrich the artistic value of facade. Another considerable subject is structural design limits of simple truss systems. Deflection limits and ratio of span to depth values are quite substantial criteria for convenient application. Maximum deflection of simple truss systems must be maximum $L/175$ and ratio of their short span to depth must be approximately 15. Moreover, it is also considerable to mention that L value must be the short span of the facade.

3.1.2.1 Mast truss systems

Mast truss systems are light-weight structural facade systems which consist of cables, masts, struts and special connection components. These systems enable to gain more transparent facade than other types of systems mentioned previously. Mast truss systems differ from simple truss systems in being initial form of light-weight facade structure which uses cables as a main load bearing component. Additionally, masts and struts are also used in order to stabilize secondary structure against compression and suction (wind) loads affecting laterally.

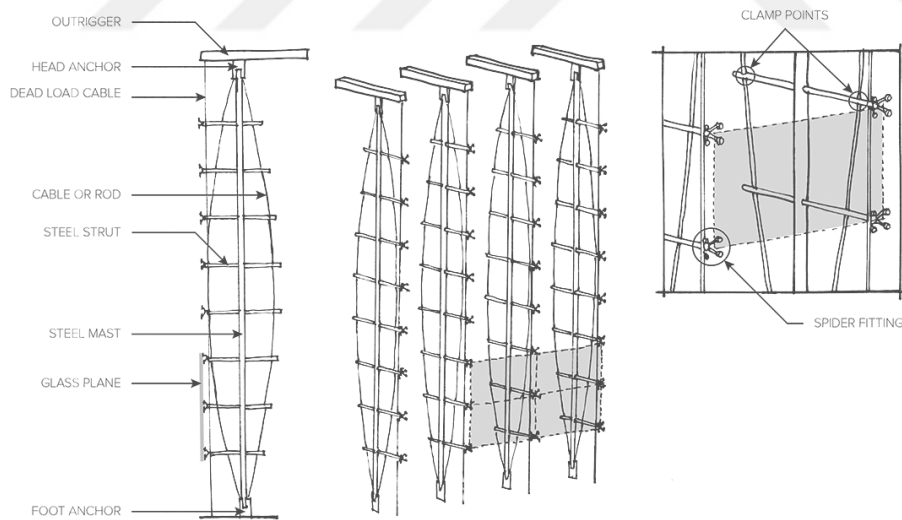


Figure 3.4 : Mast truss system, (M. Patterson, 2015).

Three different form types of cable are used in mast truss system applications which are linear, convex, and concave. Linear cable is used for dead load, convex and concave cables are used for wind pressure and suction effects. According to Patterson, maximum deflection of simple truss systems must be maximum $L/140$ to $L/175$ and

ratio of their span to depth must be approximately 15. As seen in Figure 3.4, a vertical mast anchors to upper and lower slab of the building.

Lateral effective loads (wind loads) are transferred to main structure by way of studs and cables. While facade system is flexible by means of using tensioned cable elements, struts and mast make facade system stabilized. Moreover, according to Patterson, mast truss systems can be defined as a closed system which means that any prestress loads are transferred to main load bearing structure. This feature is quite substantial in order to understand design principles of the mast truss systems because there is no need to reconfigure main load bearing system regarding pretension loads of mast truss facades.

3.1.2.2 Cable truss systems

Cable truss systems can be defined as upgraded version of mast truss systems. Unlike mast truss system, cable truss system does not contain any compression element like masts. Moreover, according to Patterson, cable truss system is designed as an open system of which pretension loads should be transferred to main load bearing system safely. As seen in Figure 3.4, cable truss systems consist of steel struts, linear, convex and concave cables and glass fittings. Cable truss systems are more flexible systems than other truss systems mentioned previously.

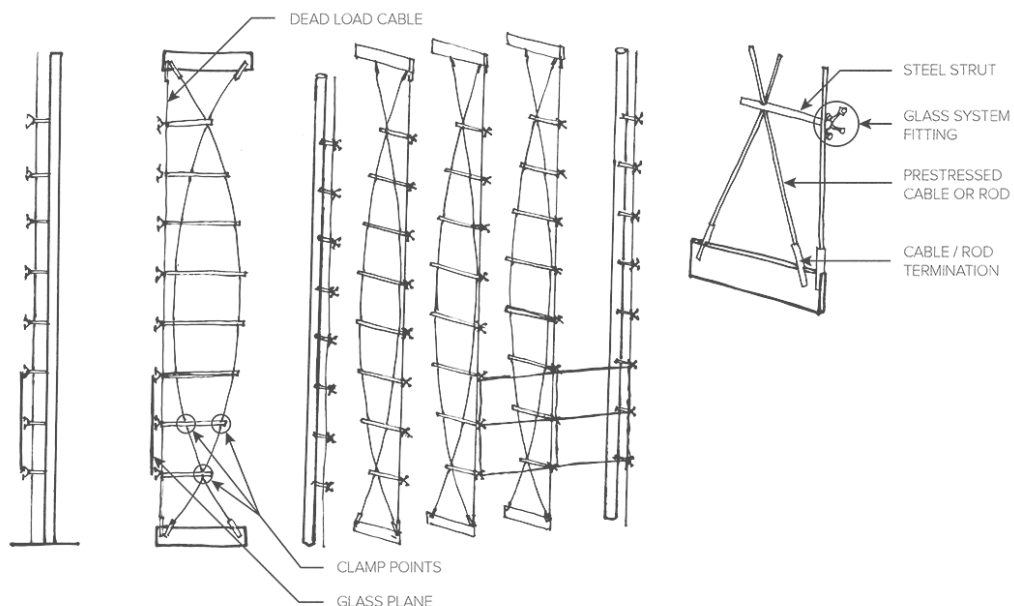


Figure 3.5 : Cable truss system, (Url-17).

According to Mesda (2013), cable truss systems enable to gain more transparency but are also more expensive facade systems than traditional cladding systems. Like other structural glass facade systems, Cable truss systems also require detailed engineering design to realize architectural needs.

3.1.3 Cable systems

Cable systems are one of the structural glass facades which consist pretension cables, connection elements and glass planes. Moreover, they are open systems, which means all prestress loads are transferred to the main structure of the building. Therefore, in addition to wind load and dead load effects, pretension load is also quite considerable for stabilization of cable-net glass facades. Additionally, As seen in Figure 3.7, Cable systems can be designed as flat and curved.

As seen in Figure 3.6, flat and curved cable systems are illustrated. Flat cable-net facades are more minimal systems than curved cable-net facades. Curved systems require more specific engineering calculation related to form finding under effective dead and live loads.

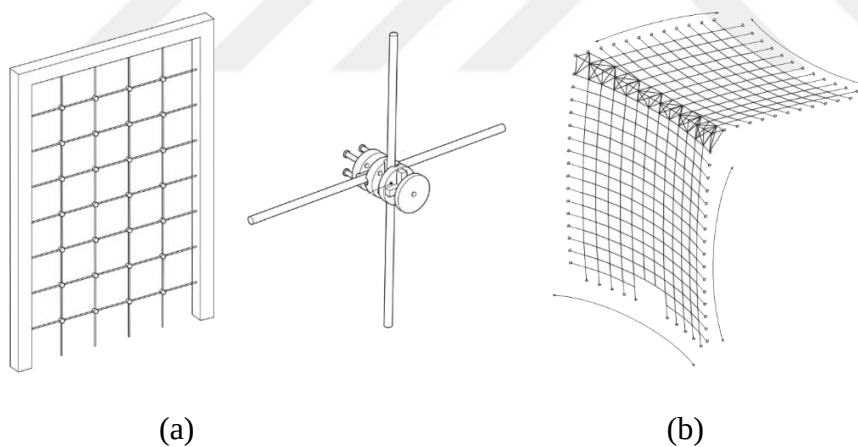


Figure 3.6 : Cable-net facades: (a) Flat cable-net, (b) Curved cable-net, (M. Patterson, 2015).

Deflection limits of structural glass facades are increasing according to their structural dematerialization which provides reducing pretension loads of cables. Therefore, cable facades are more advanced structural glass facades in terms of its higher deflection limits. Because of the mentioned features, the study focuses on cable-net facades with innovative fixing components and their behavior under effective loads. Consequently, cable-net facade is analyzed in detail in further sections in order to better understand components and design principles.

3.2 Cable-Net System and Their Components

The cable-net structural glass facades can be regarded as the most advanced version of structural glass facades. In cable-net systems, the structural system is minimized as much as possible. With that minimalism, facade concept is reconfigured by means of using light-weight load-bearing components. Thus, design of structural configuration of cable net facade is a quite considerable subject in order to realize architectural design of the facade. Furthermore, structural analyses regarding the components of cable net facade are a substantial step to understand and develop the facade systems and their components.

Cable-net facades are stabilized via pretension cables in horizontal and vertical direction. These pretension cables are connected to main load bearing structure (i.e. boundary beams and columns) with anchoring steel elements. The connection between glass panels is executed with point- fixings.

3.2.1 Structural glass

Glass is a structural element which is essential for the realization of transparency in building skin. Glass material is used as both structurally and non-structurally building components in terms of its load transferring and load bearing functionality. Although non-structural glass behaves as a membrane (glazing component), structural glass components such as glass beams and glass columns behave as load bearing structural components (Johnson, 2014).



(a)



(b)

Figure 3.7 : Glass structures (a)Apple Store, 2006 (Url-18) (b) Apple Store reconstruction, 2011 (Url-18).

As seen in Figure 3.7, non-structural (membrane) and structural glass are integrated to each other via minimal connections. Apple Store's first and last design illustrates improvements of load bearing performance of glass material in five years. Dimensions of non-structural glass components are substantially increased by way of enhancing the load bearing performance of structural glass elements (glass columns and beams) (Figure 3.7). Developments in glass technology enable to use glass material as a load bearing component which enhances transparency in buildings. There are many types of glass in terms of their structural behavior, heat insulation, light control and fire protection performances. In this study, structural performance of glass is analyzed in detail in order to develop innovative design aspects.

Although there are many metallurgical combinations of glass material, soda lime silicate glasses are used in facade constructions in general.

3.2.1.1 Mechanical properties of soda-lime-silicate glass

Soda-lime silicate glasses are widely used in building skin constructions. Therefore, mechanical properties are quite considerable for design of structural glass facades (Table 3.1).

Table 3.1 : Mechanical properties of soda-lime-silicate glass (BS EN 572-1, 2016).

Characteristic	Symbol	Value and unit
Density (at 18 °C)	ρ	2 500 kg/m ³
Hardness (Knoop)	HK0,1/20	6 GPa
Young's modulus (modulus of elasticity)	E	7×10^{10} Pa
Poisson's ratio	μ	0,2
Specific heat capacity	cp	$0,72 \times 10^3$ J/(kg · K)
Nominal value of average coefficient of linear expansion between 20 °C and 300 °C	α	9×10^{-6} /K
Thermal conductivity	λ	1 W/(m · K)
Mean refractive index to visible radiation (at 589,3 nm)	n	1,5
Emissivity (corrected)	ε	0,837

Young modulus, Poisson ratio, and density of glass are the most notable mechanical properties due to affecting structural performance of glass material dramatically. While glass density affects dead load of the structure, Young Modulus and Poisson Ratio are also considerable in terms of stress-strain relationship which determines deflection limits of glass component. Deflection limits are substantial parameter in order to design and simulate non-linear behavior of cable-net facades. Therefore, deflection limits of glass according to fixing types are mentioned in Table 3.2.

Table 3.2 : Deflection limits according to current codes, standards and systems (Morgan, 2010)⁴.

Code/ Standard	Glass Layering	Deflection Limit (mm)	Supporting Type
DIN18008	Single/Insulated	L/100	Point fixed
BS 6262	Single	L ₅ /125	Four-edge supported
BS 6262	Insulated	L/175	Four-edge supported
BS 5516	Single	(S ²) x1000)/180 or 50mm (whichever less) ⁶	Two-edge Supported
ASTM E-1300-04	Single/Insulated	19 mm	Deflection of supported edges less than L/175
AS1288-94	Single tempered	L/60	Point fixed
Pilkington Planar	Single or Insulated	L/50	Point fixed

⁴ Codes and standards are updated according to their latest version.

⁵ L is length of glass panel.

⁶ S is span of two supports.

As seen in Table 3.2, supporting diversity affects the deflection limits of glass panels. Besides the design codes and standards, Pilkington Planar System values are also applied to the table in order to emphasize the importance of system design. Pilkington Planar system is a point fixing system that allows structural components higher flexibility (Morgan, 2010). The section is related to fixing components, and this system will be mentioned in detail. Most flexible systems are point fixed structural glass facades with $L/60$, $L/50$ deflection limits for glass planes.

3.2.1.2 Classification of structural glass

Glass is classified according to their structural performance to determine convenient glass type and combination of cable-net facade and its structural component design.

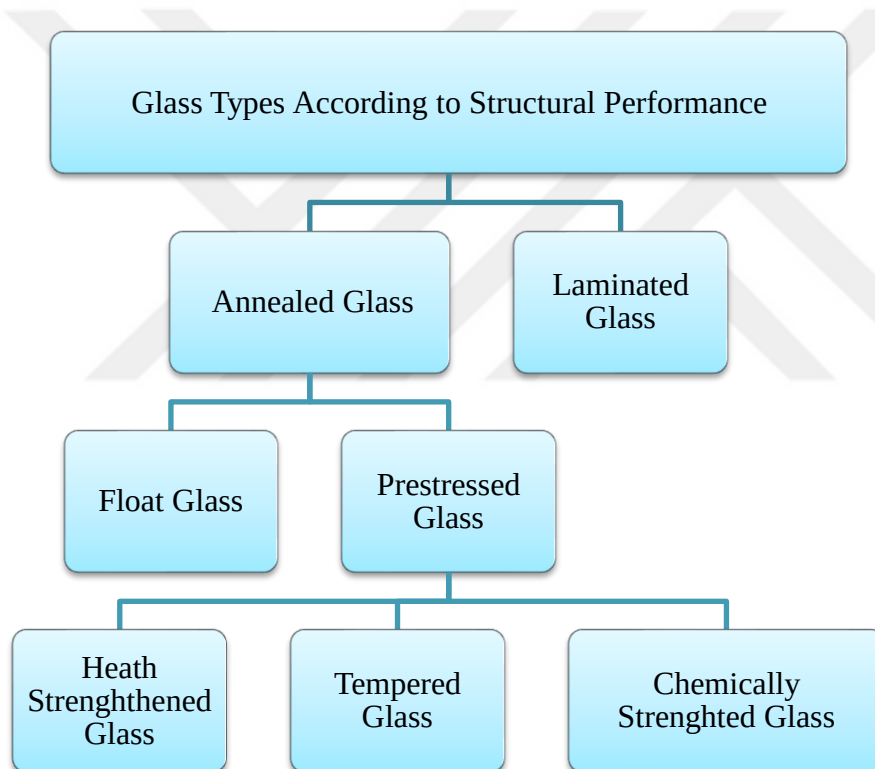


Figure 3.8 : Glass classification (prEN 16612, 2017)

- **annealed glass**

Annealed glass manufacturing is the current glass production process which enables to produce glass panels for facade technology. Annealing process is illustrated in Figure 3.9. Most important part of the process is executed at annealing lehr which is cooling the glass plane slowly. This process helps to decrease residual stress of glass material (Haldimann, 2007).

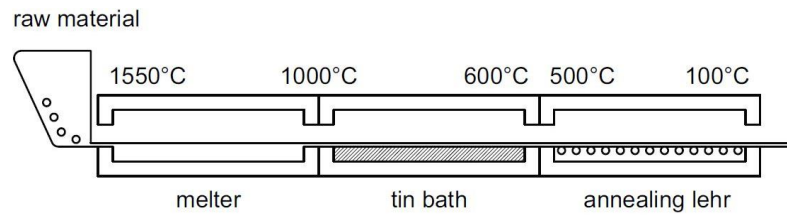


Figure 3.9 : Float glass manufacturing via annealing process, (Haldimann, 2007)

As a result of process of annealing, float glass panels are manufactured. After annealing process two main process are usually executed as heating and chemical strengthening in order to produce prestress glass. While heat strengthening procedure is heating up the flat annealed glasses and cooling them down, chemically strengthening application is based on altering the sodium ions to potassium ions of surface of glasses (Haldimann, 2007). Prestress glasses are divided into three main types according to their strengthening process which are high strength glass, tempered glass and chemically tempered glass. According to types of prestress glasses, strength of glass changes. It is also a quite considerable parameter for glass type selection. Therefore, the comparison of their structural performance of prestress glasses is shown in Table 3.3.

Table 3.3 : Annealed glass types according to their bending strength.

Glass Type	Bending Strength, $f_{b,k}$ (Feldmann & Kasper, 2014)	Ultimate Design Strength under Short Term Load Condition ⁷ (Code for Practise, 2018)
Float Glass (BS EN 572-1, 2016)	45 N/mm ²	20 N/mm ²
Heath Strengthened Glass (BS EN 1863, 2011)	70 N/mm ²	40 N/mm ²
Tempered Glass (BS EN 12150-1, 2011)	120 N/mm ²	80 N/mm ²
Chemically Strengthened Glass (BS EN 12337-1, 2000)	150 N/mm ²	-

As seen in Table 3.3, chemically strengthened glass bending strength reaches the highest value. As a result, tempering process is substantial for glass to use as a structural component. Additionally, according to Honkong Design Code Practice for

⁷ According to Honkong Code Practice for Structural Use of Glass, the ultimate design strength of glass is measured according to 8 of 1000 samples of glass units would fail.

Structural Use of Glass (2018), ultimate design strength should also be taken in consideration primarily during design process. Besides the strength of glass which enhances with heat treatment, post breakage performance of glass reduces dramatically (Haldimann, 2007). Fragmentation of tempered glass is much more than basic annealed glasses. The fragmentation can also be seen after breakage of different type of glass at Figure 3.10.

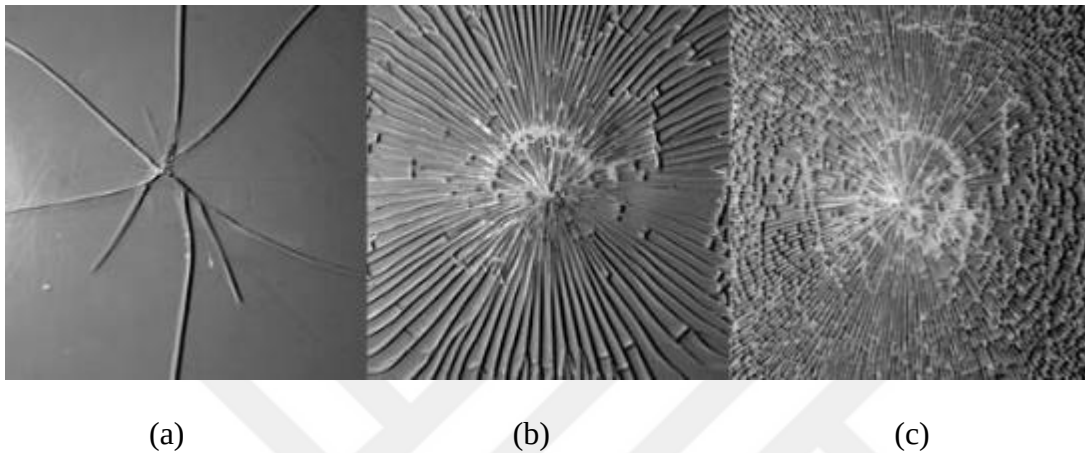


Figure 3.10 : Fragmentation of glass: (a) Flat glass, (b) Heat strengthened glass, (c) Tempered glass, (Haldimann, 2007).

3.2.1.3 Laminated glass

Laminated glasses, which are combination of two or more glass layers, conglutinate with most commonly PVB (polyvinyl butyral) polymer as interlayer (Feldmann & Kasper, 2014). Additionally, cast in place resins, EVA, polyurethane and ionomer are also other types of lamination interlayers (prEN 16612, 2017). With lamination process, glass can be manufactured in various thicknesses. The laminating process is performed by heating the PVB between two or more glass layers to 140°C and applying 14 bar pressure to the glass layers to prevent air bubbles from forming during the heat treatment (Haldimann, 2007). Most importantly, this process provides holding the fragments together after breakage of glass and reduces residual stresses of glass combination.

The composition of lamination process and post breakage behavior of different types of laminated glass units are illustrated (Figure 3.11). According this illustration, while structural performance is increasing, better remaining performance decreases. Therefore, lamination process is a sufficient way in order to optimize structural glass performance.

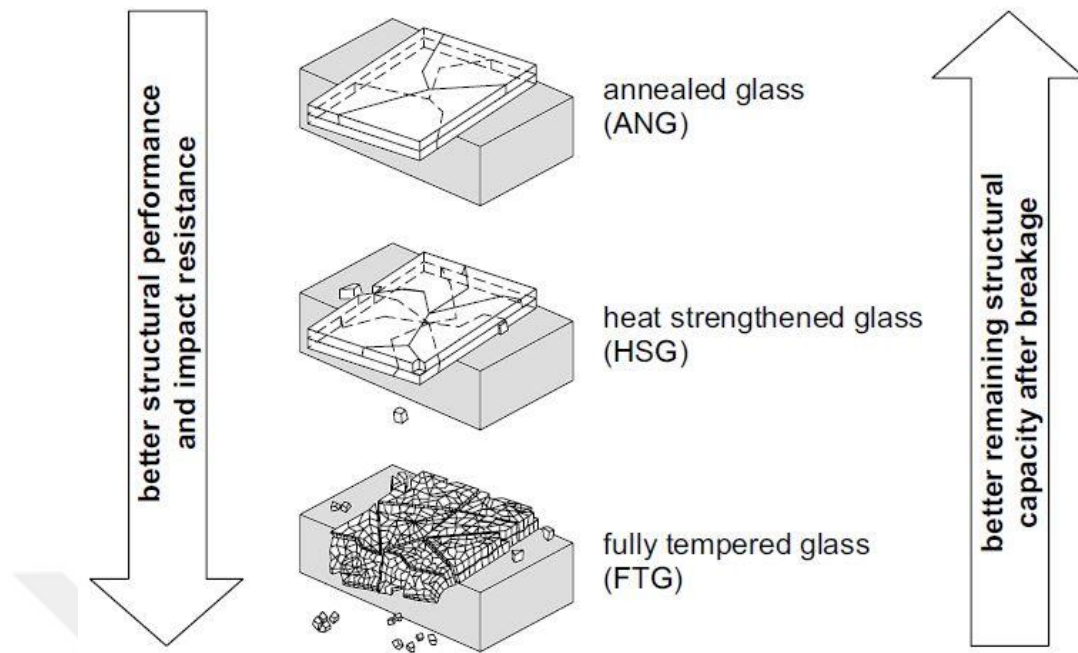


Figure 3.11 : Relationship between structural performance and fragmentation of laminated glass units (Haldimann, 2007)

If glass combination consist of prestress glass types, laminated glass units are defined as safety laminated glass which is commonly used in structural glass facades applications (BS EN ISO 12543-1, 2011). Thus, maximum strength of glass is ensured with minimum post breakage segmentation.

The key component of lamination is PVB interlayer which viscoelastic material enabling to transfer effective loads between different glass layers (Haldimann, 2007). Therefore, mechanical properties of PVB interlayer are also considerable for structural glazing applications. Mechanical properties of PVB interlayer are shown in Table 3.4.

Table 3.4 : Mechanical properties of PVB, (Haldimann, 2007).

Characteristic	Symbol	Value and unit
Density (at 18 °C)	ρ	1070 kg/m ³
Shear Modulus (modulus of elasticity)	E	0-4 GPa
Poisson's Ratio	μ	$\approx 0,5$
Tensile Strength	f_t	≥ 20 MPa
Coefficient of Thermal Expansion	αT	-1.80×10^{-6} K

As it can be seen in Figure 3.12, tensile strength of PVB interlayer should be more than 20 MPa in order to ensure the stability of laminated glass units. Additionally, lamination process also provides combining several types of glass and even other polymers such as acrylic according to application needs. These features also develop the concept of insulated glass unit. Using lamination, insulated glass units (IGU) which are shown in Figure 3.12, can have much more stability under effective design loads.

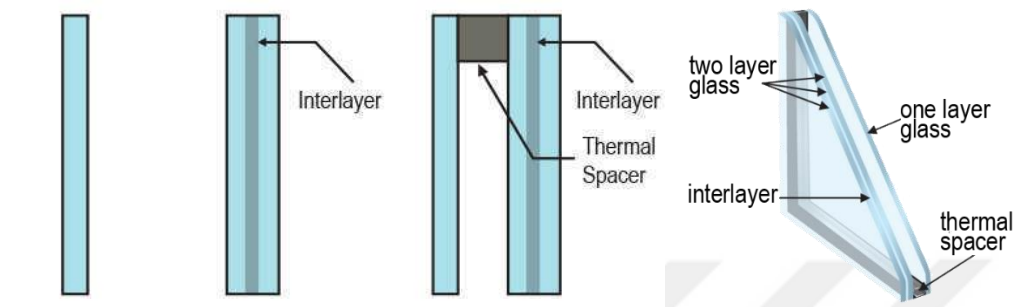


Figure 3.12 : (a) Left to right, monolithic, laminated, laminated IGU. (b) Perspective view of laminated IGU (Url-19).

In the process of cable-net facades, several types of glasses can be used according to design limits such as environmental conditions and design loads. Therefore, selecting the glass units is a quite considerable subject for qualified facade design. Additionally, using laminated glass units as structural component is also another feature of glass technology development. Thus, innovative transparent structural components can also be designed.

3.2.2 Point fixings

Cable- net facades are stabilized with point fixing components which enable to connect glass units and steel cables. There are several types of point fixings. It derives according to structural design of cable-net facade and architectural needs. According to Eurocode, there are four types of point fixings: clamping system, connection with drilled holes, embedded connection, adhesive connection, and (Feldmann & Kasper, 2014). These types of connection are preferred according to architectural needs and structural considerations. These connection types are shown in Figure 3.13.

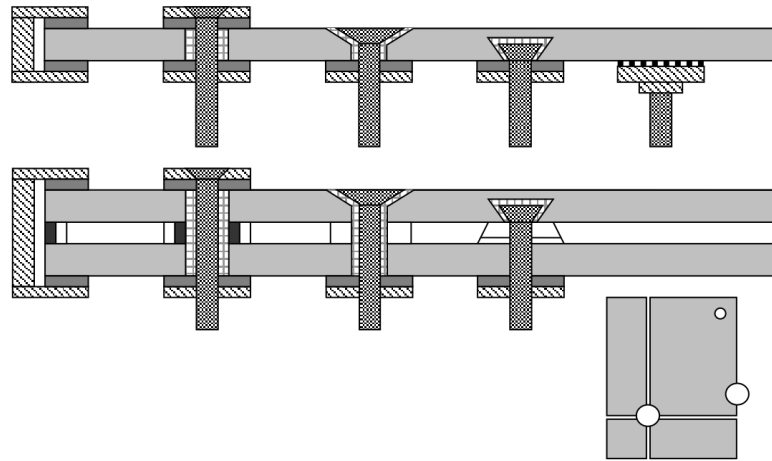


Figure 3.13 : Point fixing types for single and double glazing, (Feldmann & Kasper, 2014).

3.2.2.1 Clamp fixings

Clamps are executed at near edges of glass units in order to provide punctual stabilization of cable-net glass facades. Two of clamp fixings can be seen in Figure 3.14.

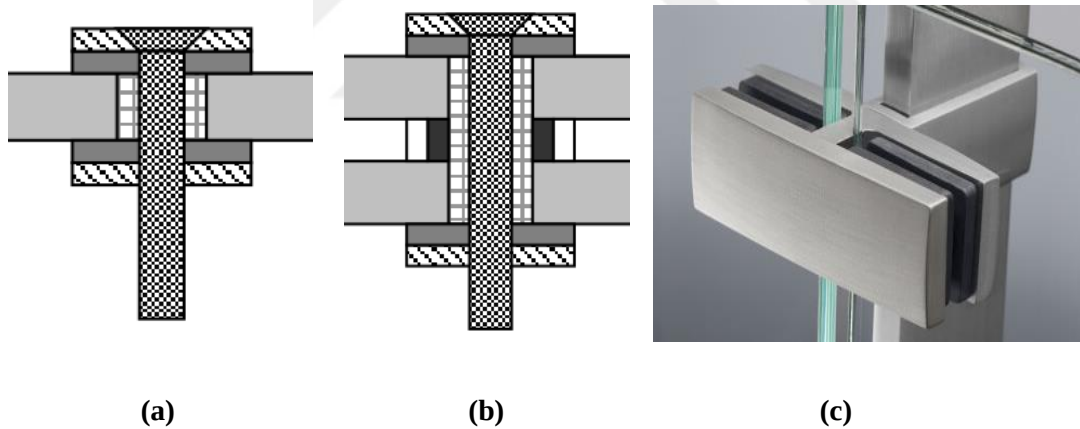


Figure 3.14 : Clamp types: (a) Single layer clamping, (b) Double glazing clamping, (c) Photo of clamp sample, (Url-20).

According to Eurocode clamp fixing detail design and testing procedure are mentioned at DIN18008-3. According to DIN18008-3, monolithic glasses must be thermally or chemically toughened with a minimum of 6mm thickness, and laminated glass units must be annealed. Moreover, clamping surface must be higher than 1000 mm² and FEM analysis and testing must be executed in order to validate serviceability and ultimate limit states and stresses around the clamp (German Institute for Standardization, 2013). Additionally, BS 6180 and BS 6262 are also related to design of bolted and unbolted point fixing components (Feldmann & Kasper, 2014).

3.2.2.2 Drilled hole fixings

Drilled hole fixing is executed by drilling a hole on the surface of glass units in order to stabilize the cable-net facades punctually. According to Figure 3.15, holes can be three types such as cylindrical hole, conical hole and blind hole (Feldmann & Kasper, 2014).

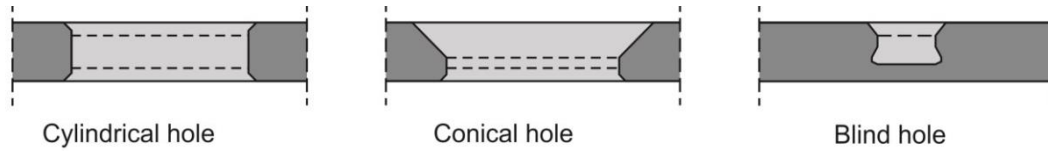


Figure 3.15 : Hole types for drilled hole fixings, (Feldmann & Kasper, 2014).

Drilling hole application is a crucial procedure due to dramatic fragmentation possibility of thermally toughened glasses. Hole position must be executed according to BS 12150. According to BS 12150, distance limits between hole and edge of thermally toughened glass must be adjusted as illustrated in Figure 3.16.

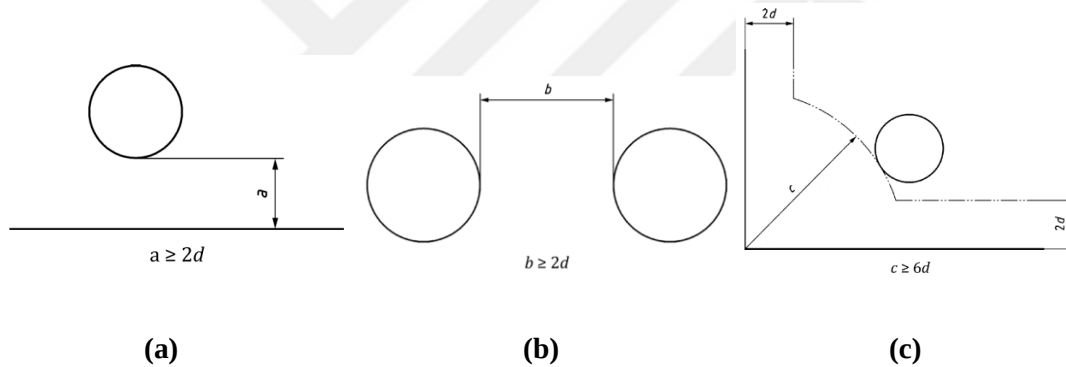


Figure 3.16 : Hole positions according to hole diameter: (a) Minimum distance to edge of glass plane. (b) Minimum distance between two holes. (c) Minimum distance between corner of glass plane (BS EN 12150-1, 2011).

According to BS EN 12150-1, diameter of holes determines the minimum distances to edge of the glass units. Distances should be greater than two times of diameter of holes (Figure 3.16). Additionally, complex hole shapes require more complex and combined FEM analysis in order to specify stress levels around the holes (Feldmann & Kasper, 2014). Thereby, simplification is quite considerable for reducing failures. Moreover, glass type selecting is also significant in order to reduce failure due to glass breakdown. Breakage behaviors of different glazing direction are shown in Table 3.5.

Table 3.5 : Breakdown risks of vertical and horizontal glazing according to glass types, (Feldmann & Kasper, 2014).

Glazing Direction	Glass Type	Behavior of glass units after breakage
Vertical	Tempered	Small glass pieces can fall down
Vertical	Heat Strengthened and Laminated (PVB)	High residual resistance
Vertical	Tempered and laminated (PVB)	Risk of pulling out of the point fixing and because of it hole glass unit can fall down
Horizontal	Heat Strengthened and Laminated (PVB)	High residual resistance

Hole drilled fixings are designed as several forms such as four armed spiders, rectangular and cylindrical shaped hole drilled fixings. As it can be seen in Figure 3.17, the steel spider with four arms was produced by the manufacturer to pass through fewer openings than the tensioning systems. The bolts used in connection with the glass are of M14 type. Permitted wind pressure value for each arm; 2500 N, suction pressure value of 2300 N with wind effect and 1300N of dead load with maximum load value are allowed.

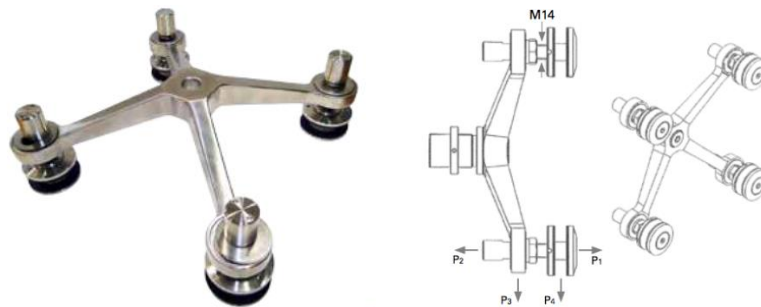


Figure 3.17 : Four-armed spider (Url-21)

Spider fasteners are widely used by opening holes in the glass or by mounting them on the surface of the glass material with special adhesives to ensure the stability of the structural glass facades against vertical and horizontal loads.

3.2.2.3 Embedded fixings

Embedded fixing emerged with the invention of ionomer lamination interlayer which enhances the transparency, durability and stability of glass units with minimum

thickness and bigger dimensions (Feldmann & Kasper, 2014). One of the most considerable examples of embedded fixing system is Pilkington Planar Glazing System which enhances the transparency of cable-net facades (Figure 3.18).

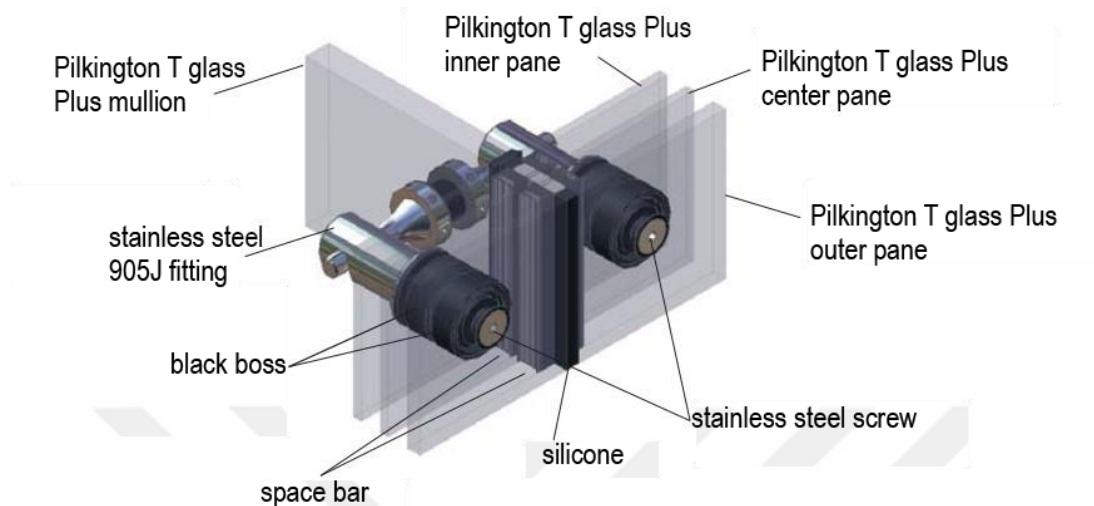


Figure 3.18 : Embedded fixings, (Pilkington, 2009).

Embedded fixing system uses the laminated glass interlayer as an element of fixing component. This system can be used in several types of structural glass facades such as glass mullion systems and cable net facade systems.

3.2.2.4 Adhesive fixings

Adhesive fixing is an alternative solution to drilled hole fixing applications. Adhesive fixing is more advantageous because there is no mechanical failure because of drilling. Moreover, load distribution of glass panel is more homogeneous and this situation decreases local stresses at glass panels (Feldmann & Kasper, 2014). Despite being advantageous, long term behavior of adhesives is not certainly predictable.



(a)



(b)

Figure 3.19 : Transparent structural silicone: (a) Spider fittings example 1 (Url-22), (b) Spider fittings example 2 (Url-23).

Adhesive fixings are most generally four armed spider or punctual buttons (Figure 3.19).

Commonly used adhesives are epoxies, acrylates, polyurethanes, silicones of which strength differs in terms of chemical combination. Behaviors of structural adhesives are explained in detail in Chapter 3.2.1.7.

3.2.3 Structural steel wire ropes

Structural wire rope technology was developed by the German Engineer Wilhelm Albert in the 1830s. According to Patterson, steel wires are wrapped around each other and around a steel core strand (M. R. Patterson, 2008). Reversing the winding directions of the main core cable with the wrapped secondary cable is necessary in order to ensure equal load distribution on different axes of cable.

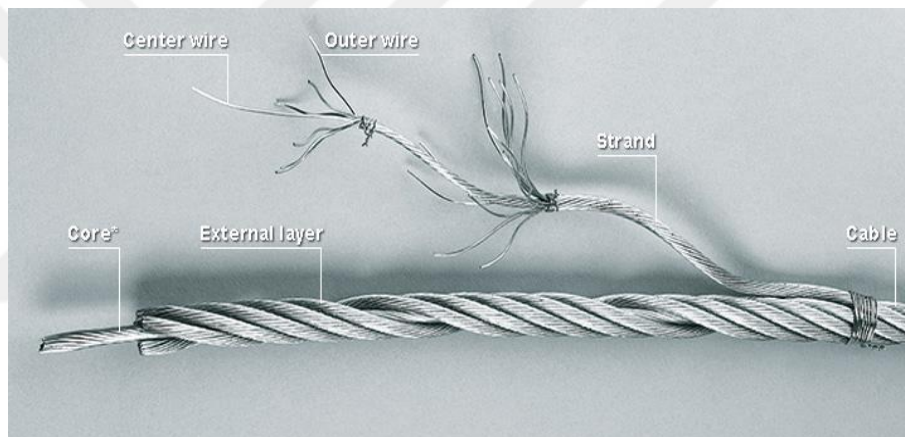


Figure 3.20 : Layering of steel wire ropes, (Charl Stahl, 2018).

As seen in Figure 3.20 shows steel wire ropes consist of steel cables or steel wire ropes hierarchically. The hierarchy of twisting enables to gain more strengthened steel wire ropes while main cable-net structure remains flexible.

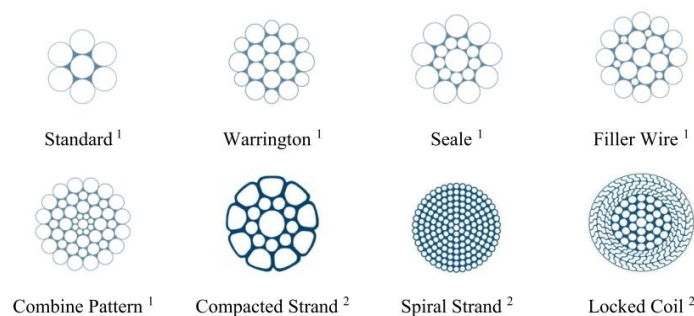


Figure 3.21 : Different Types of steel wire ropes according to their wire combination (BS EN ISO 12385-10, 2003).

There are several types of steel wire combinations according to their twisting principle (Figure 3.21). These types of cables have different breaking load values according to BS 12385-10. As seen in Figure 3.22, breaking load levels for steel wire ropes are illustrated.

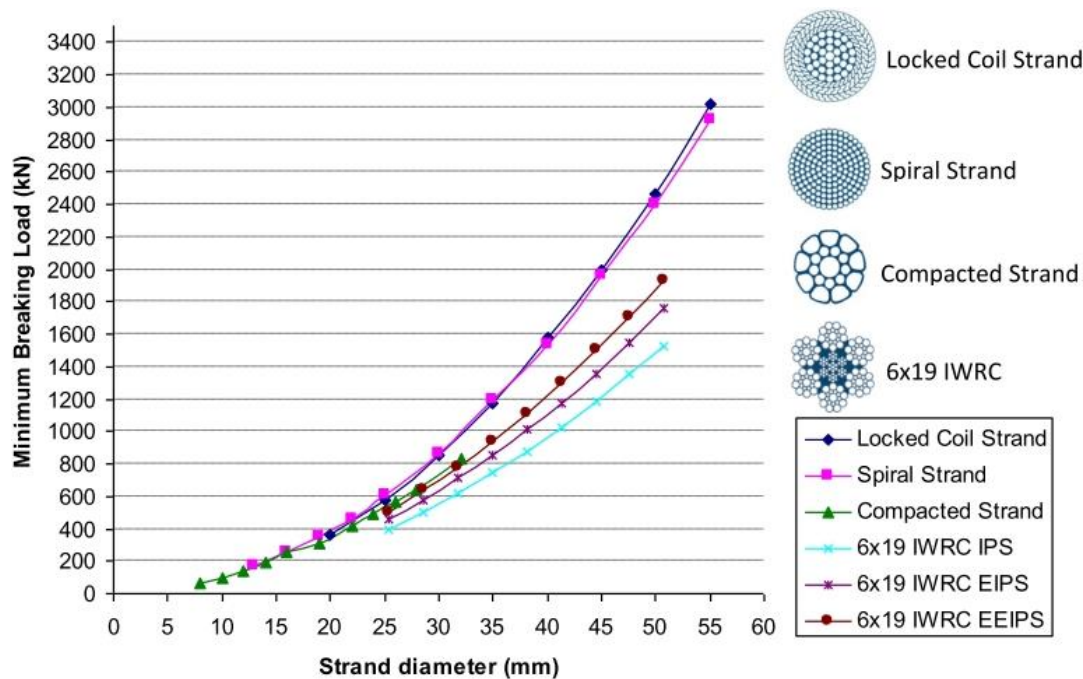


Figure 3.22 : Breaking loads of steel wire strands, (BS EN ISO 12385-10, 2003).

According to Figure 3.22, structural performance of spiral strand and locked coil strand are significantly better than other types of steel strands. It is seen that the density of twisting is quite substantial criteria about structural performance of steel wire strands. After specifying effective stresses of cable–net glass facade structure, selection of steel wire ropes should be carried out according to their minimum breaking loads. Additionally, deflection of the cable is also significant for cable selection. At that point, pretension level of cable and deflection limits must be evaluated simultaneously, and an optimization process should be carried out.

In addition to technical evaluations about steel wire cables mentioned in previous paragraphs, innovations related to steel wire rope also enhance the cable-net facade structures and their components. For instance, besides the traditional manufacturing of steel wire cables, modern technologies related to cable manufacturing such as polyamide coated steel wire ropes are also developing. Polyamide coating protects the steel wire ropes against harmful environmental effects such as corrosion, high capacity

of bending cycles, low adherence of dust and dirt by means of their smooth surface. It also provides protection against penetration of particles (Charl Stahl, 2018).

3.2.4 Fittings, bolts and plates

Fittings, bolts and plates are secondary components of cable- net facades in order to connect cable-net structure to main load bearing structure. There are many types of fittings derives according to producers. An appropriate anchor component can be selected from product brochures provided by cable manufacturers. As seen in Figure 3.23, several types of anchors are produced.



Figure 3.23 : Anchor types, (Url-24).

In addition to anchors, bolts and plates are also used for stainless steel cables assembling. These anchors must be manufactured according to AISI 316 and European Technical Approval (ETA-10/0358).

Bolts and stainless-steel plates should also be manufactured according to ISO and ASTM standards.

3.2.5 Structural adhesives

Structural adhesives are used in order to connect different types of structural glass components and transferring the effective loads to main structural components of facade. There are four types of structural adhesive: epoxy resins, polyurethanes, acrylates and silicones. Structural silicones are the most commonly used adhesive

material due to their transparency feature. According to Feldmann and Kasper (2014), there are some structural requirements to be fulfilled by structural adhesives mentioned below:

- Load transfer of shear forces,
- Reduction of stress peaks by way of elastic behavior of adhesive,
- Compensation of constraint forces due to possible thermal expansion,
- Compensation of fabrication tolerances (gap-filling behavior).

In order to understand and select the most effective adhesive for cable-net facade glazing, a performance analysis is carried out according to studies of Feldmann and Kasper (Table 3.6).

Table 3.6 : Performance analysis of structural adhesives (Feldmann & Kasper, 2014).

Structural adhesive type	Tension and shear strength	Stiffness	Ductility	Viscosity	Temperature resistance	Ageing behavior	UV resistance	Transparency
Epoxy resin	+++	+++	+	+++	++	++	++	+
Polyurethane	++	+++	++	++	++	++	++	++
Acrylate	++	++	++	++	++	+++	+++	+++
Silicone	+	+	+++	+	+++	+++	+++	+

In addition to Feldman and Kasper's analysis, ionomer-based materials are also used as structural adhesive for metal glass connection. Sentry glass is an ionomer-based adhesive which can be used not only for glass lamination process but also used for metal glass bonding. Moreover, new generation structural adhesives are also used at glass metal connections. Dow-Corning TSSA is one of transparent structural silicones enabling metal-glass bonding stronger (Url-25). Thus, mechanical properties of Sentryglass and Dow-Corning TSSA are shown in Table 3.7.

Table 3.7 : Mechanical properties of Sentryglass (DuPont, 2012), and Dow-Corning TSSA (Url-25).

Materials	Density g/cm ³	α_T	Elasticity Modulus MPa (E)	Poisson Ratio ν	σ_{max} MPa	ϵ_{max} %
Sentryglass	0,95	15-10	692-0,5	0,5-0,4	34,5	400
Dow-Corning TSSA	n/a	n/a	9,0-4,5	n/a	8,5	250

Mechanical properties vary according to temperature levels of materials. Therefore, an experimental study is carried out by (Santarsiero, Louter, & Nussbaumer, 2016). The research is based on investigating structural performance of Sentryglass and Dow-Corning TSSA in different temperatures. Experimental setup is shown in Figure 3.24.

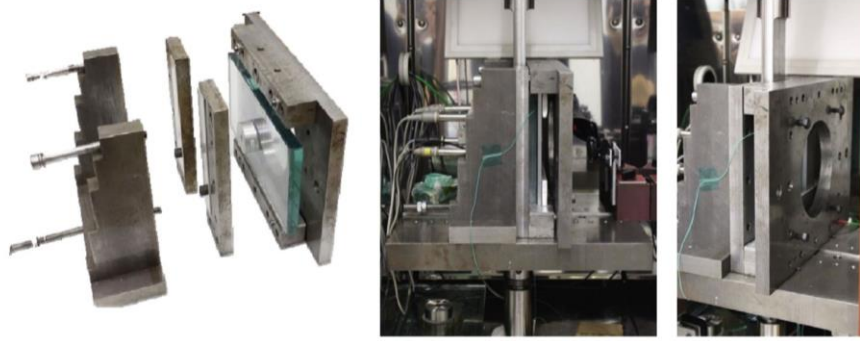


Figure 3.24 : Test setup with climatic chamber, (Santarsiero et al., 2016).

Test scenario is applied at different shear loads (8 kN to 13 kN) and temperatures (-20 °C to +80 °C). According to the test results, behavior of Sentryglass and Dow-Corning TSSA is illustrated in Figure 3.25. According to Figure 3.25, displacement ratio of Sentryglass is depends more on temperature change. Nevertheless, Dow-Corning TSSA behaves similarly at almost all temperatures. On the other hand, Sentryglass shear strength is more effective than Dow-Corning TSSA between -20 °C and 60 °C.

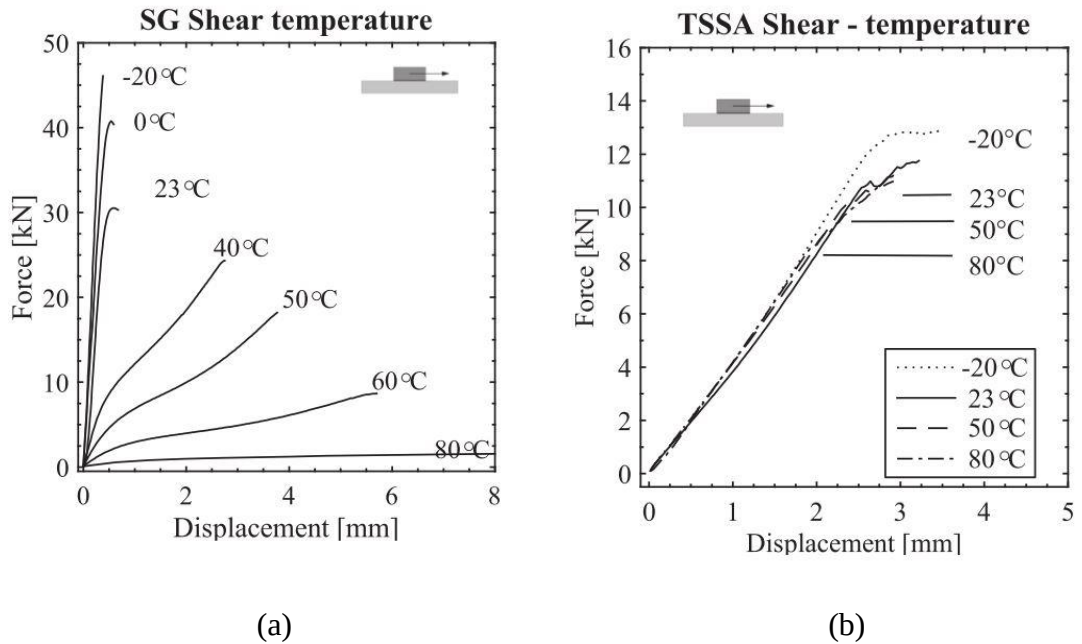


Figure 3.25 : Test results of structural silicones (a) Sentryglass shear force-displacement chart. (b) Dow-Corning TSSA shear force-displacement chart. (Santarsiero et al., 2016).

As a result, material selecting process should be carried out by considering effective temperature values of materials. Moreover, strain based calculation method with considering temperature is more applicable according to (Feldmann & Kasper, 2014).

3.2.6 Energy dissipative devices

The special energy dissipative devices enable to absorb accumulated energy due to earthquake and wind loads which affect cable-net facades. One of the most considerable loads which affect cable-net facades is wind loading which may cause to collapse of the facade (Amadio et al., 2013). The most possible reason for this failure would be is that the structure of the cable-net facade system could not transfer static and dynamic wind loads to main load bearing components. In this context, the use of viscoelastic damping additive materials in the connection elements of the structural facade systems (spider, structural cable) decreases the impact of static and dynamic wind loads. (Sivanerupan et al., 2014).

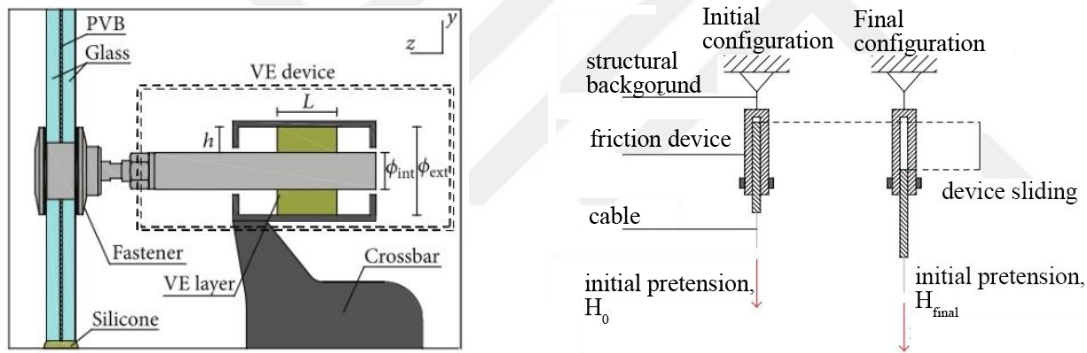


Figure 3.26 : Test configuration of viscoelastic devices of point fixings (Sivanerupan et al. 2014).

While Sivanerupan, Wilson, Gad and Lam used viscoelastic rubber materials in spider connection elements in their work on energy damping devices, they also used rigid-plastic (i.e. yielding) energy-damping elements against the effect of load bearing on the cables and observed the behavior of the structural system under effective wind load. The research was carried out using the experiment and end-of-line method and the results were evaluated comparatively. As a result, it has been observed that the viscoelastic energy absorbing members especially dampen the axial loads.

4. DESIGN AND ANALYSIS OF A CABLE -NET FACADE SYSTEM WITH A PROPOSED NOVEL GLASS NODE

As discussed in previous chapters, cable-net facades are innovative structural facade systems which can enable to develop structural dematerialization. In this chapter, design approach, architectural and engineering design of cable-net facades, determining criteria of effective loads, design limits and their explanations, optimization and form finding process are explained in detail. Additionally, a proposed novel glass node design is applied to cable-net facade design as a component which will be also explained in Chapter 5 in detail. There are mainly three design limits of cable net facades, namely deflection limits of stainless steel wire rope, deflection limits of glass panels and design strength of all components of cable net facades. These design limits should always be considered while designing cable-net facades under possible loads such as wind, earthquake and pretension. Architectural design of cable-net facade unit is developed for a possible future testing at Facade Testing Institute (FTI)'s concrete test stand. After that, finite element modeling of cable-net facade is carried out by using SAP 2000 software. Mainly two structures are analyzed in SAP 2000: cable structure and main load bearing steel structure. Main load bearing system is designed and analyzed according to reaction forces from effective loads (wind, prestress and dead loads). During the engineering design process, optimization and form finding procedures are also executed in order to gain the most effective results.

4.1 Design Process of Cable Net Facade

Design of cable net facade is based on architectural detailing and engineering calculation. Basic principle of design is to use that; using minimum structural material by considering design limits. As seen in Figure 4.1 design process of cable-net facade is a step by step process. Firstly, conceptual design should be carried out in order to determine what kind of architectural articulation would like to be seen. In order to do that, literature review is carried out which is the mentioned in previous chapters. After

that, sectoral research and interviews are sustained. In that research, structural engineers of Metal Yapi supervised about the engineering design and calculations. Additionally, as a base design, Cable-net facade of Yapi Kredi Cultural Center is analyzed in detail in terms of component selection, design limits, and determining effective loads. After analyses was developed, system sketch was drawn and idea of applying a glass node to cable-net structure emerges. While glass node design process continues simultaneously, component selection of facade is also carried out. Initial draft drawing was completed according to selection components. Then, design limits and effective loads were determined according to specified design codes and standards. Cable-net systems were calculated and analyzed according to non-linear FEM analyses in SAP2000. While SAP2000 analyses were carried out, glass unit deflection and strength control were executed by using Mepla ISO software. According to the analyses, optimization and form finding process was performed in order to gain optimum deflections, reaction forces, and minimum cable diameter of wire ropes. With execution of engineering design of wire ropes and glass units, main load bearing system was also designed via SAP2000 by using reaction forces due to prestress, dead loads and wind loads. Secondary optimization was applied for main load bearing system in terms of re-dimensioning. After the analyses were completed, connection components were sized according to the effective loads. Stainless steel plates, welding, bolting connections were calculated manually. Final process was the revision of shop drawings of the system. After revisions, manufacturing drawings were completed.

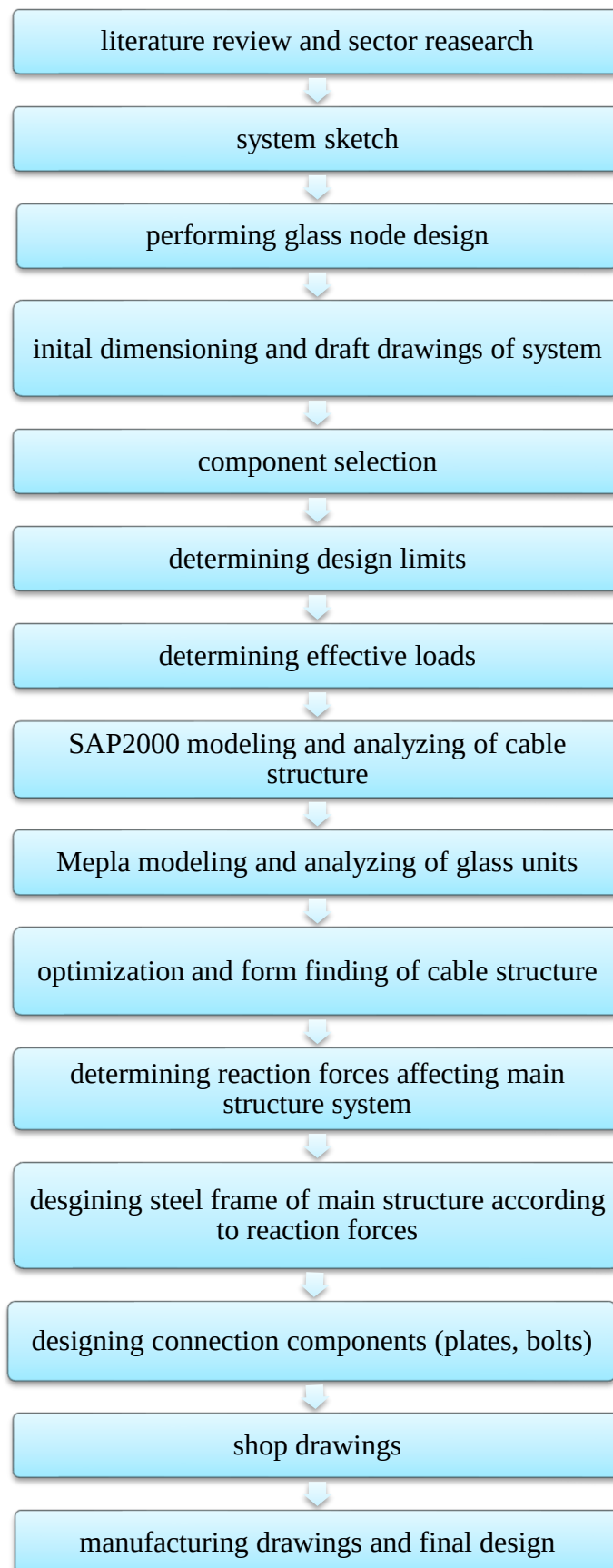


Figure 4.1 : Design process of cable-net facade.

4.2 System Sketch

System sketch is the initial step of designing a cable-net facade. Sketch contains first ideas about form, modulation types and dimensions and primer equations about nonlinear calculations. The first decisions are about point fixing type and glass panel's type. Clamped fixing and insulated glass units are chosen to be applied to the cable-net facade system considered here in. Edge of facade requires also another architectural detail which is also mentioned in the system sketch. Additionally, support type is determined to be pin supported in order to allow cable deflection. Besides all, the first ideas about integration of cable structure and glass units are also mentioned in a system sketch (Figure 4.2).

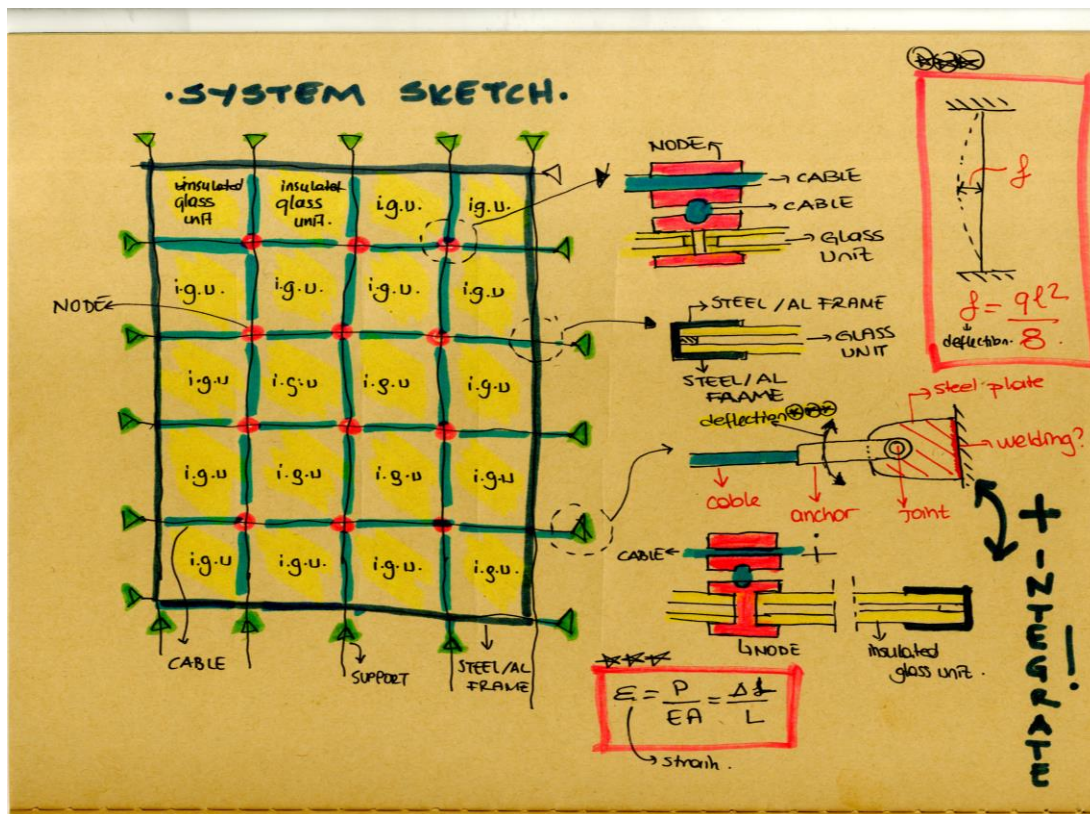


Figure 4.2 : System sketch of selected cable-net facade.

Architectural and engineering acknowledgements can be integrated by means of initial sketches. Therefore, system sketch studies are significant steps for developing innovative detail and component design ideas such as glass nodes which are developed and tested and explained in detail in Chapter 5.

4.3 Analyses of Test Stand and Initial Dimensioning of Cable-Net Facade

Dimensioning process is carried out by considering the FTI's existing reinforced concrete (RC) test stand (Figure 4.3).

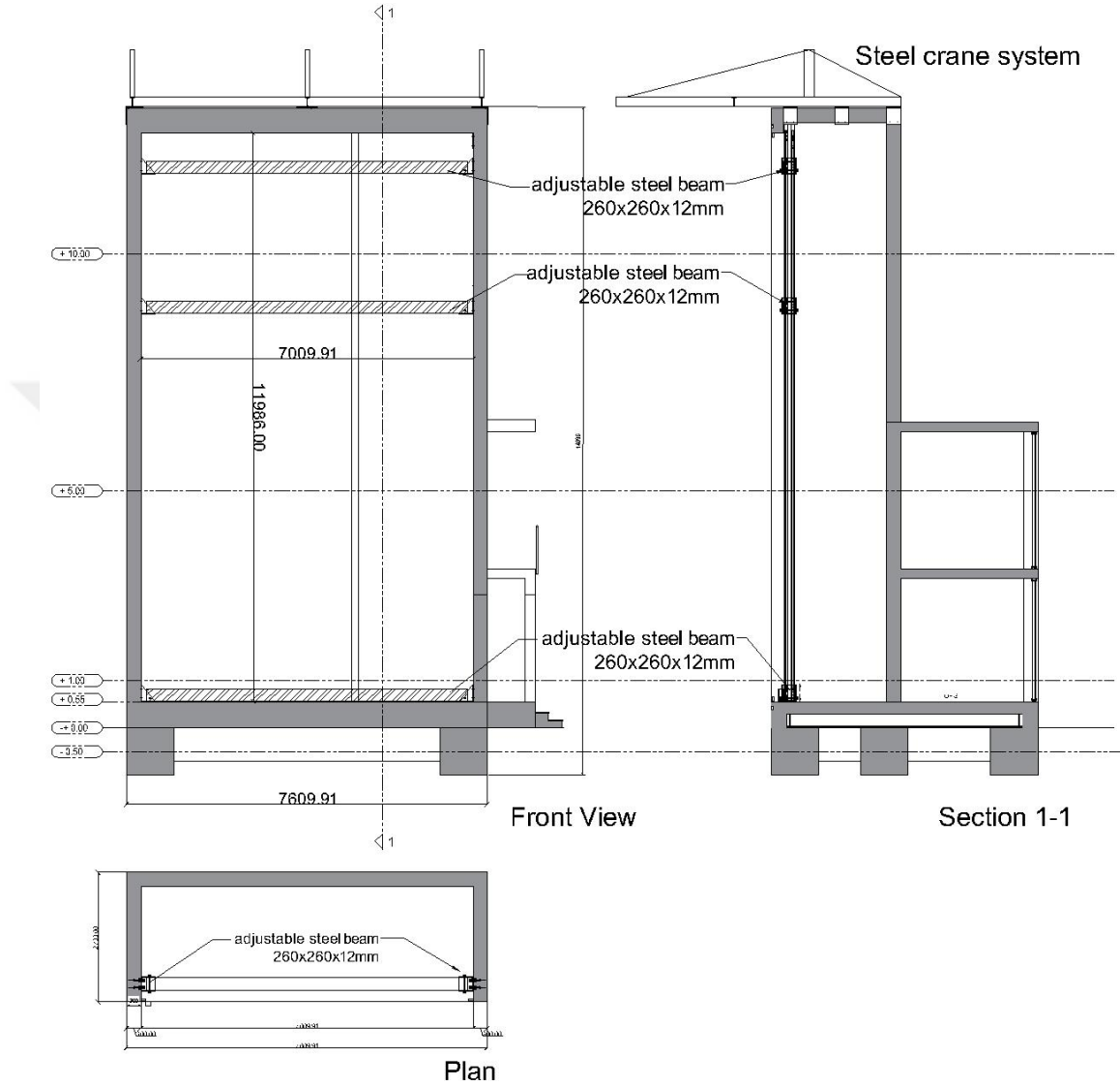


Figure 4.3 : FTI's RC test stand.

According to Figure 4.3, In addition to the RC frame, there are 3 units of 260 x 260 x 12 mm box profile of steel beams. Therefore, main load bearing system of cable-net facade should be configured by using the existing structural components. Additionally, inner dimension of the test stand is 7,009 m x 11,986 m. These dimensions also determine the dimensions of cable-net facade components such as glass units and cable lengths.

After analyzing the existing test stand is physical characteristics, 20 modules (4 module horizontally, 5 modules vertically) of 1m x 2m insulated glass units are determined to be used. Cable net facade dimension is approximately 5m x 10m by using these glass units (Figure 4.4).

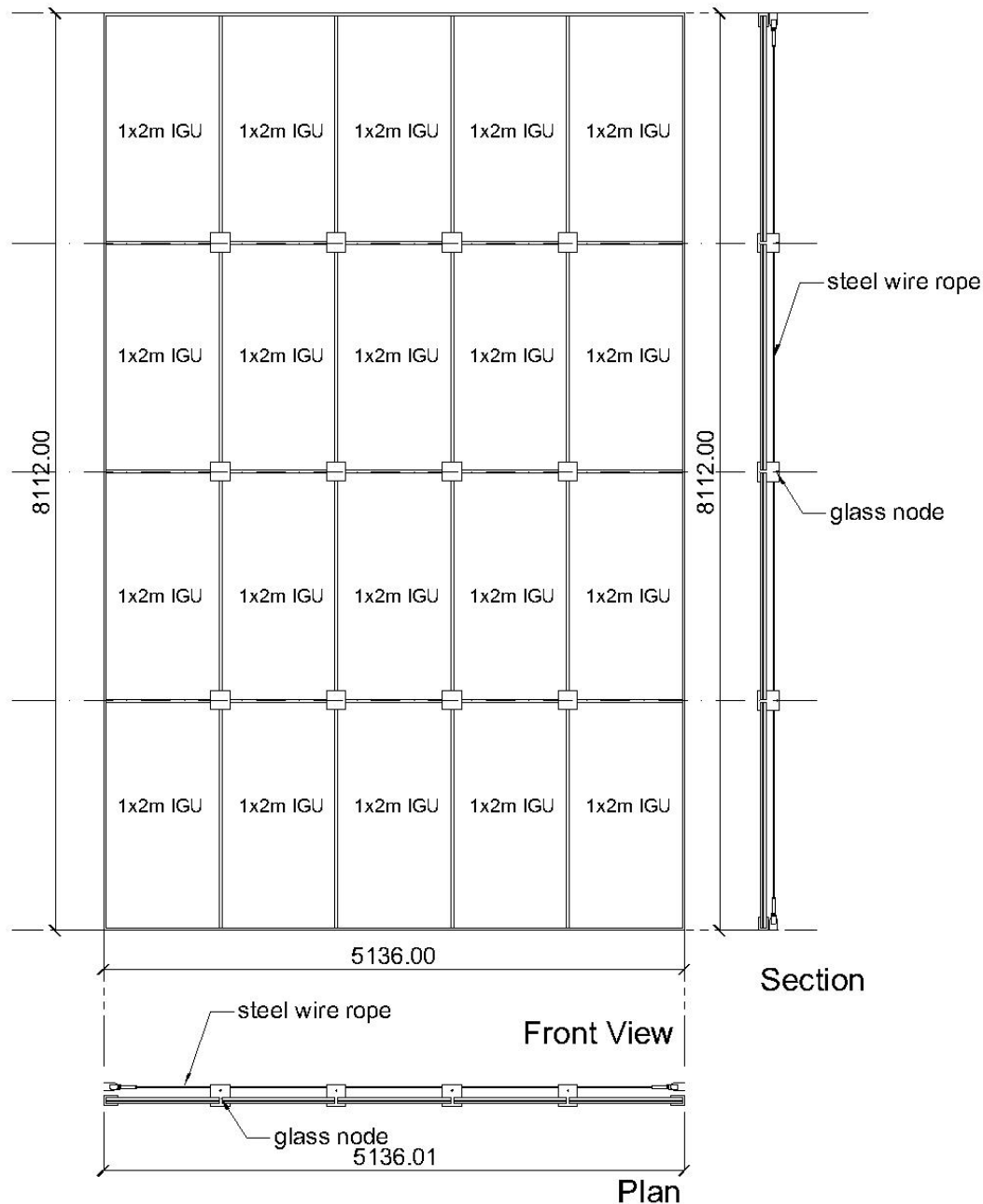


Figure 4.4 : Draft drawings of cable-net glass facade system.

As seen in Figure 4.4, draft drawing was completed after the system's sketch study. Insulated glass units and cables are roughly combined in order to understand possible connection detail configurations.

4.4 Application Drawings of Cable-Net Glass Facade

After gaining general idea about form of cable-net glass facade revealed in previous design steps, integration of structural system of facade into main load bearing system was detailed during the application drawings (Figure 4.5).

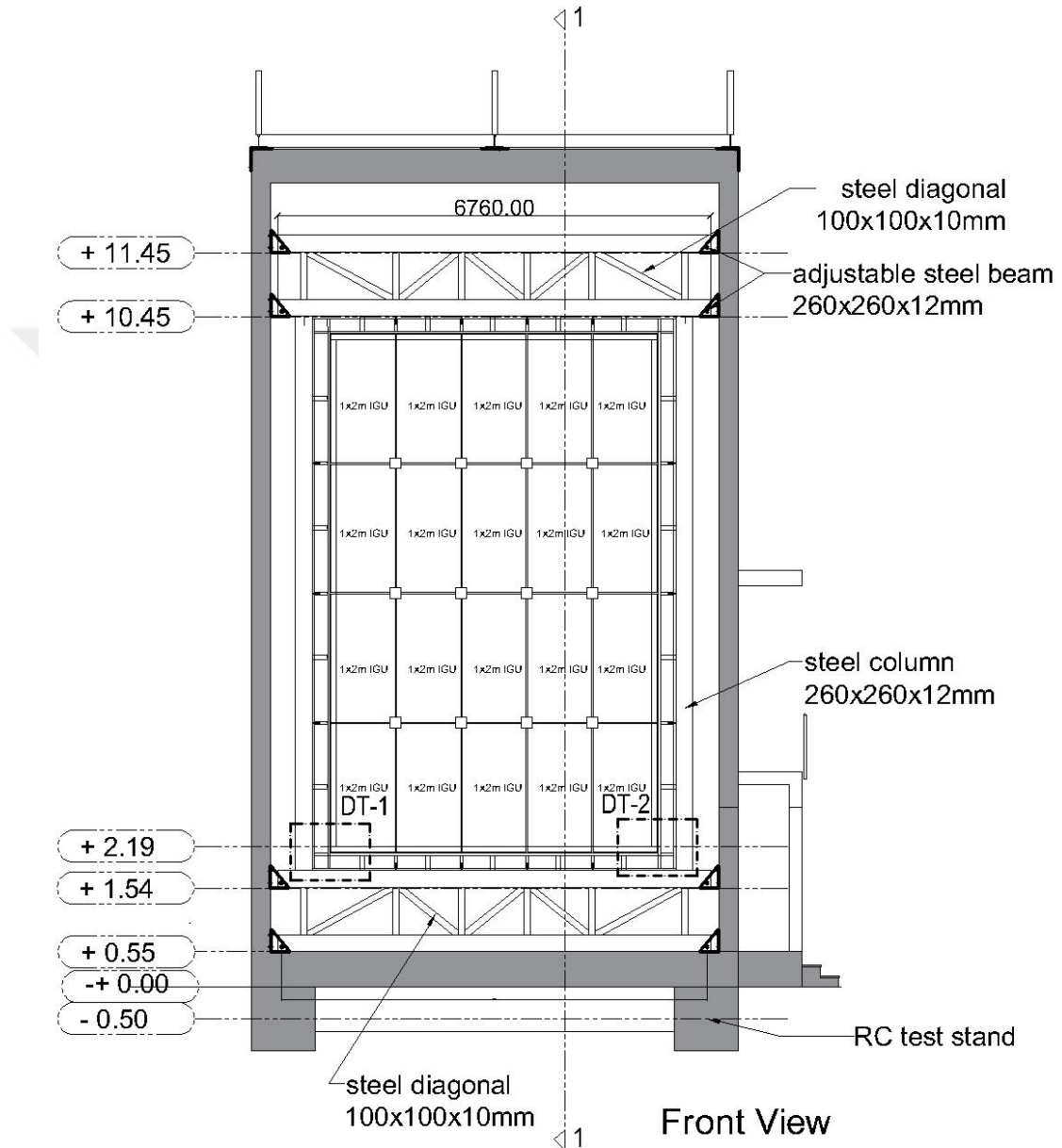


Figure 4.5 : Front view of application drawing of cable-net glass facade.

1 m x 2 m IGU and cable-net structure are integrated into main load bearing system (Figure 4.5). Integration is enabled by using secondary adjustable steel beams (260 mm x 260 mm x 12 mm), steel columns (260 mm x 260 mm x 12 mm) and steel diagonal braces (260 mm x 260 mm x 12 mm) in order to transfer effective loads to main RC structure and create a base frame for glass units. Short span of the steel

structure is 6760 mm, and long span is 8919 mm. Tensioned cable spans (from pin to pin) are 5518 mm, 8543 mm for short and long spans respectively. All application drawings with measurements can be seen in Appendix A.

4.4.1 Connection detailing and component selection

Application details such as connection detailing are developed for the cable-net glass facade system. There are two connection details marked at front view of cable-net glass facade. Two drawings illustrate the connection detail of the system in plan and section views respectively (Figure 4.6 and Figure 4.7).

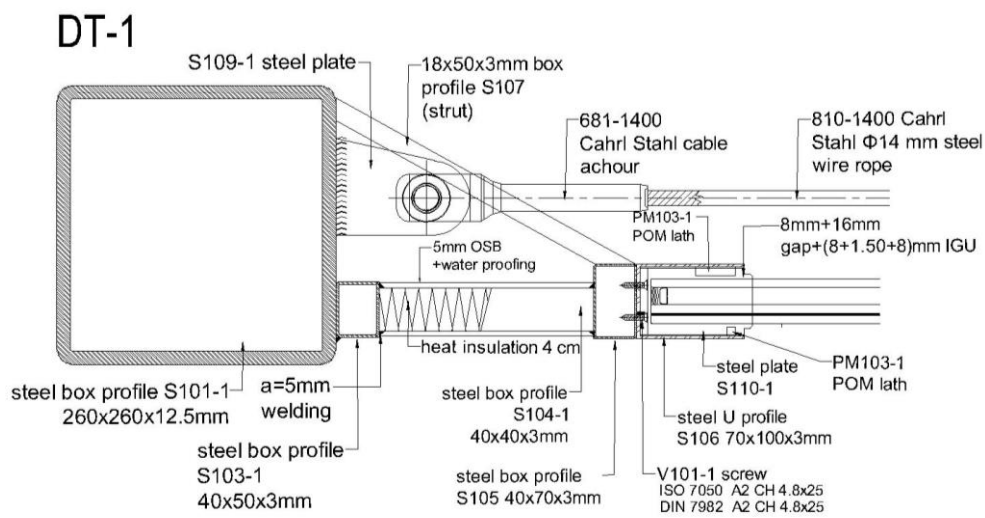


Figure 4.6 : Connection Detail 1 of cable net glass facade (plan view).

As seen in Figures 4.6 and 4.7, $\Phi 14$ mm steel wire rope and its anchoring accessories, 1 m x 2 m IGU panels and steel structural profiles are main structural component of cable-net structural glass facade. $\Phi 14$ mm steel wire rope is connected to the steel box profile column by steel plates and cable anchor accessories. Two types of anchoring are used as adjustable and non-adjustable which are illustrated in Detail 1 and Detail 2 respectively. Moreover, 1 m x 2 m IGU is applied to secondary steel structure by steel U profile (bolted connection) which also transfers effective loads to main load bearing system via a welded connection. Additionally, in order to provide water proofing and heat insulation, waterproofing membrane is used over two units oriented strand board OSB (5 mm) layers which are filled by 4 cm heat insulation. The reason for using rough material combination such as (OSB) for finishing is to reduce the application costs. Besides, this detail can be reconfigured according to designer's preferences.

DT-2

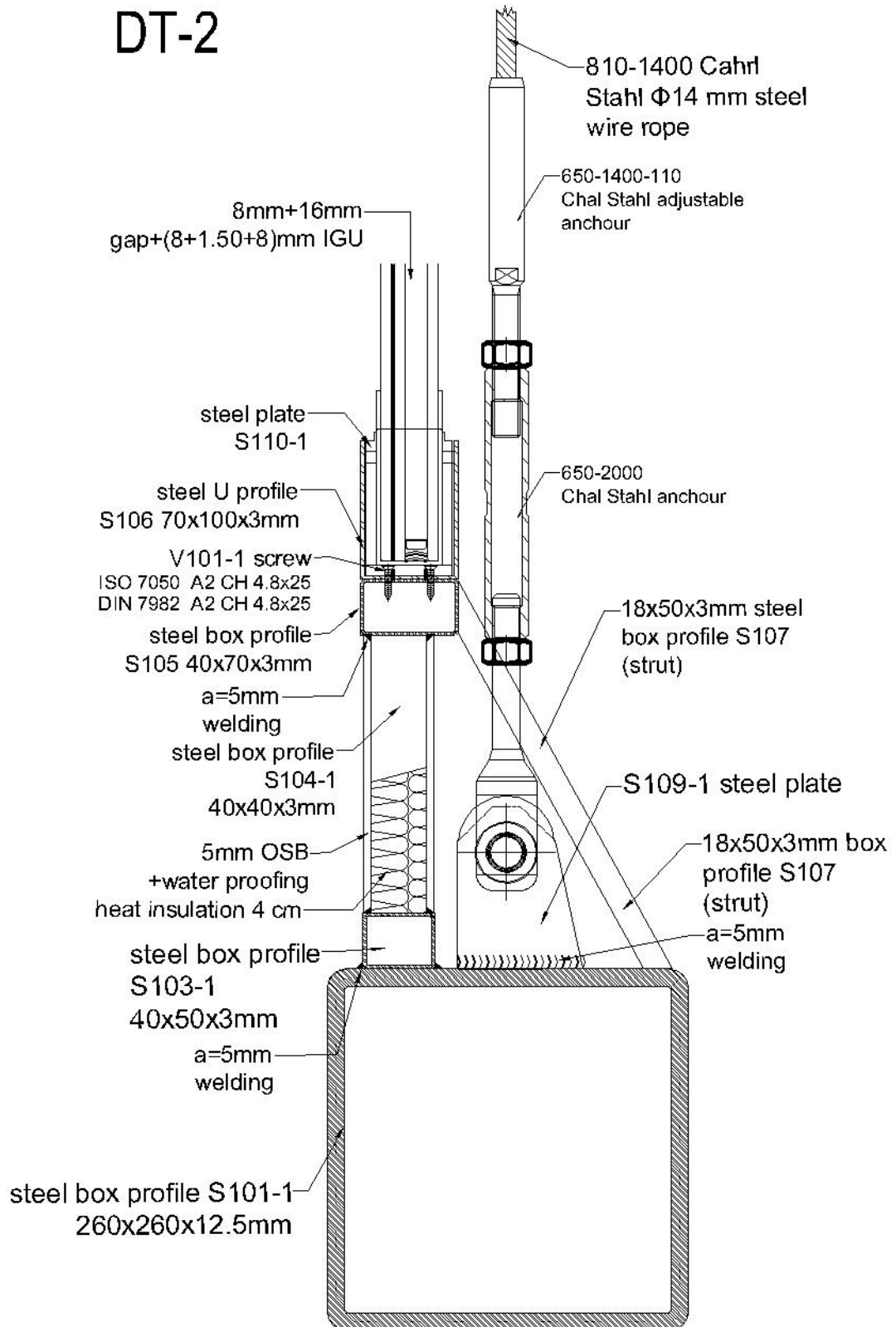


Figure 4.7 : Connection Detail 2 of cable-net glass facade.

4.4.1.1 Insulated glass unit

1 m x 2 m IGU is combined as 17,52 mm laminated and heat strengthened glass (8 mm HSG + 1.52 PVB lamination sheet + 8 mm HSG), 16 mm air gap and 8 mm tempered glass which is illustrated in Figure 4.8.

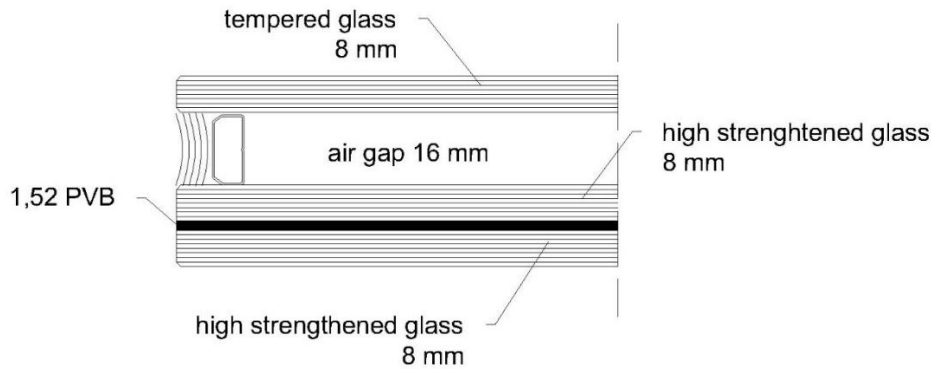


Figure 4.8 : Layers of insulated glass unit used.

This combination of glass unit is more layered than other glass units usually used in cable-net glass facades. With this combination, cable deformation due to dead load is much more observable. Mechanical properties of high strengthened glass and tempered, which will be used in mathematical calculations, glass are mentioned in Chapter 3.2.1 and engineering analyses are explained in Chapter 4.5.

4.4.1.2 Steel wire rope and fittings

Steel wire ropes are connected to steel box profile column by steel plates and cable fittings. Steel wire rope and anchor accessories are selected via Charl Stahl product brochure and specific application details are applied to cable-net glass facade. Steel wire rope⁸ consists of 1x19 spiral winded strands and section and side view of the material can be seen in Figure 4.9.



Figure 4.9 : . $\Phi 14$ mm steel wire rope, product code: 810-1400, (Charl Stahl, 2018).

⁸ Steel wire rope diameter is determined after non-linear analysis and optimization process of cable-net structure in SAP2000. These two processes will be explained in further chapters.

In addition to physical properties of steel wire rope, mechanical properties are also quite considerable for non-linear analysis of cable-net structure. Therefore, mechanical properties of steel wire rope are illustrated in Table 4.1.

Table 4.1 : Mechanical properties of $\Phi 14$ mm steel wire rope, product code: 810-1400, (Charl Stahl, 2018).

Characteristic	Symbol	Value and unit
Material type	AISI 316	-
Shear modulus (modulus of elasticity)	E	$1,3 \times 10^5$ N/mm ²
Minimum breaking strength	$S_{\min}$	131 kN
Metallic cross section	A	116,99 mm ²

As seen in Table 4.1, material type of steel wire rope is AISI 316 which is one of the stainless-steel classes according to AISI standard. This type of stainless steel is durable, rigid with low stretch characteristics and high minimum breaking load. Therefore, it is proper for structural applications such as cable-net structures.

Note that in addition to steel wire ropes carbon fiber reinforced polymer's (CFRP) bars/wires are also being used as an alternative material currently. High strength and high corrosion resistance properties of such components are worth mentioning.

Fittings are selected according to diameter of steel wire rope by Charl Stahl Product Catalogue. Two types of fitting are used, one of which is adjustable and the other one is nonadjustable, in order to designate calculated prestress load to steel wire rope. Technical drawing of adjustable and non-adjustable anchor accessories is illustrated in Figure 4.10.

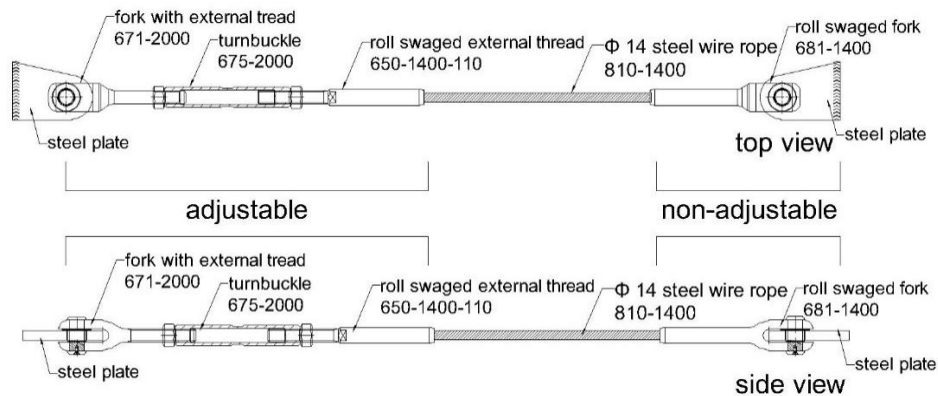


Figure 4.10 : Adjustable and non- adjustable fittings, (Charl Stahl, 2018).

Figure 4.10 revealing that, while roll swaged fork is used as non-adjustable anchor, adjustable anchor consists of fork with external tread, turnbuckle and roll swaged external tread. Using adjustable fittings enables to adjust wire rope length precisely according to prestress value during construction of cable-net glass facade. Determining which side of the cable to mount with adjustable fitting to main structure is considerable during vertical cable application. Adjustable fittings should be used at reachable level of cable. Therefore, while adjustable fittings are to be used at bottom level, non-adjustable fittings are to be used at top level of cable-net structure in order to simplify assembling process.

Additionally, mechanical properties of fittings are shown in Table 4.2 in order to carry out essential calculations.

Table 4.2 : Mechanical properties of fittings, (Charl Stahl, 2018).

Characteristic	Symbol	Value and unit
Material type	AISI 316	-
Elasticity modulus	E	$2,1 \times 10^5 \text{ N/mm}^2$
Minimum breaking strength	$S_{\min}$	131 kN

As seen in Table 4.2 breaking load/tensile rupture of fittings and cable has same value. Thus, Cable and fittings are able to behave as a single unit.

4.5 Structural Design of Cable-Net Glass Facade

Structural design process, in general, consists of mainly three steps: Determining design characteristics, structural modeling, and analyzing, optimization and final dimensioning (Figure 4.11).

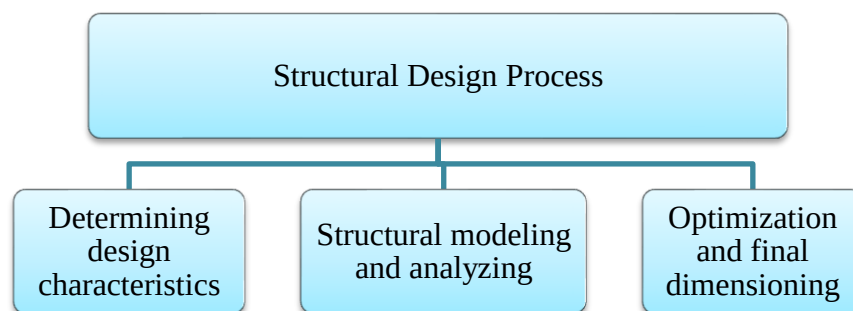


Figure 4.11 : Structural design process.

Structural design process given in Figure 4.11 is also applicable for structural design of cable-net glass facade. However, cable-net glass facades include mainly three interdependent structural subsystems/components, namely cable-net, main load bearing steel structure and connection components. All these systems are to be analyzed with distinctive design characteristics. Therefore, structural design process of a cable-net glass facade is divided into three main parts (Figure 4.12).

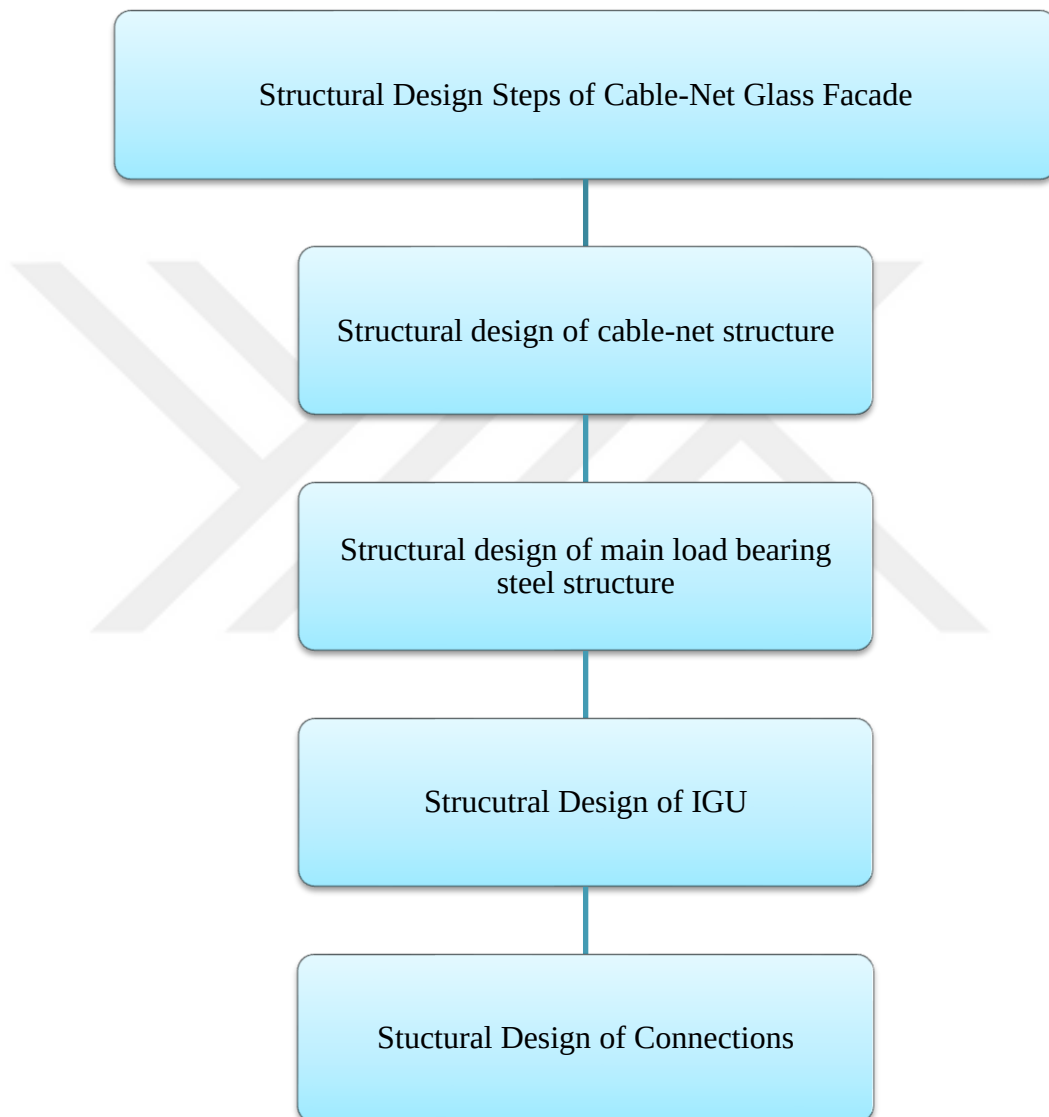


Figure 4.12 : Structural design steps of cable-net glass facade.

As given in Figure 4.12, cable-net structure, main load bearing steel structure and connection components should be designed in a step by step order to transfer analyzed data to each other. Structural design process in general (Figure 4.11) should be applied to each interdependent subsystem of cable-net glass facade. Thus, gained data can be used for next structural subsystem/component of cable-net glass facade.

4.5.1 Structural design of cable-net structure

Cable-net structure is defined as the system which consists of cables and glass panels for this study. Therefore, structural design of cable-net structure includes determining design characteristics, structural modeling and analyzing, optimization and final dimensioning of cable-net. Analyses are performed by using SAP2000 software.

Design characteristics of cable-net facade are design method and design limits of structure, effective loads, and combinations. These three characteristics are quite considerable for a precise structural analysis. Therefore, they should be determined according to international codes and standards.

4.5.1.1 Design method and design limits (ASCE 19-16 and AISC 360-10)

Design process of cable-net structure is carried out according to Allowable Stress Design Method (ASD). According to ASCE 19 and AISC 360-10, strength and deflection limits are calculated with equations mentioned below:

- **Strength Limits**

Design shall be performed in accordance with Equation (4.1), (4.2), (4.3) to determine strength limits.

$$S_a \leq (S_{min} \times N_f) / \omega = (S_{min} \times N_d) / \omega \quad (4.1)$$

where,

S_a = allowable strength

S_{min} = minimum breaking strength

N_f = fitting reduction factor

N_d = deflection reduction factor ($N_d = 1$ for the case of no deflector)

ω = safety factor

As mentioned in Equation (4.1), allowable strength is calculated by dividing nominal strength of material by a safety factor. According to ASCE 19-16, safety factor (Ω) for cable structures is to be taken as 2.2 in order to determine allowable tensile strength of cable. Fitting reduction factor (N_f) is taken as 1 because, swaged fittings are used in design (ASCE 19-16). There is no deflector applied to system. Therefore, N_d is taken as 1.

$$S_a \leq S_{min}/\omega \quad (4.2)$$

Allowable design strength of cable is calculated by using the equation 4.2 and Table 4.1.

$$S_{a \text{ cable}} \leq 131/2,2 \text{ kN}$$

$$S_{a \text{ cable}} \leq 59,55 \text{ kN}$$

Allowable design strength of fittings is calculated by using the equation 4.2 and Table 4.2.

$$S_{a \text{ fitting}} \leq 131/2,2 \text{ kN}$$

$$S_{a \text{ fitting}} \leq 59,55 \text{ kN}$$

- **Deflection Limit**

According to Patterson, deflection limit of cable-net glass facades can be assumed to be L/40-L/50 there. L is the short span of cable-net glass facade. In this study, deflection limit is taken as L/50. Short span of the structure is 5518 mm. Thus;

$$\delta_{limit} = L/50 \quad (4.3)$$

$$\delta_{max} \leq \delta_{limit} \quad (4.4)$$

where;

δ_{limit} = Deflection limit of structure.

L= Short span of structure.

$$\delta_{limit} = 5518/50 \text{ mm}$$

$$\delta_{limit} = 110,36 \text{ mm}$$

4.5.1.2 Design loads and combinations

- **Design loads**

Design loads of cable-net facades are dead load as cable-net structure (D) and insulated glass units (SDL), wind load as pressure (W+) and as suction (W-), earthquake loads as (EQX+), (EQX-), (EQY+), (EQY-) temperature loads as (T+), (T-), and prestress loads as P_r .

- Dead load (D) of cable-net is calculated automatically in SAP2000 which can be seen in Appendix B.
- Insulated glass units (SDL) are calculated by using the equation shown below;

$$SDL = \rho x t \quad (4.5)$$

- According to equation 4.5, ρ is density of glass and t is total thickness of glass unit.

$$SDL = 2,5 \text{ t/m}^3 \times (8 + 8 + 8) \times 10^{-3} \text{ m}$$

$$SDL = 60 \text{ kg/m}^2 \sim 6 \times 10^{-7} \text{ kN/mm}^2$$

- Wind load is determined according to Eurocode 3 and Istanbul High Rise Buildings Regulation (2008);

$$(W+) = 80 \text{ kg/m}^2 \sim 8 \times 10^{-7} \text{ kN/mm}^2 \quad (4.6)$$

$$(W-) = -80 \text{ kg/m}^2 \sim -8 \times 10^{-7} \text{ kN/mm}^2 \quad (4.7)$$

Wind load affects cable-net facade as a distributed load. According to the direction of wind, wind load is applied to structure as pressure (WIND+) or suction (WIND-) loads as mentioned in Equation (4.6) and (4.7). Because of the flexible structure of the cable-net, deflection values mostly depend on dramatic effects of wind.

- Earthquake loads (EQX+), (EQX-), (EQY+), (EQY-) are determined according to Specification for Building to be Built in Seismic Zones (2007) and evaluated in SAP2000 (Appendix B).
- Thermal loads are determined according to Turkish State Meteorological Service. During the 98-year time period (1929-2017), maximum and minimum

temperatures are measured as +41,5 °C and -16.1 °C (mgm.gov.tr). Difference between the minimum and maximum temperatures is approximately 60 °C. Therefore, thermal loads are determined as;

$$(T+) = +30\text{ }^{\circ}\text{C} \quad (4.8)$$

$$(T-) = -30\text{ }^{\circ}\text{C} \quad (4.9)$$

- Prestress load is one of the most important loading types for cable net structures in order to enhance stability of the facade structure. Prestressing (P_r) load is determined according to P_d value of cable. According to ASCE 19-16, P_r value shall not exceed 55% of minimum breaking strength. Therefore

$$P_r \leq 0,55 \times S_{min} \quad (4.10)$$

$$P_r \leq 0,55 \times 131\text{ kN}$$

$$P_r \leq 72\text{ kN}$$

Although, P_r value can be determined according to equation 4.10, several applications are carried out by considering P_r as approximately 50% of allowable strength of cable. Therefore, after optimization, P_r is determined as -35,00 kN for the cable-net structure.

- Pretension load is assigned strain load (ε) in SAP2000 software. Strain is applied to structure as negative load in order to gain pretensioned stainless steel wire rope (Appendix B). Determining strain value is performed by using Equation (4.11).

$$\varepsilon = \frac{P_r}{EA} \text{ mm/mm} \quad (4.12)$$

where,

ε = Strain (mm/mm)

P_r = Pretension load, according to equation 4.10; 32 kN.

E = Elasticity modulus of $\Phi 14$ steel wire rope according to Table 4.1; $1,3 \times 10^5 \text{ N/mm}^2$.

A = Effective cross section of steel wire rope according to Table 4.1; $116,99 \text{ mm}^2$.

When numerical values are substituted into equation 4.11, following is obtained;

$$\varepsilon = \frac{-35 \times 10^3}{(1,3 \times 10^5) \times 116,99} \text{ mm/mm} \quad (4.12)$$

$$\varepsilon = -2,3 \times 10^{-3} \text{ mm/mm}$$

- **Load combinations**

After determining design loads, design combinations are determined according to ASCE 7-10⁹.

- LC01= Pr+D+SDL
- LC02 = (T+)+PR+D+SDL
- LC03 = (T-)+PR+D+SDL
- LC04 = (W+)+(T+)+PR+SDL+D
- LC05 = (W-) + (T+) + PR + SDL+ D
- LC06 = (W+) + (T-) + PR + SDL + D
- LC07 = (W-) + (T-) + PR + SDL +D
- LC08 = (EQX+) + 0,3(EQY+) + D
- LC09 = (EQX-) + 0,3(EQY+) + D
- LC10 = (EQX+) + 0,3(EQY-)+D
- LC11 = (EQX-) + 0,3(EQY-)+D
- LC12 = 0,3(EQX+) + (EQY+) + D
- LC13 = 0,3(EQX-) + (EQY+) + D
- LC14 = 0,3(EQX+) + (EQY-)+D
- LC15 = 0,3EQX(-) + EQY(-)+D.

Design loads and combinations are determined in order to model and analyze the cable structure in SAP2000.

⁹ However, reduction coefficient is determined to be 0,7 for wind load, 0,75 for earthquake load as ASCE 7-10, all coefficients is preferred to be taken as 1 due to dramatic effects of wind and earthquake.

4.5.1.3 Cable Catenary Theory and computational modeling

Design theory of cable structures are based on Hooke Law and emerged with Frei Otto. Afterwards, Cable Catenary Theory was developed by Peyrot and Goulois in 1979 (Greco, Impollonia, & Cuomo, 2014). Thus, several load combinations could be determined by using computational analysis tools such as SAP2000. Cable theory is based on several preconditions which are;

- Cable's behavior is elastic (Hook's Law) and non-linear,
- Accuracy and presence of point forces of cable do not rely on sub-element division. Therefore, nodes and conception points are located at intersection of cables and support points.

According to preconditions, basic theory and deformed of a cable is illustrated in Figure 4.13.

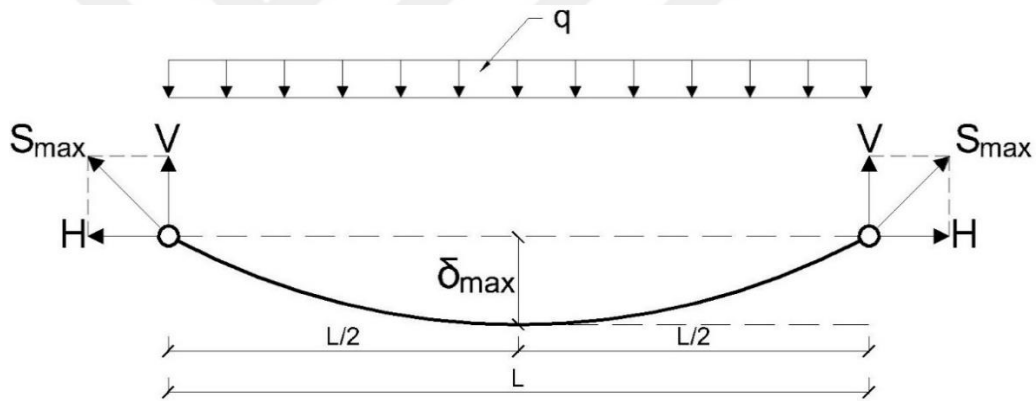


Figure 4.13 : Cable behavior under distributed load (q), (Karataş, 1974).

According to Figure 4.13, V is vertical force, H is horizontal force, $S_{\max}$ is the maximum reaction force, and $\delta_{\max}$ is maximum deflection due to a uniformly distributed load (q). As seen below, cable behavior is catenary (funicular) under distributed loads (q). Additionally, reaction forces are also determined by equation 4.13, 4.14 and 4.15.

$$H = \frac{qxl^2}{8} \quad (4.13)$$

$$V = \frac{ql}{2} \quad (4.14)$$

$$S_{max} = \sqrt{H^2 + V^2} \quad (4.15)$$

where,

V = Vertical force reaction,

q = Distributed load,

H = Horizontal force reaction,

S_{max} = Maximum reaction force.

When numerical values are substituted into equation 4.15, following is obtained;

Besides the reaction forces, maximum sag is also considerable for cable structures. Therefore, sag calculation can be carried out via Equation (4.16).

$$\delta_{max} = \frac{5}{384} \frac{ql^4}{EI} \quad (4.16)$$

As it can be seen in the equations expressed above, S_{max} and δ_{max} are calculated by using vertical and horizontal reaction forces which are also acceptable for cable-net facades. However, there are additional effective loads applied to cable-net structure which can be seen as plan and section views in Figure 4.14 and 4.15 respectively.

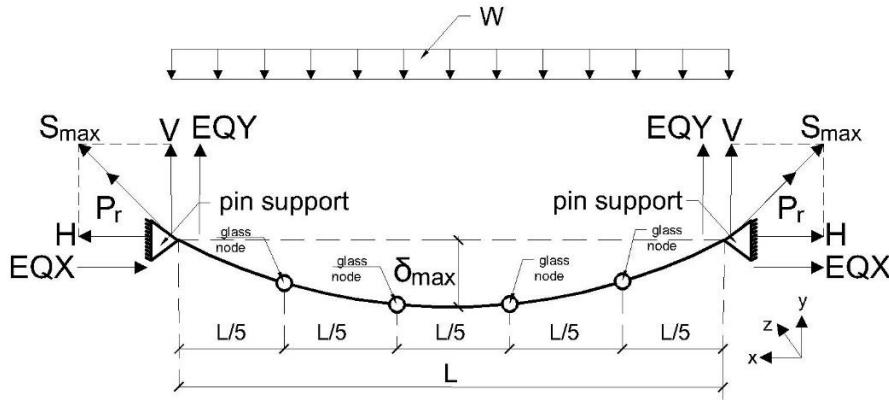


Figure 4.14 : Effective loads of cable-net facade in plan view¹⁰.

As also seen in Figure 4.15 shows that wind load (W) is applied as distributed load. Moreover, direction of P_r , EQX and EQY is also illustrated. In plan view, cable

¹⁰ Even though temperature load is not illustrated in Figure 4.14, their effects are included computational structural analyses.

intersects with vertical cables via glass nodes which divide the cable length into 5 equal parts. However, calculation of cable should be carried out by considering the total length of cable (L)¹¹. Moreover, section view also enables to comprehend effective load actions to structure.

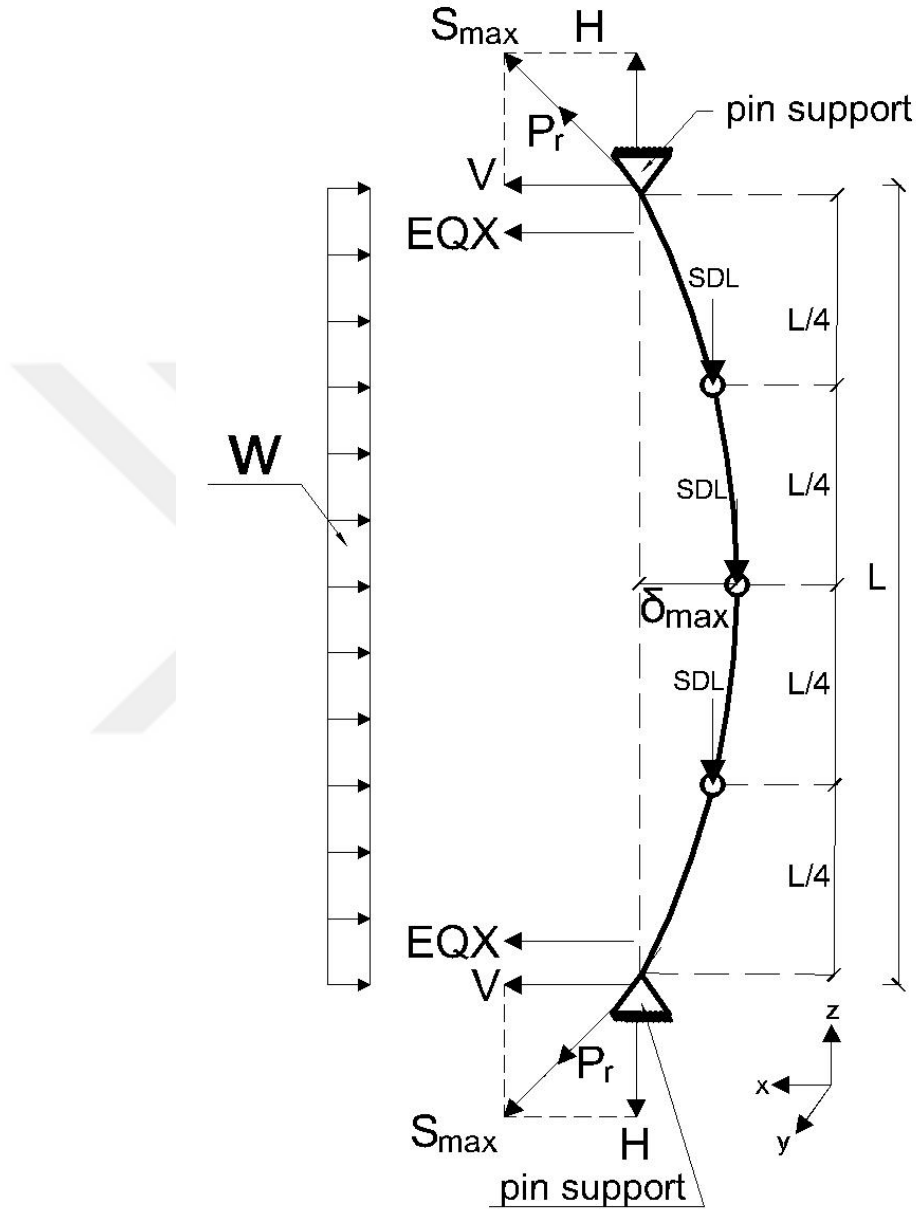


Figure 4.15 : Effective loads of cable-net facade in section view¹².

¹¹ This approach was mentioned in preconditions of cable theory previously (see p.64).

¹² Even though temperature load and EQY could not to be illustrated in Figure 4.15, these effects are included in the computational structural analysis.

As also seen in Figure 4.15, effective loads are mostly the same as the plan view of cable-net facade. Both views explain that several load types are applied to structure in the computational analysis. Thus, maximum deflection and reaction forces would determine precisely. Afterwards, main load bearing steel structure and structural connections (welded or bolted) designed by using these reaction forces of cable-net structure.

As mentioned below, computational modeling and analyzing have a non-negligible role in providing design limits of structure. Computational modeling is carried out by using SAP2000 software as nonlinear analysis due to non-predictable behavior of cable-net structure as mentioned below. SAP2000 calculates the support reactions with performing the analyzes according to combined loads which are listed on p.63. Analysis of the software focuses on mainly two parameters, namely reaction forces at pin supports of structure and deflections at nodes. Several steps of modeling are carried out and shown in Figure 4.16.

From Figure 4.16, first of all material properties, mass source, section properties, coordinate system grids are defined. Material properties of cable and glass panels are defined as FCL and FICTIVE respectively. FCL is obtained by mechanical properties of cable shown in Table 4.1. However, mechanical properties of glass panels are not applied to SAP2000 analysis because glass panels do not behave as structural components. On the contrary, they behave as membrane components. Therefore, glass is defined as a fictitious shell material that affects the structure only with their dead loads (SDL). However, besides the cable-net structure analysis of cable-net, structural analysis of the IGUs is also necessary. Therefore, structural analysis of insulated glass unit is carried out via SJ Mepla. Mass source is defined in order to assign dead load of cables to structure automatically. Cable sections are defined as CS12 and CS14 in order to sustain optimization. While CS12 refers to $\Phi 12$ mm steel wire rope, CS 14 refers to $\Phi 14$ mm steel wire rope. Even though final design is generated with CS14, design process is started with CS12. Coordinate system and grids are also defined with regard to application drawings of cable-net glass facade. Spans are determined according to length from pin to pin and distance between glass nodes. Afterwards, load patterns are defined as D (dead load of cable), W+ (positive wind load), W- (negative wind load), EQX+ (positive earthquake in x direction), EQX- (negative earthquake in x direction), EQY+ (positive earthquake in y direction), EQY- (negative earthquake in

y direction), PR (strain /prestress load), T+ (positive temperature), T- (negative temperature). Load cases and combinations are determined according to defined loads combinations¹³. Afterwards, design preferences are determined as AISC-ASD 360-16. According to preference, lateral factor for wind is taken as 1.15, lateral factor for seismic loads is applied as 1.33.

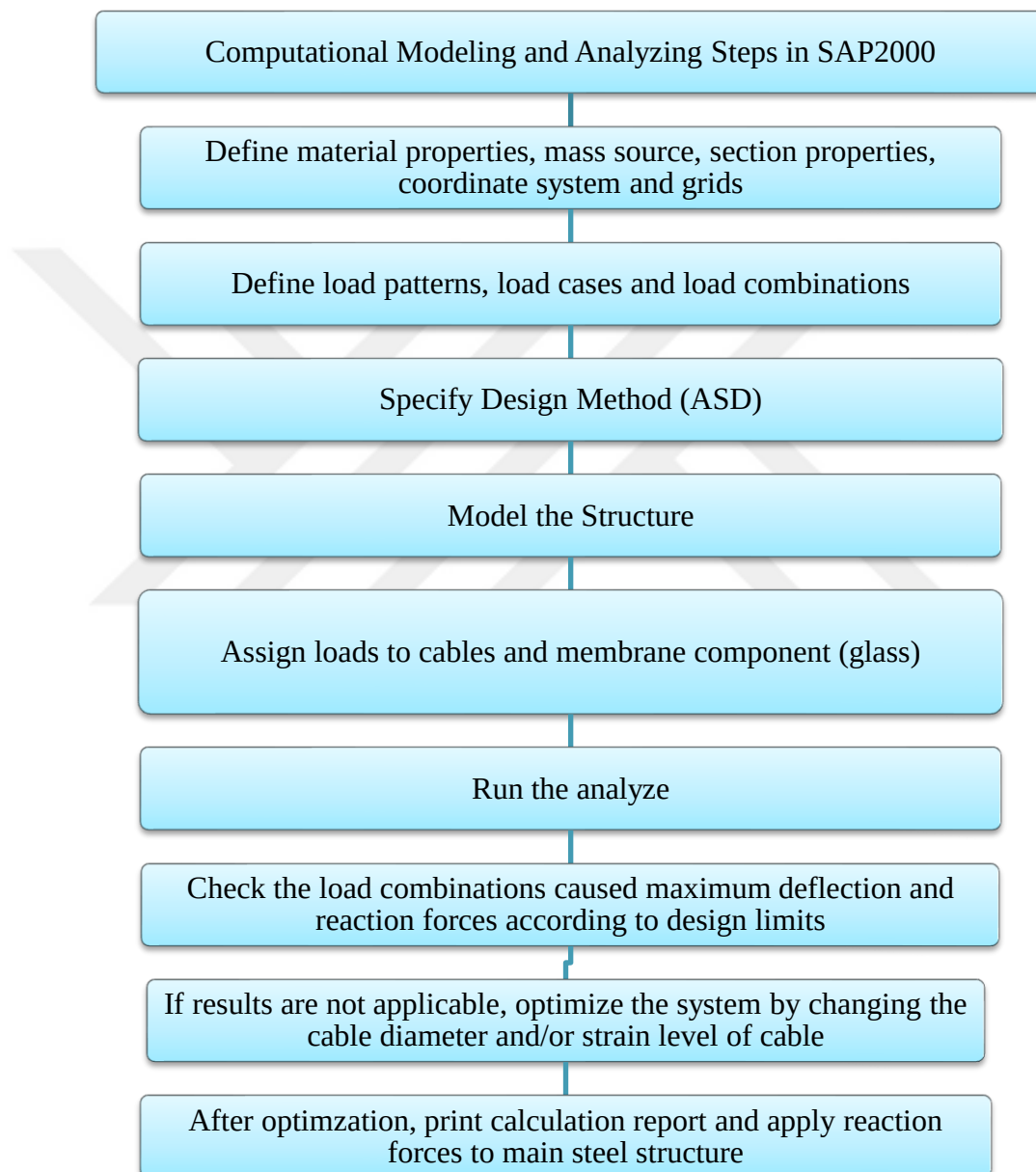


Figure 4.16 : Computational modeling and analyzing steps in SAP2000.

¹³ See p. 63.

As seen in Figure 4.17, model of structure is generated by regarding to draw cables from pin to node, from node to node and from node to pin respectively. Support type is selected as pin support according to application drawings. Glass panels are also modeled as fictitious component.

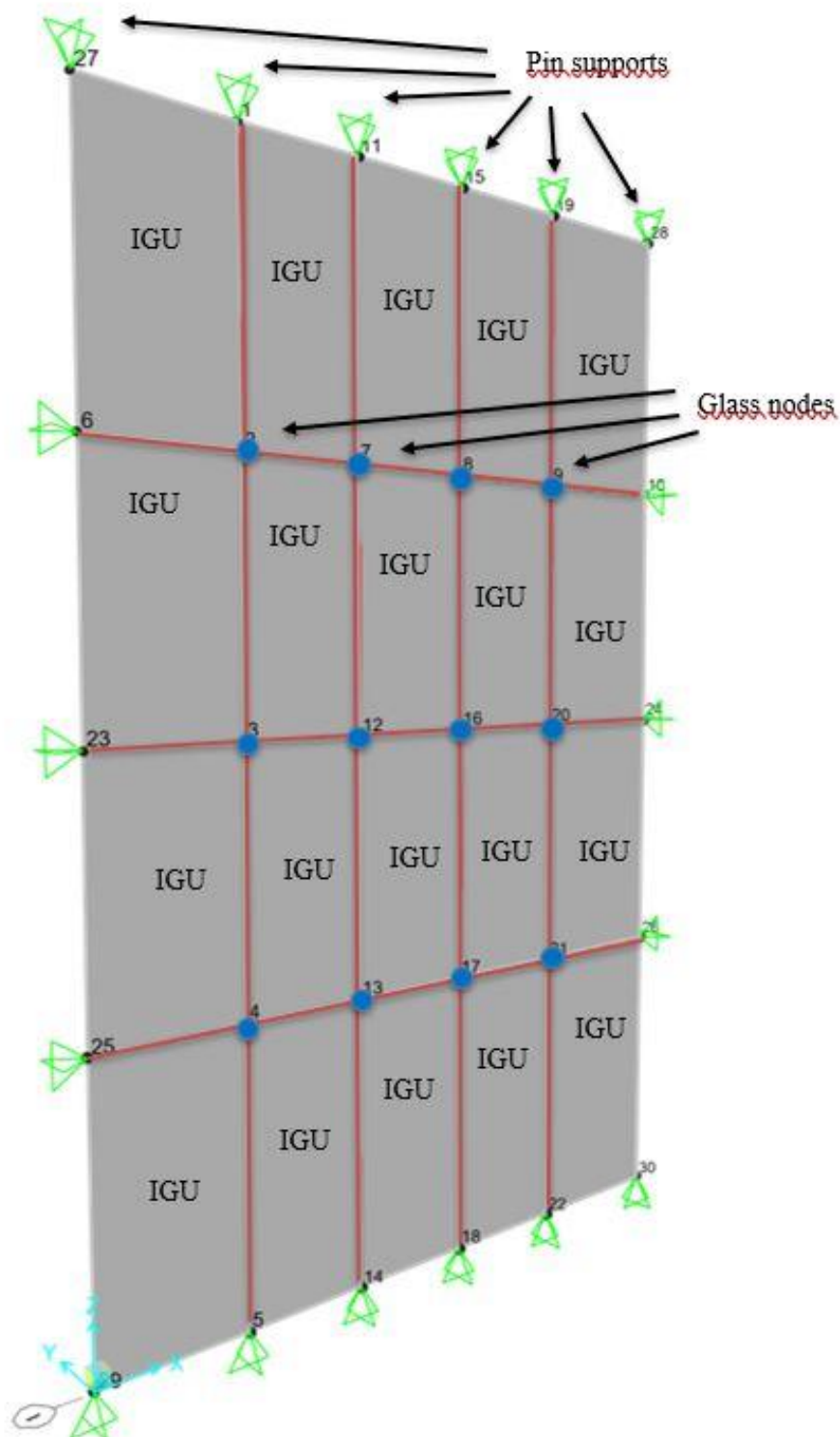


Figure 4.17 : General view of cable-net structure in SAP2000 model.

- **Strength Limit Check**

After assigning loads to structure, analysis is run. According to the analysis, maximum reaction forces occur at LC04¹⁴ which defined as; (W+)+(T+)+PR+SDL+D. Maximum reaction forces are observed at support points of horizontal cable, which are defined as Joint Object 23 and Joint Object 24 in SAP2000, located at middle zones of structure as illustrated in Figure 4.18.

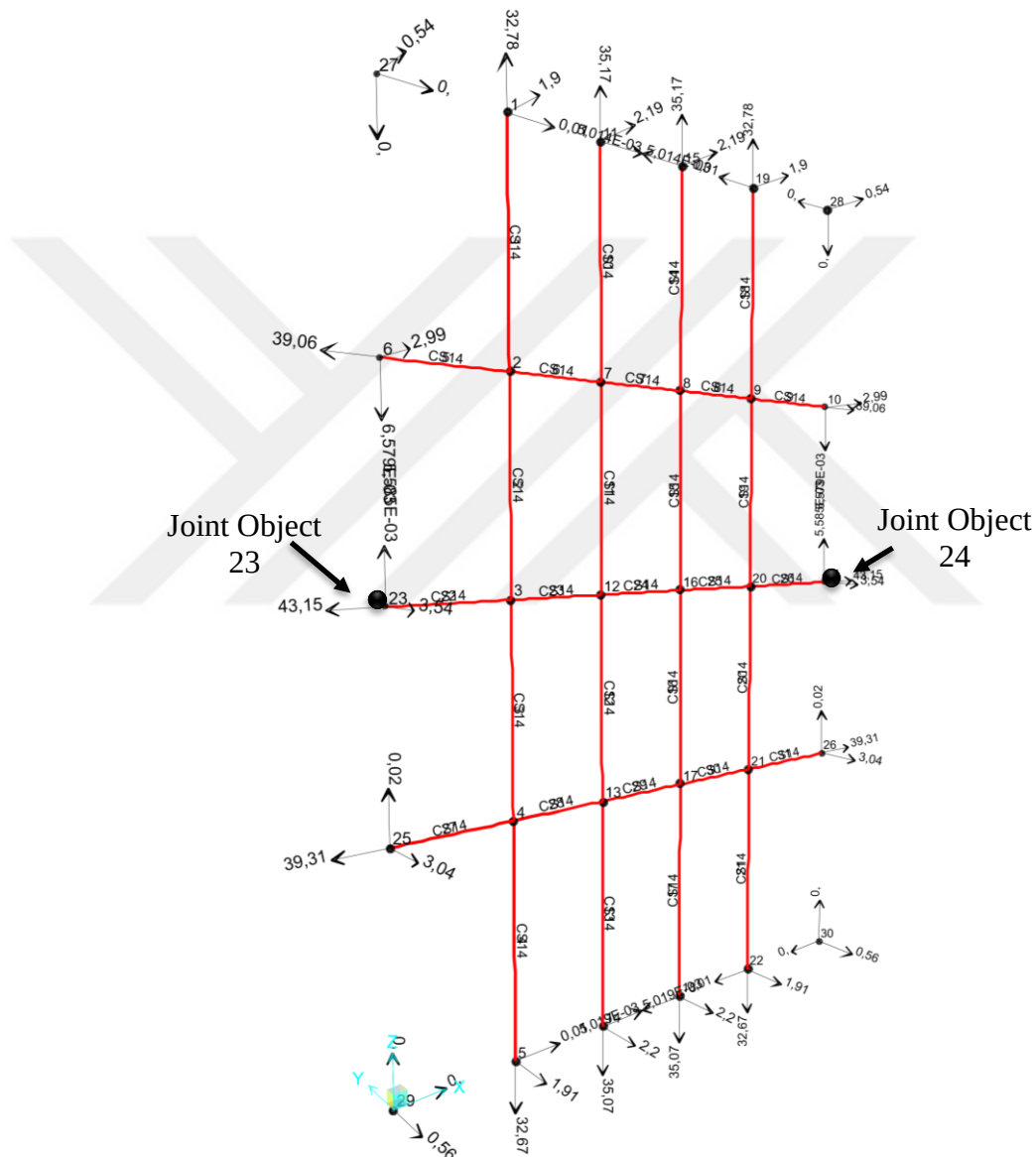


Figure 4.18 : Maximum reaction forces of cable-net structure, combination load; LC04.

¹⁴ See p.63.

As seen in Figure 4.18, maximum joint reactions are 43,15 kN in X direction, 3,54 kN in Y direction and $5,6 \times 10^{-3}$ kN in Z direction. Additionally, in vertical cables, remarkable reaction forces of vertical cables are observed in Z direction which means that, while vertical cables bear dead loads, horizontal cables bear prestress, wind and earthquake loads.

In order to calculate allowable strength or maximum reaction force of structure, equation 4.17 is used.

$$S_{a_{cable}} = S_{max} = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (4.17)$$

where,

S_a = allowable strength

S_{max} = maximum breaking strength

F_x, F_y, F_z = Reaction forces in X,Y,Z directions

$$S_{a_{cable}} = S_{max} = \sqrt{(43,15)^2 + (3,54)^2 + (5,6 \times 10^{-3})^2} kN$$

$$S_{a_{cable}} = S_{max} = 43,29 kN$$

If allowable strength value/ maximum reaction force (43,29 kN) is substituted into equation 4.2 given previously, it can be seen that the strength of cable-net structure is adequate.

$$S_{a_{cable}} \leq 59,55 kN \quad (4.2)$$

$$43,29 kN < 59,55 kN \quad \checkmark$$

- **Deflection Limit Check**

After strength limit check, maximum deflection of cable-net structure should be determined. Deflection value depends on strain level of cables. If strain is increased, deflection value decreases. Therefore, strain level is to be optimized in order to gain maximum deflection which is to be less than the limit deflection.

According to the analyses, maximum deflection occurs at LC04¹⁵ defined as (W+)+(T+)+PR+SDL+D. Maximum deflection is observed at Point Object 12 and 16 which are connection point of glass nodes located in the middle of cable-net structure (Figure 4.19).

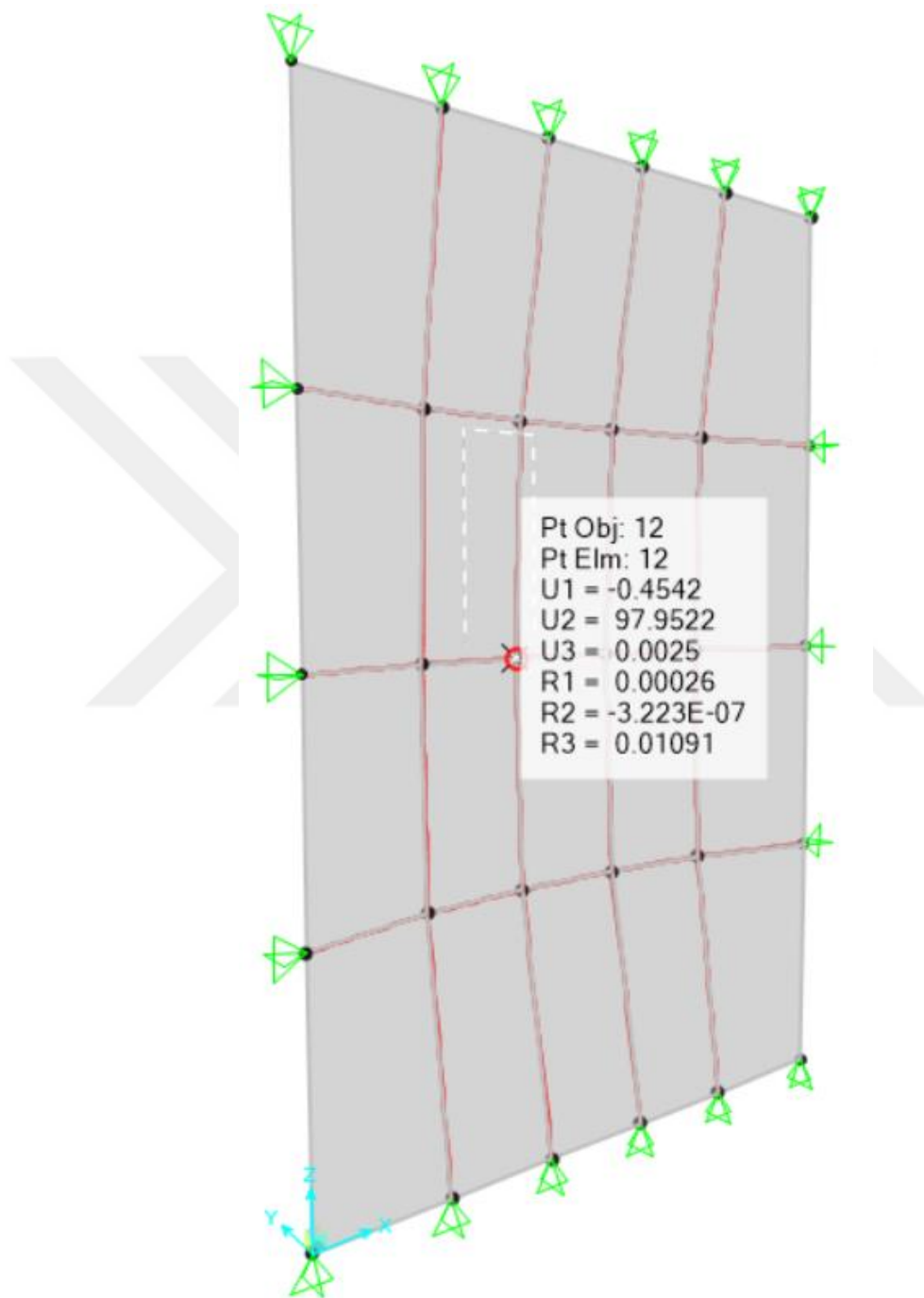


Figure 4.19 : Deflected shape of cable-net structure under combination LC04.

¹⁵ See p.63.

Deflection limit is calculated by considering the short span of the cable structure. Therefore, horizontal span is taken to calculate deflection limit in equation 4.4. S_{max} found to be 97,95 mm according to SAP2000 analysis¹⁶ and S_{limit} is assumed as $L/50$ as given equation 4.3 previously.

$$\delta_{limit} = 5518/50 \text{ mm} \quad (4.3)$$

$$\delta_{limit} = 110,36 \text{ mm}$$

$$\delta_{max} \leq \delta_{limit} \quad (4.4)$$

$$97,95 \text{ mm} < 110,36 \text{ mm} \quad \checkmark$$

As seen in equations 4.3 and 4.4 maximum deflection is less than the limit deflection of structure. Therefore, maximum deflection is adequate.

- **Optimization process**

Optimization process is carried out by changing P_r and strain values and cable (steel wire rope) diameters according to design limits. Firstly, design process is begun with assigning $\Phi 12$ mm steel wire rope to SAP2000 model. But allowable strength of $\Phi 12$ mm steel wire rope was not adequate for P_r value which is necessary for gaining the maximum deflection value less than the limit deflection. Therefore, cable diameter needs to be changed to $\Phi 14$ mm and then P_r value for the new diameter is determined according to allowable strength of cable. Afterwards, maximum reaction forces and maximum deflection are checked according to design limits and design process of cable-net structure is finalized. It can be observed that $\Phi 14$ steel wire rope ensures the design limits determined according to international codes and standards so that the structure analysis of main load bearing steel frame can be carried out by using the reaction forces obtained previously at pin supports.

¹⁶ SAP2000 analysis is given in detail in Appendix B.

4.5.2 Structural design of main load bearing steel frame

Main load bearing steel structure is designed as a steel frame which consists of columns (260x260x12mm), beams (260x260x12mm) and diagonal braces (100x100x10) anchored to existing reinforced concrete (RC) test stand (Figure 4.20).

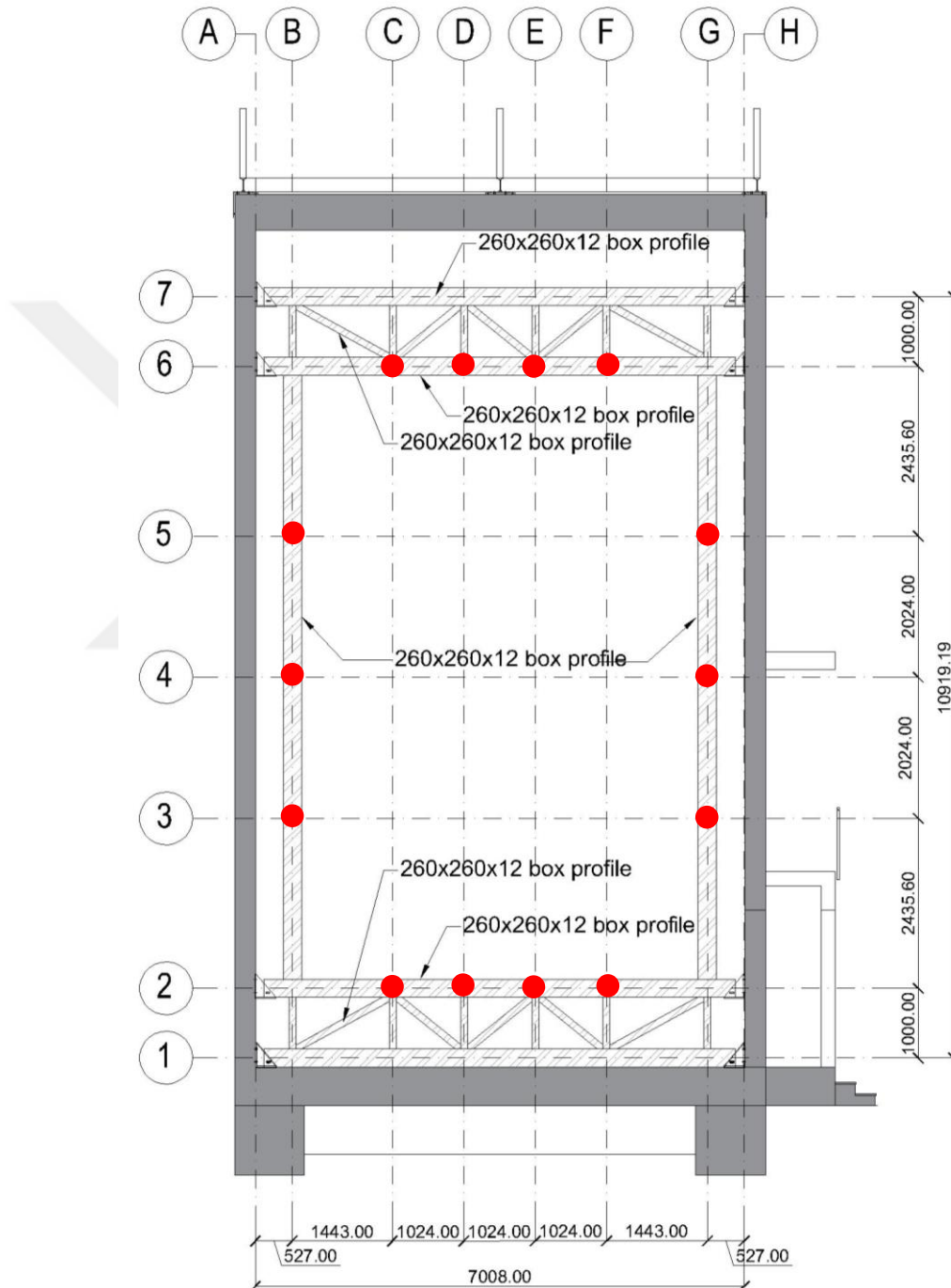


Figure 4.20 : Front view of main load bearing steel frame of cable-net facade.

Figure 4.20 shows the designed according to the axes of cable-net structure. Connection points, which are the support points enabling to transfer reaction forces of cable-net facade, are emphasized with red marks. Reaction forces of the cable-net structure are subjected to steel frame via these connection points. Additionally, other types of loads are also assigned to structure which will be explained in forthcoming chapters. Moreover, diagonal braces are applied in order to decrease bending moment effect and maximum deflection of beam. Finally, it is proved that RC test stand had an adequate strength for transferred loads from the steel frame (Figure 4.20).

Structural design of main load bearing steel frame includes determining design characteristics, structural modeling and analyzing, optimization and final dimensioning. The analysis is done by using SAP 2000 software.

Design characteristics of main load bearing steel structure are design method and design limits, effective loads and combinations. These three characteristics are quite considerable in order to analyze the structure precisely. Therefore, they should be determined according to international codes and standards.

4.5.2.1 Design method and design limits (ANSI/AISC 360-10)

Design process of the main load bearing steel structure is carried out according to Allowable Stress Design Method (ASD). According to ANSI/AISC 360-10, design limits are strength and deflection which should be calculated with equations mentioned below:

- **Strength Limits**

Design shall be performed in accordance with main equation (4.28) of strength limit.

$$R_a \leq R_n/\omega \quad (4.28)$$

in which,

R_a = Required strength using ASD load combinations

R_n = Nominal strength

ω = Safety factor

R_n/ω = Allowable strength.

As seen in equation 4.18, allowable strength is calculated by dividing nominal strength of material by safety factor. Using the equation 4.18 as a base, the strength of tension (beams), compression (columns), flexural (beam and columns), shear (beams, columns) members are to be performed in order to check stability of structure. Allowable tensile strength is calculated in accordance with Equation, 4.19 and 4.20.

$$P_n = F_u \times A_e \quad (4.19)$$

$$P_d \leq P_n / \Omega_t \quad (4.20)$$

where,

$\Omega_t = 2.00$ (ANSI/AISC 360-10)

A_e = Effective net area, (mm²)

F_u = Specified minimum tensile stress, (MPa)

P_n = Tensile rupture in net section, (kN)

P_d = Allowable tensile strength, (kN).

Allowable compression strength is calculated in accordance with equations 4.21 and 4.22:

$$P_n = F_{cr} \times A_g \quad (4.21)$$

$$P_d \leq P_n / \Omega_c \quad (4.22)$$

where,

$\Omega_c = 1.67$ (ANSI/AISC 360-10)

A_g = Effective gross area, (mm²)

F_{cr}^{17} = Limit state of buckling, (MPa)

P_n = Nominal compression strength, (kN)

P_d = Allowable compression strength, (kN).

¹⁷ Calculation of limit state of buckling is explained in detail in ANSI/AISC 360-10.

Allowable flexure strength is calculated in accordance with equation 4.23.

$$M_d \leq M_n/\Omega_b \quad (4.23)$$

where,

$\Omega_b = 1,67$ (ANSI/AISC 360-10).

P_n = Nominal flexural strength, (kN)

M_d^{18} = Allowable flexural strength, (kN).

Allowable shear strength is calculated in accordance with equation 4.24 and 4.25.

$$V_n = 0,6x F_y x A_w x C_v \quad (4.24)$$

$$P_d \leq V_n/\Omega_v \quad (4.25)$$

where,

$\Omega_v = 1,67$ (ANSI/AISC 360-10).

A_w = Effective net area, (mm²)

C_v^{19} = Web shear coefficient, (mm²)

F_y = Limit state of shear yielding, (MPa)

V_n = Nominal shear strength, (kN)

P_d = Allowable shear strength, (kN).

All equations mentioned above should also be integrated into combined load conditions. Therefore, strength limit checks are performed with regard to outputs obtained from SAP2000.

- **Deflection Limits**

Deflection limits vary according to loading types and which component to be subjected to the effective loads. According to ANSI/AISC 360-10, deflection limits are determined by SAP2000 software which can be seen in Table 4.3.

¹⁸ Calculation of nominal flexural strength in different load conditions is explained in detail in ANSI/AISC 360-10.

¹⁹ Calculation of shear coefficient for various conditions is explained in detail in ANSI/AISC 360-10.

Table 4.3 : Deflection limits according to load combination of main load carrying steel structure.

Load combination	Deflection limit
Dead load	L/120
Dead+live loads	L/120
Superimposed live loads	L/360
Total loads	L/240

As seen in Table 4.3, deflection limits vary according to load combinations.

4.5.2.2 Design of steel frame in SAP2000

Design process of main load bearing steel frame is performed according to ANSI/AISC 360-10. Design loads are defined in SAP2000 as dead load of structure (D), live load (L), wind loads (W+) and (W-), earthquake loads (EQX+), (EQX-), (EQY+), (EQY-), and temperature loads (T+), (T-). Live loads are the reaction forces at pin supports of cable-net structure. After determining design loads, design load combinations are calculated according to ASCE 7-10. Design of the frame is performed in SAP2000 as an elastic design just to protect the steel frame from inelastic deformations during testing. Structural steel analyses show that, dimensions are applicable for strength and deflection limits. As seen in Figure 4.21, main columns and beams are 260x260x12 mm box profiles, while diagonal braces are 100x100x10 mm box profiles. Additionally, steel design results (i.e. member capacity ratios) are found to be sufficient and also shown bottom of Figure 4.21.

Design process of steel frame is shortly explained in this chapter. Nevertheless, analyses and design reports of the main load bearing steel structure are explained in detail in Appendix C.

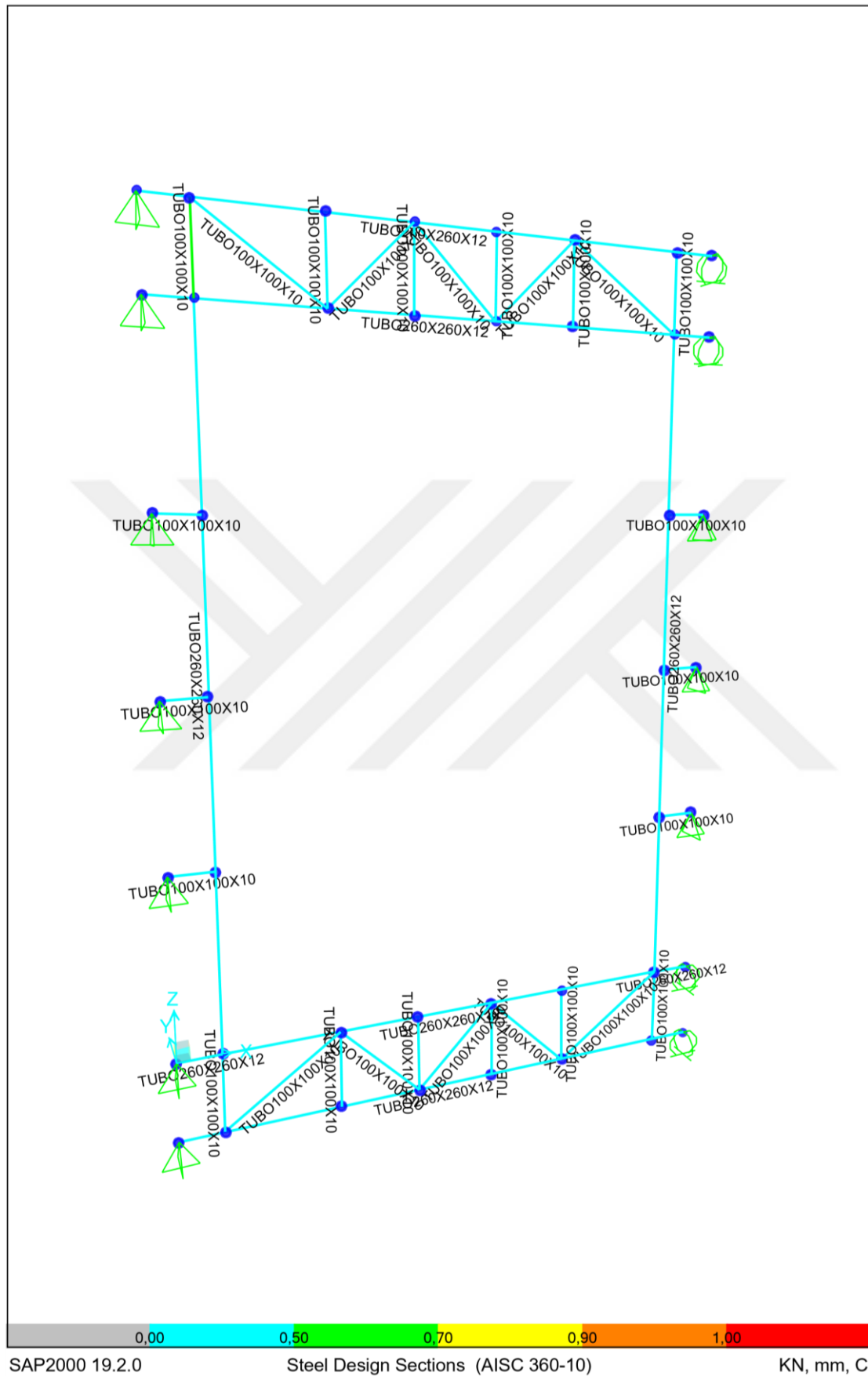


Figure 4.21 : Final design of main load bearing steel frame

4.5.3 Structural design of insulated glass units

Insulated glass units are combined as 8 mm two layered and semi tempered laminated glass, 16 mm air gap and 8 mm tempered glass. While tempered part of IGU is located inside the cable-net glass facade, two layered laminated part of insulated glass units is located at outside of cable-net glass facades in order to prevent small fragmented glass breakage.

Strength and deflection limits are determined according to DIN 18008 which are shown in equations 4.26 and 4.27 respectively.

$$\sigma_{lim} = 80 \text{ MPa} \quad (4.26)$$

$$\delta_{lim} = \frac{L}{100} = \frac{1000}{100} = 10 \text{ mm} \quad (4.27)$$

Allowable stress of IGU is determined as 80 MPa at SJ Mepla with regard to DIN18008. After determining design limits, structural analysis is performed in SJ Mepla and results of applicable for cable-net glass facade shown in Figure 4.22

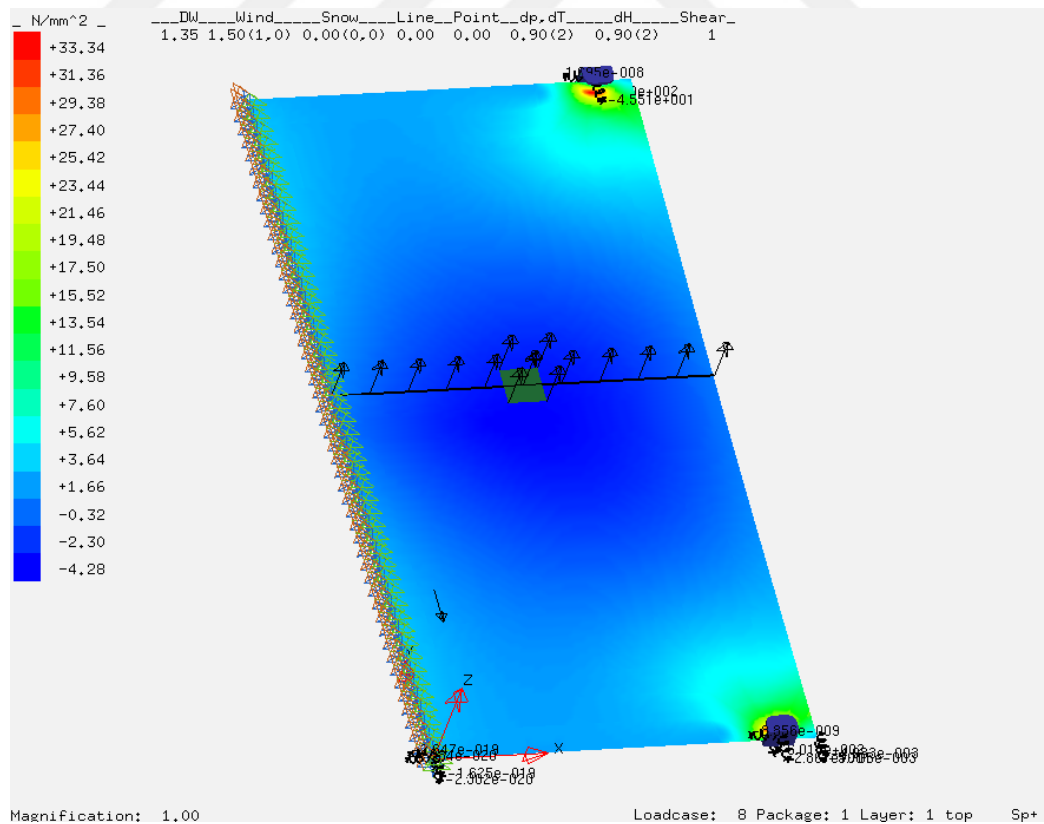


Figure 4.22 : Structural analysis of IGU in SJ Mepla.

As seen in Figure 4.22, IGU is modeled as linearly fixed at its left edge and point fixed at its right edge in order to investigate critical stresses. According to SJ Mepla results, maximum stress is obtained to be 33,34 MPa which is significantly lower than the allowable stress of IGU. All details are explained in detail in Appendix D.

4.5.4 Structural design of connections

Structural design of connections includes connection plate design which is used as a pin support that provide to assemble stainless steel wire rope to main load bearing steel frame.

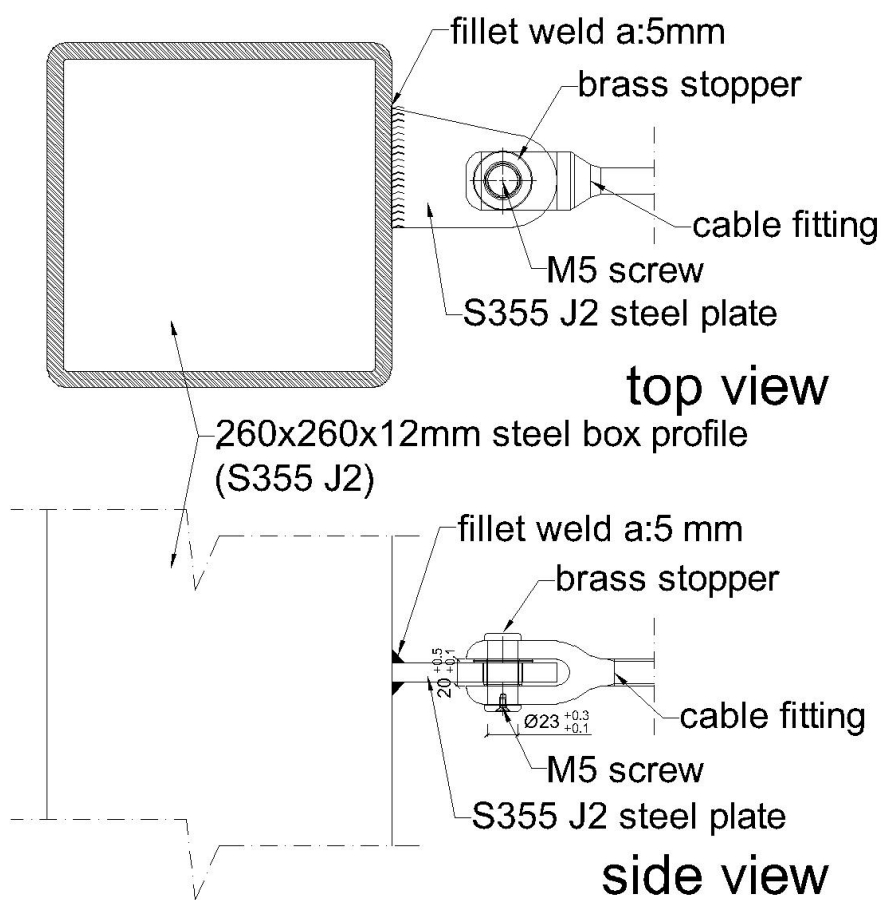


Figure 4.23 : Connection detail of pin support of cable-net glass facade.

Cable fittings are connected to main load bearing steel structure via angled 20 mm thick steel plate Figure 4.23. Steel plate class is S355-J2 according to the ASTM standards. While design of steel plate is performed according to Eurocode 3, welding check were carried out per TS 648. All calculation details are explained in Appendix E.

5. NOVEL GLASS NODE: DEVELOPMENT, DESIGN, AND TESTING

Day by day, technological developments are integrated into the structural glass facade systems in order to develop innovative designs. Cable-net glass facades are one of the most innovative structural glass facade systems which continue to be developed by researchers. With that aspect, point fixings which are one of the most key components of cable-net glass facades have non-negligible potential for research and development. Point fixings are usually manufactured as stainless steel components which enable to construct point supported cable-net glass facades. In this chapter, innovative design potentials of point fixing components are investigated and a different type of “Glass Node” is designed by re-configuration of stainless steel point fixings.

The idea of “Glass Node” is created with the concept of reaching the maximum transparency in cable-net glass facades. When structural components are overviewed, cables and fittings are recognized to be stainless steel in order to satisfy design limits of cable-net glass facades. Additionally, however stainless steel fittings negatively affect the transparency of the whole cable-net facades, “Glass Node” increases the transparency ratio up to %17 percent for the designed cable-net facade. Therefore, point fixing by glass material is a quite innovative movement in terms of enhancing transparency.

This study includes architectural and structural design, prototyping and testing process of an alternative node element. Literature research has been mainly carried out for manufacturing and testing processes. Architectural and structural designs are carried out according to designed cable-net glass facade which was explained in detail in Chapter 4. Prototyping process comprises 3D printing and manufacturing of “Glass Node” with real materials. Testing process is carried out following international test protocol DIN18008-3.

5.1.1 Architectural Design of “Glass Node”

Architectural design of “Glass Node” is designed in accordance with cable-net glass facade explained in detail in Chapter 4. The concept arises with enhancing the point fixing component as transparent as possible. Therefore, core of point fixing is configured as stainless steel and other parts of point fixing are designed with using glass material. The initial design idea is illustrated in Figure 5.1.

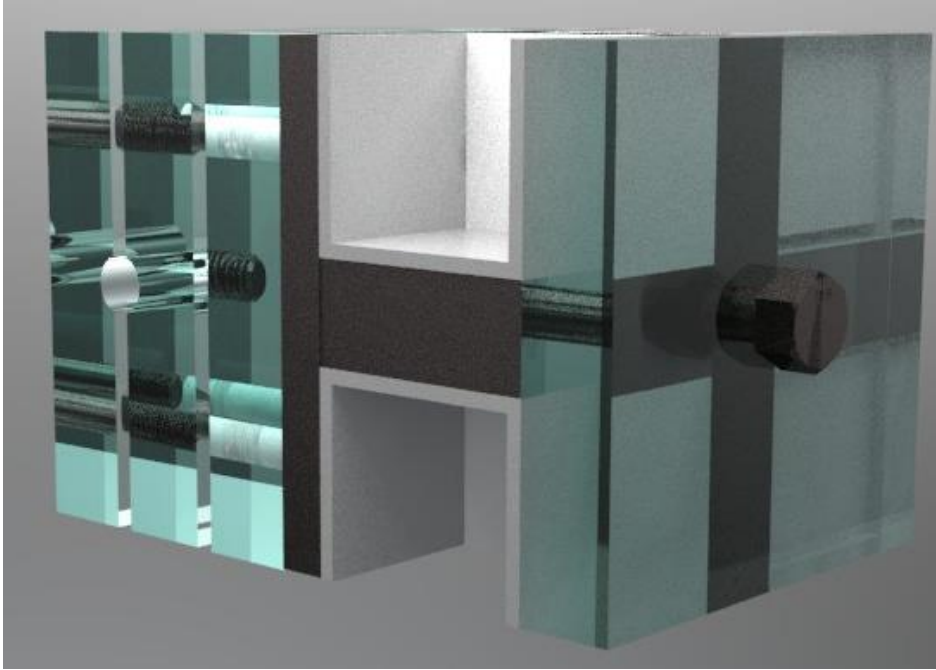


Figure 5.1 : Perspective render of initial design of Glass Node.

As seen in Figure 5.1, Figure 5.2 node consists of mainly tempered glass elements and stainless-steel core. The design consists of 4 pieces of single layer tempered glass, stainless steel core and POM sheets. The connection is provided by using metal screws. POM sheets are used in order to protect insulated glass panels. When initial design is evaluated in terms of applicability to cable-net glass facade, some handicaps are detected. First of all, creating channels at tempered glass for mounting the cables to node would not be possible because of inadequate facilities of manufacturers in Turkey. Secondly, cables and screws should not interact with glass surfaces directly due to breakage risks. Finally, multi-layer tempered glass usage is more effective than single-layer tempered glass in order to ensure design limits of “Glass Node”. As seen in Figure 5.2, the initial design of “Glass Node” is also shown in exploded perspective.

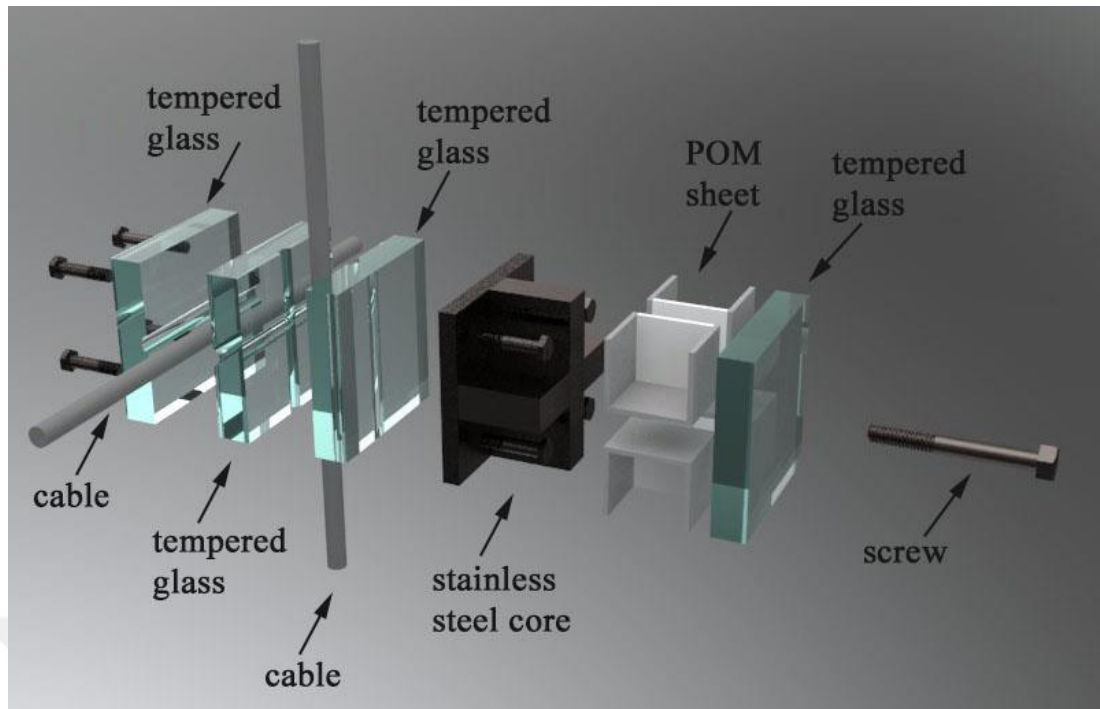


Figure 5.2 : Initial design of “Glass Node” as exploded perspective.

Due to the reasons mentioned below, architectural design is revised based on cable-net glass facade. All drawings are executed as CAD drawings and 3D modeling process is performed once again (Figure 5.2 and Figure 5.3).

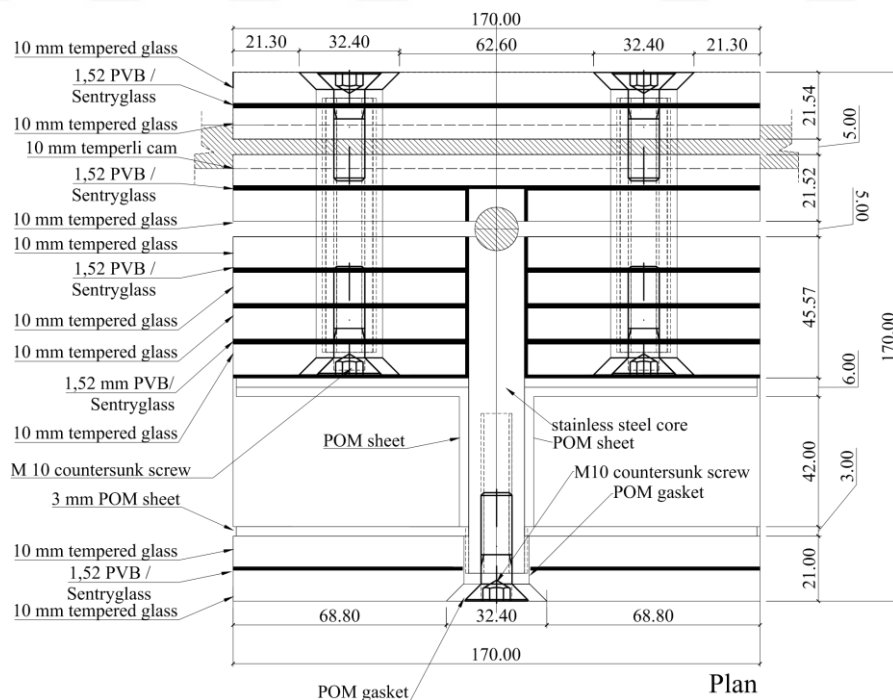


Figure 5.3 : Plan view of final design of Glass Node.

Glass Node consists of 10 mm-thick tempered glasses, T shaped stainless-steel core, stainless steel beddings for mounting cables, roll pins, M10 countersunk screws, POM sheets and gaskets. Moreover, render of final design of Glass Node is shown in Figure 5.3.

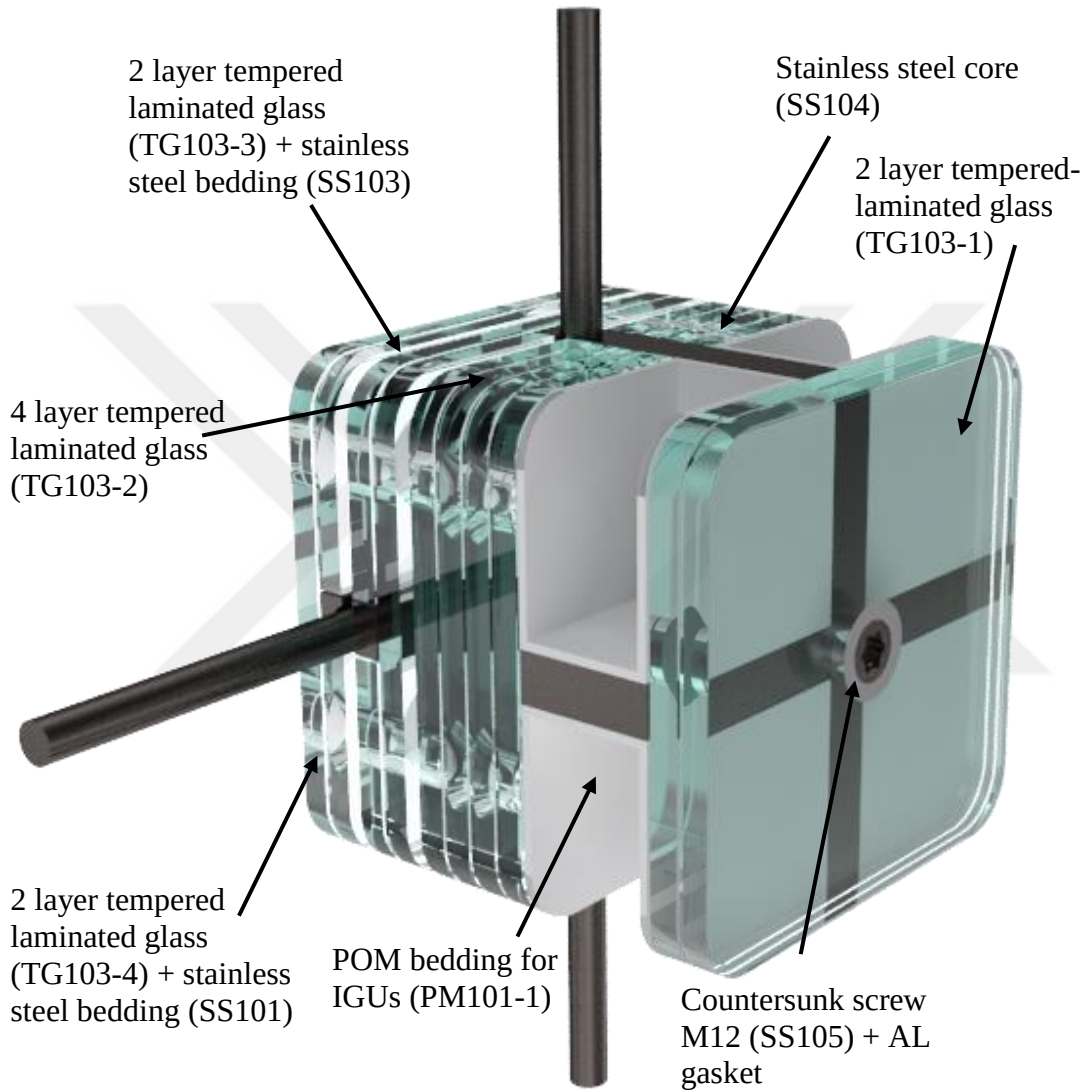


Figure 5.4 : Render of final design of Glass Node.

As illustrated in Figure 5.4, each component of Glass Node is coded by using pose numbers which are substantial for prototyping and manufacturing processes. Moreover, all application drawings are added to study as Appendix F.

Design process of Glass Node can be explained briefly as follows; tempered glasses are laminated according to cable-net glass facade design which is explained in Chapter 4. Afterwards, stainless steel elements are planned to be integrated into laminated

tempered glass elements by structural bonding. Determining the bonding materials is executed by selecting three different adhesives: Sikasil SG-500 structural silicone, Sentryglass (ionomer based lamination material) and SikaFast-3131 (methacrylate based adhesive). Preliminary experiments carried out as explained in forthcoming chapters in detail. Mechanical connection between laminated tempered glass elements is provided by stainless steel roll pins and countersunk screws. Moreover, stainless steel pins also enable to stabilize the horizontal and vertical cable elements. During the mechanical connection of laminated tempered glasses, POM sheets and gaskets are used in order to prevent the interaction between glass and stainless steel materials. All components of “Glass Node” are shown in Figure 5.5 in an exploded perspective and classified according to their materials in forthcoming sub-chapters.

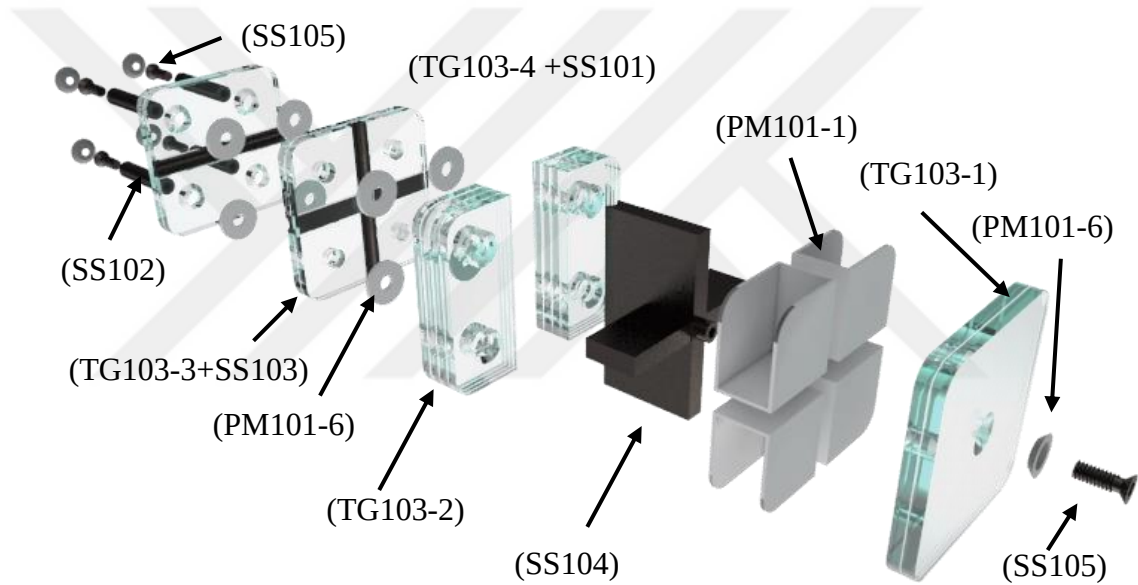


Figure 5.5 : Exploded perspective of final design of Glass Node.

Final design of Glass node is improved according to durability and applicability parameters which enable to be used as a facade component. Moreover, the revisions also enable Glass Node to gain adequate strength and with that node can be used as load bearing facade component.

5.1.2 Laminated and tempered glass elements

Glass elements of “Glass Node” are the key materials for this proposed novel design. All glasses are fully tempered²⁰. Furthermore, dimensions and positions of holes are

²⁰ See Chapter 3.2.1 for mechanical properties of tempered glass components.

determined according to BS-EN 12150-1 which is shown in Figure 5.6. In Figure 5.4, d is the dimension of hole and a and b are to be greater than $2d$ while c is greater than $6d$.

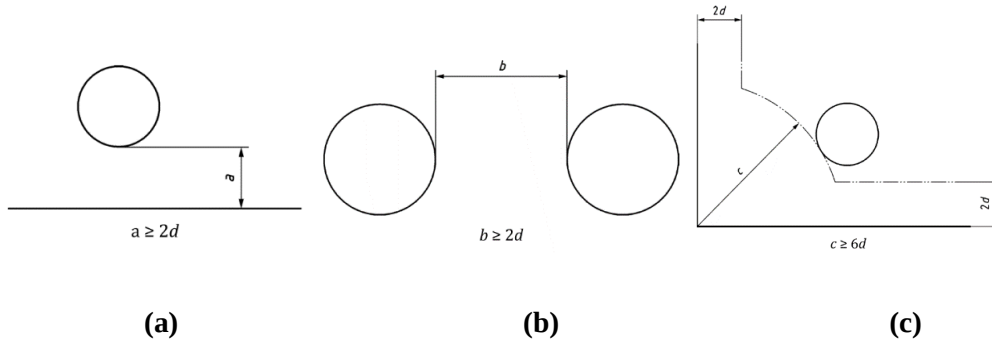


Figure 5.6 : Hole positions according to hole diameter (BS EN 12150-1, 2011). (a) Minimum distance to edge of glass plane. (b) Minimum distance between two holes. (c) Minimum distance of hole edge from corner of glass.

Five types of tempered glass are used at “Glass Node” which are 170x170x10 mm (TG102-1) with one countersunk hole, 170x170x10 mm (TG102-2) with one regular hole, 170x170x10 mm (TG102-5) with four countersunk hole, 170x75x10 mm (TG102-3) with two countersunk holes, and 170x75x10 mm (TG102-4) with two regular holes as seen in Figure 5.7.

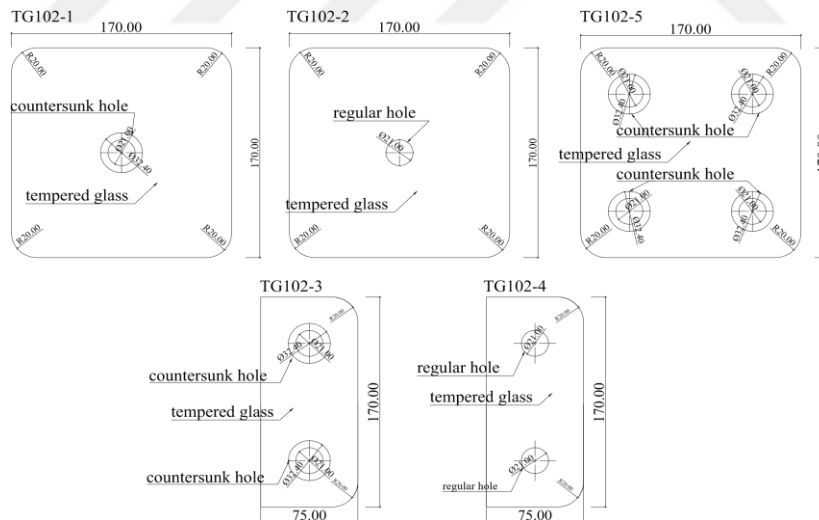


Figure 5.7 : Tempered glass types of “Glass Node”

Tempered glasses are planned to be laminated by using Sentryglass lamination material. There are mainly four types of tempered and laminated glass combination emerges according to “Glass Node” application drawings (Figure 5.8).

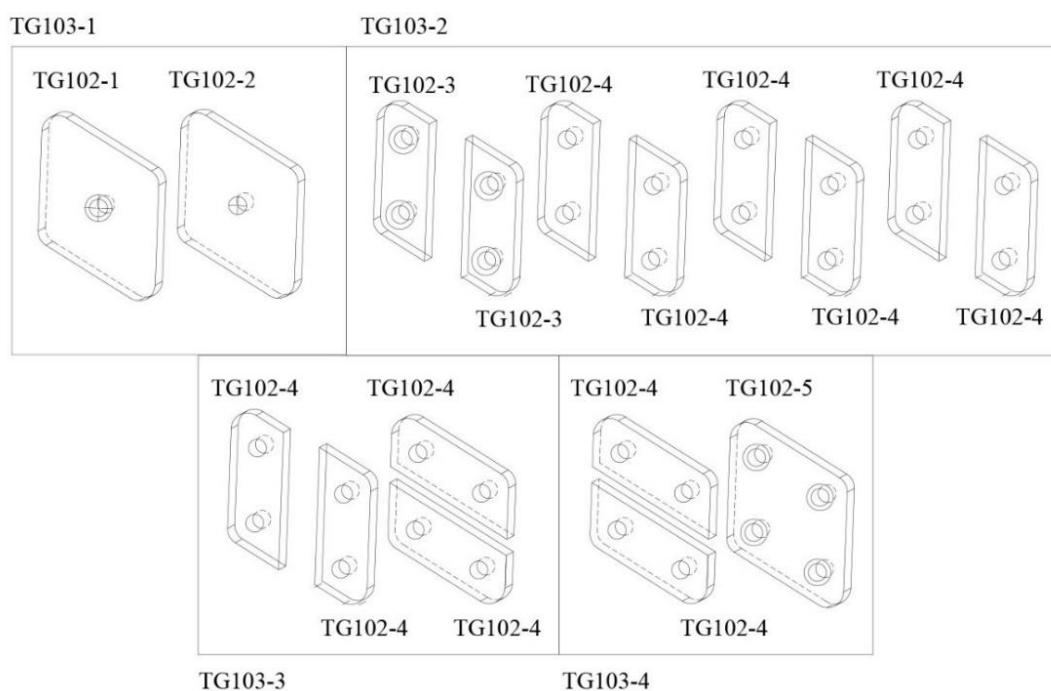


Figure 5.8 : Lamination combinations of tempered glasses.

As illustrated Figure 5.8, there are four types of laminated tempered glass combinations. TG103-1 consists of TG102-1 and TG102-2, TG103-2 consists of two units TG102-3 and six units TG102-4, TG103-3 consists of four units 102-4, TG102-4 consists of two units TG 102-4 and one unit 102-5. These lamination processes are performed with Sentryglass ionomer based lamination material. During the lamination process, Sentryglass datasheet and application manual were used in order to have an impeccable application. According to the application manual, all glass elements are cleaned with de-ionized water. Afterwards, a solution is prepared including adhesion enhanced silane which is applied to glass surfaces. Sentryglass materials are cut in accordance with dimensions of glass elements. Furthermore, in order to prevent air bubbles between two layers of glass element, all glasses are vacuumed via vacuum bag. Finally, vacuumed glass components are put in autoclave furnace and heated to 130 °C. Cooling process is also executed according to application manual of Sentryglass.

5.1.3 Stainless steel elements

Stainless steel elements are used for three main functions which are; bedding for cable mounting, load bearing and load transferring. The grade of all stainless steel elements

is determined as AISI304 (A2) according to AISI standards. Mechanical properties of AISI304 are shown in Table 5.1.

Table 5.1 : Mechanical properties of stainless steel components, (ASTM Handbook).

Characteristic	Symbol	Value and unit
Material type	AISI 304	-
Modulus of elasticity	E	193-200 GPa
Shear Modulus	G	
Tensile stress, ultimate	F _u	505 MPa
Tensile stress, yield	F _y	215 MPa
Poisson ratio	ν	0,29

There are five several types of stainless steel elements made by AISI 304 grade of stainless steel which are shown in Figure 5.9.

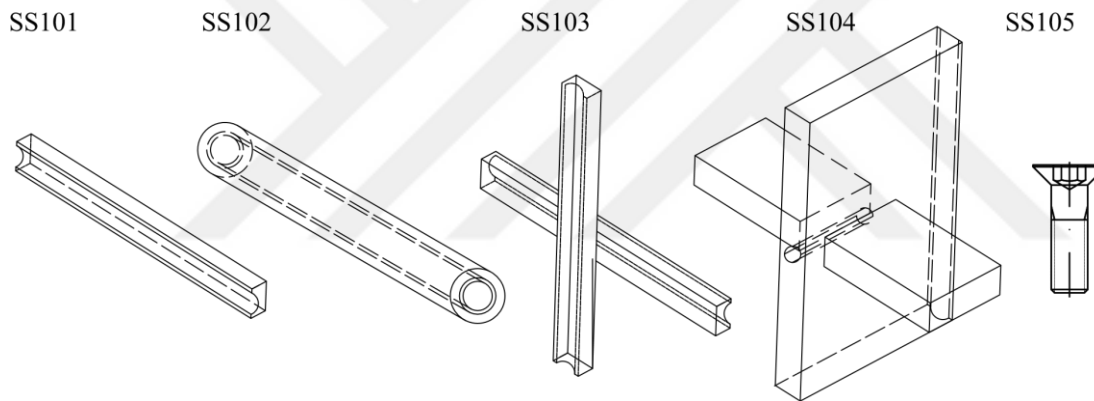


Figure 5.9 : Stainless steel elements of Glass Node.

SS101 and SS103 are designed as bedding elements for steel wire ropes. SS102 (pins) enable mechanical connection between laminated glass elements. SS104 is designed in order to transfer dead load of glass panels (1m x 2m) and effective wind load to steel wire ropes. SS105 are the M10, A2-70 APL countersunk bolts which are used for mechanical connections. However, M10 countersunk bolts are revised after primarily testing process as M12 in order to enhance structural performance of Glass Node.

5.1.4 Glass-stainless steel composites

Glass and stainless steel elements are planned to be combined by structural bonding and lamination processes in order to obtain composite components. There are three independent composite components which are designed in accordance with final CAD

drawings of Glass Node. As already mentioned previously, there are three types of bonding material planned to be used which are Sikasil SG-500 structural silicone, Sentryglass (ionomer based lamination material) and SikaFast-3131 (methacrylate based adhesive). As seen in Figure 5.10, glass-stainless steel composites are shown.

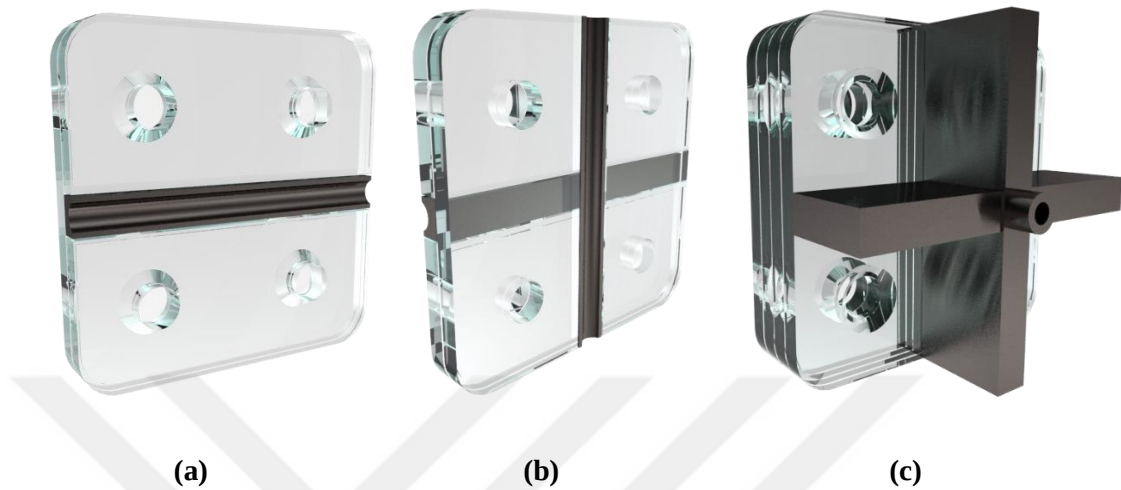


Figure 5.10 : Glass-metal composites; (a) TG103-4+SS101, (b) TG103-3+SS103, (c) 2x(TG103-2)+SS104.

TG103-4+SS101 and TG103-3+SS103 are bonded with Sentryglass lamination, Glass and stainless steel elements are autoclaved together. However, 2x(TG103-2)+SS104 has 4-layer-glass and a solid core and behavior of the elements are not predictable during the autoclave process. Therefore, bonding procedure is planned to be carried out by using three different bonding materials (Sentryglass, Sikasil SG-500, SikaFast-3131) in order to determine the true adhesive for 2x(TG103-2)+SS104. In order to understand the performance of the bonding materials, mechanical properties are crucial. Therefore, mechanical properties of Sentryglass, Sika SG-500 and SikaFast-3131 are compared in Table 5.2.

Table 5.2 : Mechanical properties of adhesives (DuPont, 2013), (Sika, 2012).

Material name	Material base	Modulus of elasticity (E)	Tensile stress (F_y)	Melting point
Sentryglass	ionomer	300 MPa	34,5 MPa	94 °C
Sikasil SG-500	silicone	-	2,2 MPa	200 °C
SikaFast-3131	methacrylate	-	7 MPa	-

As seen in Table 5.2, while Sentryglass has the highest tensile stress value, tensile stress of Sikasil SG-500 is the lowest value as 2,2 MPa. Moreover, the strength of SikaFast-3131 is 7 MPa which possesses an intermediate level of strength.

5.1.5 Buffer and bedding elements

POM (polyoxymethylene) elements are mainly used as buffer and bedding elements in order to prevent instantaneous breakages because of the interaction between glass and metal components of Glass Node. As seen in Figure 5.11, there are six distinct types of POM elements which were used in glass Node design. PM101-1 is used as 1m x 2m double glazing bedding, PM101-2 enables to protect TG103 glass series, which have countersunk holes, from pins (SS102).

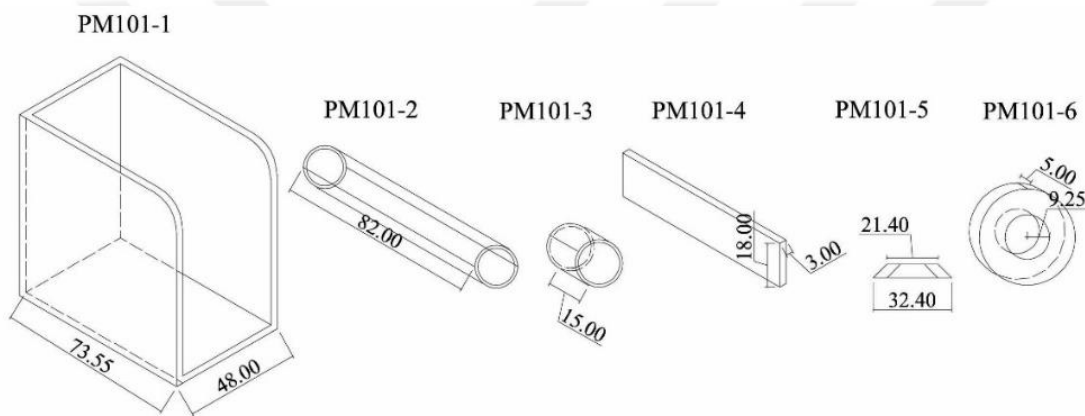


Figure 5.11 : POM elements of Glass Node.

Moreover, PM101-3 and PM101-4 are used to prevent the interaction between SS104 and TG103-1. PM101-5 is designed as a gasket for countersunk holes. Mechanical properties of POM are shown in Table 5.3.

Table 5.3 : Mechanical properties of POM at 23 °C (Url-26).

Characteristic	Symbol	Value and unit
Material type	POM	-
Modulus of elasticity	E	3,1 GPa
Tensile stress, yield	F _y	72 MPa
Tensile strain, yield	ε	%25
Melting temperature	°C	178

Besides using POM material for buffering and bedding functions, after the primary experiments, some of the gaskets are reproduced as aluminum material in order to

improve the structural performance of Glass Node. Aluminum grade is determined as tempered (H12) Aluminum EN AW-1050A (Al 99,5) according to BS-EN 485-2. Mechanical properties of aluminum gaskets are shown in Table 5.3. As seen in Table 5.2 and 5.3, load bearing capacity of aluminum is greater than POM's. Therefore, improvements are executed by using aluminum gaskets.

Table 5.4 : Material properties of aluminum en AW-1050A (Al 99,5), (BS-EN485-2).

Characteristic	Symbol	Value and unit
Material type	EN AW-1050A (Al 99,5)	-
Temper grade	H19	-
Tensile stress, yield	F _y	130 MPa
Tensile stress, ultimate	F _u	150 MPa
Hardness	-	45

In addition to gaskets, PM101-6 is made with POM and it is implemented among tempered and laminated glass units (TG103-2, TG103-3 and TG103-4) as a buffer element.

5.2 Structural Design of Glass Node

Structural design of Glass Node is carried out according to Eurocode 1993-1-1. The design of Glass Node includes determining design loads, creating 3D structural digital modeling by using Solidworks Software and performing strength check of structure (Appendix G).

5.2.1 Determining effective design loads

First step of structural analysis is to determine total effective loads of Glass Node in order to execute strength limit check. Positive wind load (+W; $+8 \times 10^{-7}$ kN/mm²) and dead load of 1 unit IGU are taken into consideration because these effective load values generate the most critical load combination of structural design of cable-net facade which is explained in Chapter 4. In order to calculate total loads affecting Glass Node, widely used load distribution method (i.e. tributary area) is applied and illustrated in Figure 5.12.

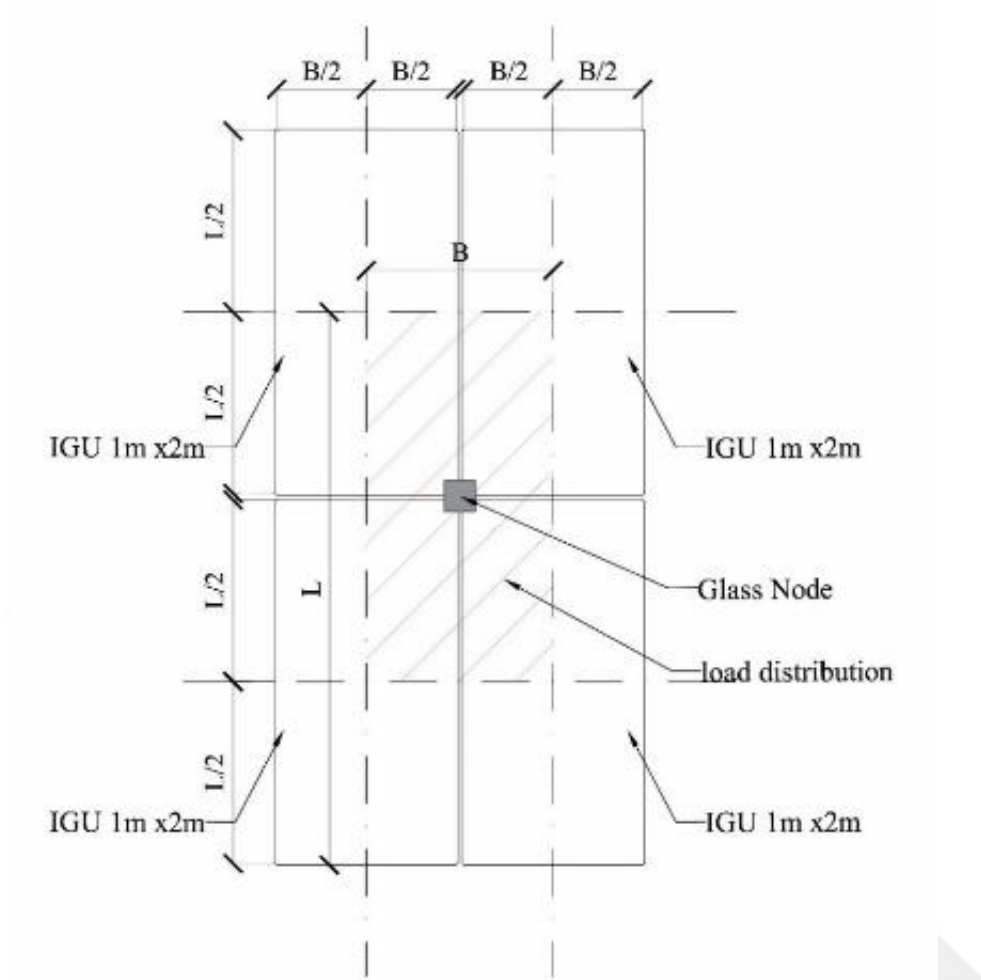


Figure 5.12 : Effective distributed load of Glass Node

As seen in Figure 5.12, 1 unit of Glass Node bears dead load and wind load of 1 unit IGU. Therefore, effective total wind load is calculated in accordance with equation 5.1 and effective total dead load is calculated in accordance with equation 5.2.

$$P_{wd} = W \times B \times L \times \Omega \quad (5.1)$$

where,

P_{wd} = Design load for wind effect, (kN/mm²).

B = Short edge of IGU

L = Long edge of IGU

W = Effective wind load per unit (kN/mm²)

Ω = Safety Factor

$$P_{wd} = 8 \times 10^{-7} \times 1 \times 10^3 \times 2 \times 10^3 \times 1,5 \text{ kN/mm}^2$$

$$P_{wd} = 2,40 \text{ kN} \cong 240 \text{ kg}$$

As seen in equation 5.1, design load for wind effect of Glass Node is 2,40 kN. Therefore, structural strength of Glass Node is to be greater than P_{wd} values.

Furthermore, dead load of Glass Node is shown in Equation (5.2).

$$P_{sdl} = SDL \times B \times L \times \Omega \quad (5.2)$$

where,

P_{sdl} = Design load for dead load effect, (kN/mm²).

B = Short edge of IGU

L = Long edge of IGU

SDL = Effective dead load per area (kN/mm³)

Ω = Safety Factor

$$P_{sdl} = 6 \times 10^{-7} \times 1 \times 10^3 \times 2 \times 10^3 \times 1,35 \text{ kN}$$

$$P_{sdl} = 1,65 \text{ kN} \cong 165 \text{ kg}$$

As seen in Equation (5.2), SDL value is dead load of an IGU (1m x2m) per mm². In order to determine total dead load affecting the Glass Node, equation (5.2) is used. Thus, total effective dead load is determined as 1,65 kN.

5.2.2 3D modeling and strength checks

3D modeling of the node is created by using Solidworks Software in order to execute structural analysis of glass and steel components. Structural performance of bonding materials is experimentally analyzed, which will be explained in coming chapters in detail.

Modeling and analyses include strength checks of TG103-1, SS104 and TG103-2, TG103-3 and TG103-4. While TG103-1 and SS104 are mainly affected by wind load

(P_w), TG103-2, TG103-3 and TG103-4 are affected by dead load of IGU (P_{sdl}) and positive wind load (P_w) simultaneously.

Firstly, strength checks of TG103-1 under positive wind load effect are illustrated with resulting Von Mises Stress Contours and deformed shape in Figure 5.13. The analysis is carried out by modeling one layer of tempered glass because limit tensile stress of two layer laminated and tempered glass is accepted the same as one layer tempered glass unit which is (σ_{lim}) 80 MPa (Code for Practise, 2018).

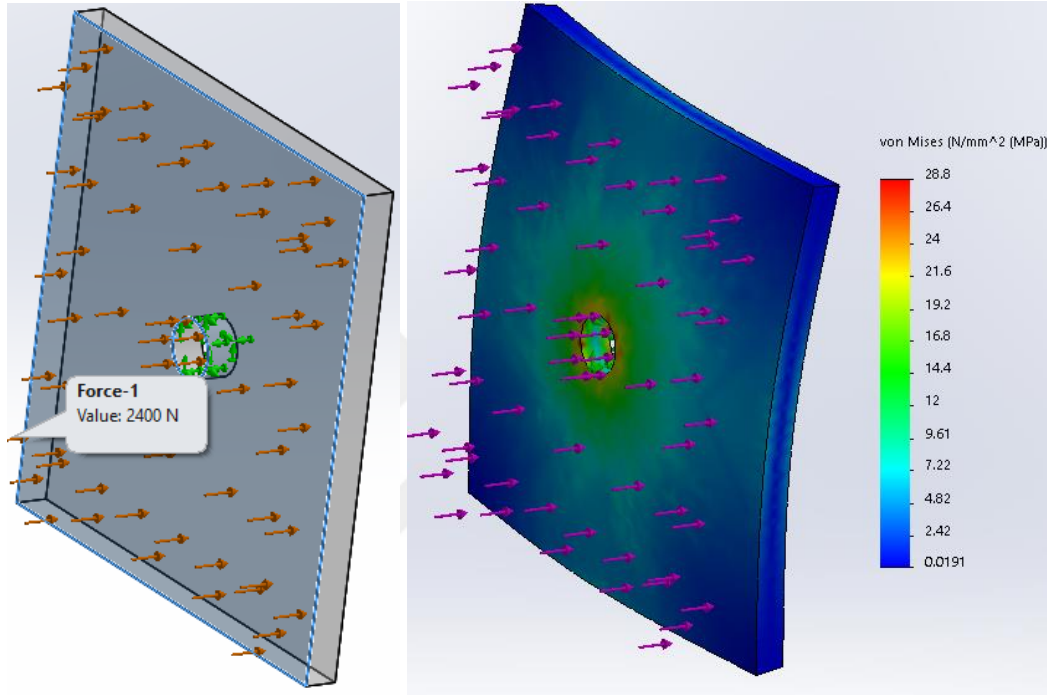


Figure 5.13 : Structural analysis of TG103-1 (exterior cap).

According to the analysis illustrated in Figure 5.13, maximum stress (σ_{max}) under effective wind load is 29 MPa which mainly emerges around the countersunk hole of the component. According to Eurocode 1993-1-1, Equation (5.3) is verified. As seen that maximum stress is approximately 0,30 of the limit stress value.

$$\sigma_{max} \leq \sigma_{lim} \quad (5.3)$$

$$29 \text{ MPa} < 80 \text{ MPa} \quad \checkmark$$

Secondly, strength check of stainless steel core component (SS104) under positive wind load effects are illustrated in Figure 5.14.

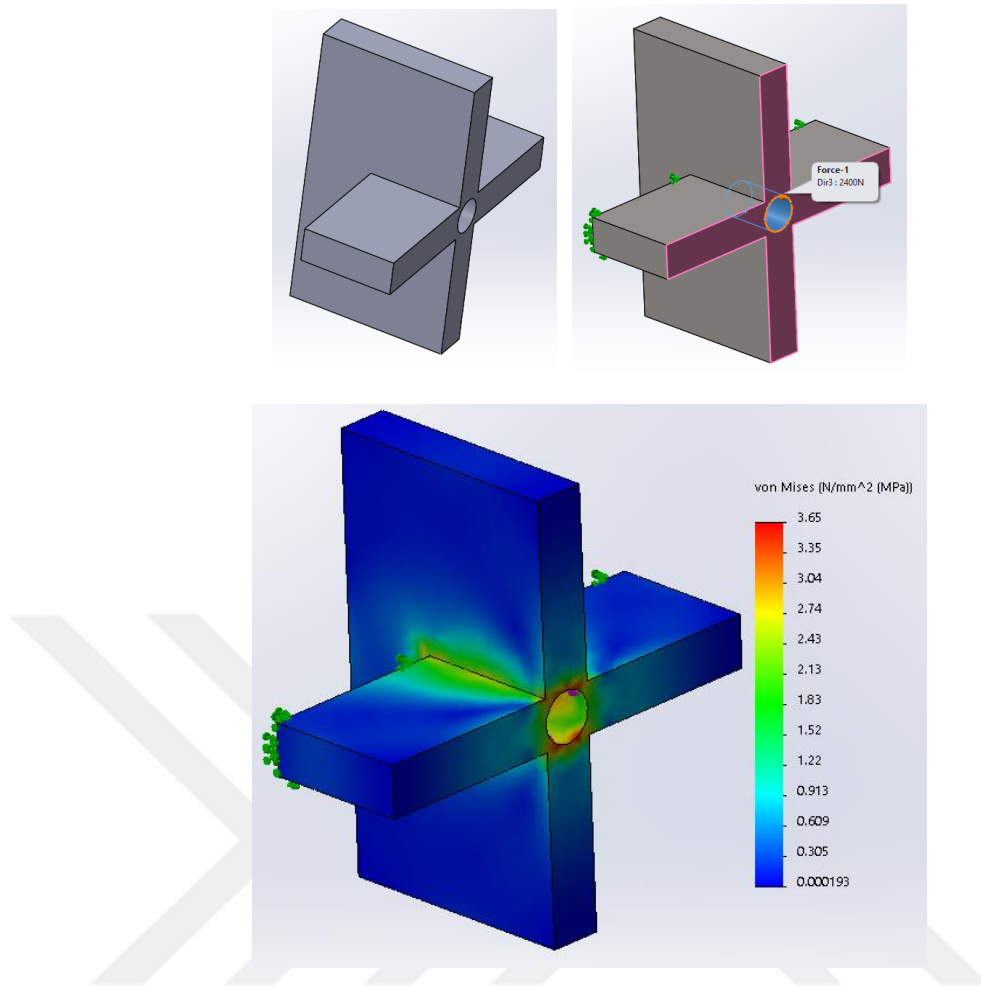


Figure 5.14 : Structural analyze of SS104 (stainless steel core).

As seen in Figure 5.14, SS104 is modeled and P_{wd} is applied as total design wind load. Again, maximum stress is determined by using Solidworks Software. According to analysis results, maximum stress (σ_{max}) is obtained to be 4 MPa which is observed near the connection zone similar to TG103-1. The limit stress of SS104 is determined according to Table 5.1 which is 210 MPa. Strength checks are carried out in accordance with equations 5.4 and 5.5. According to Eurocode 1993-1-1, a safety factor of 1,1 is applied.

$$\sigma_{lim} = f_u / \Omega \quad (5.4)$$

in which;

σ_{lim} = Limit tensile stress

f_u = Yield tensile stress

Ω = Safety factor

When actual values are substituted into equation, following is obtained:

$$\sigma_{lim} = 215 \text{ MPa}/1,1 \quad (5.4)$$

$$\sigma_{lim} = 195,45 \text{ MPa}$$

$$\sigma_{max} \leq \sigma_{lim} \quad (5.5)$$

where;

σ_{max} = Maximum tensile stress

σ_{lim} = Limit tensile stress

$$4 \text{ MPa} < 195,45 \text{ MPa} \quad \checkmark$$

As seen in Equation (5.4) and Equation (5.5), maximum tensile stress is considerably lower than the limit tensile stress.

Thirdly, the combination of TG103-2, TG103-3 and TG103-4 is modeled and analyzed in Solidworks Software. Total dead load (P_{sdl}) and total positive wind load (P_w) are applied to the model and maximum shear stress is calculated.

TG103-2, TG103-3, and TG103-4 glass components are illustrated in Figure 5.15. Laminated and tempered glass units are modeled as a one-layer glass in Solidworks.

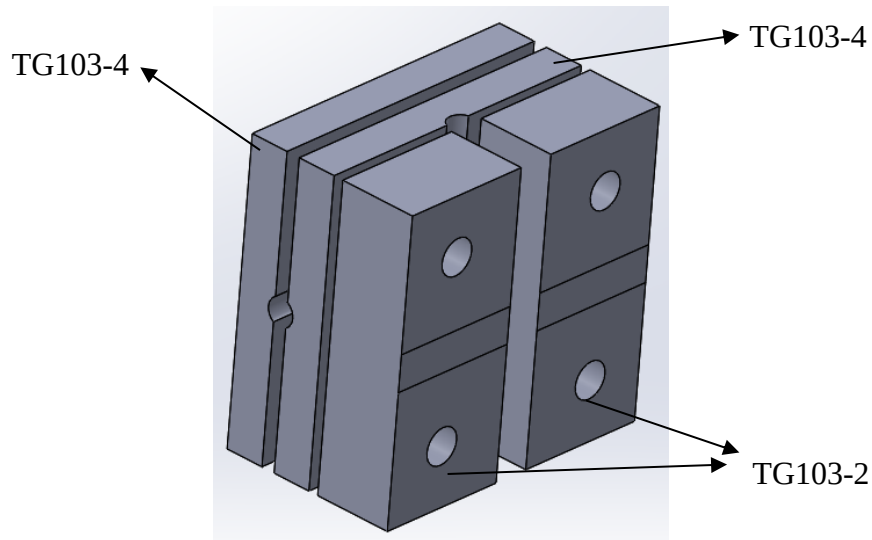


Figure 5.15 : TG103-2, TG103-3 and TG103-4 glass components of Glass Node.

After solid modeling, total dead load (P_{sdl}) and total positive wind load (P_w) are applied, which is also shown in Figure 5.16.

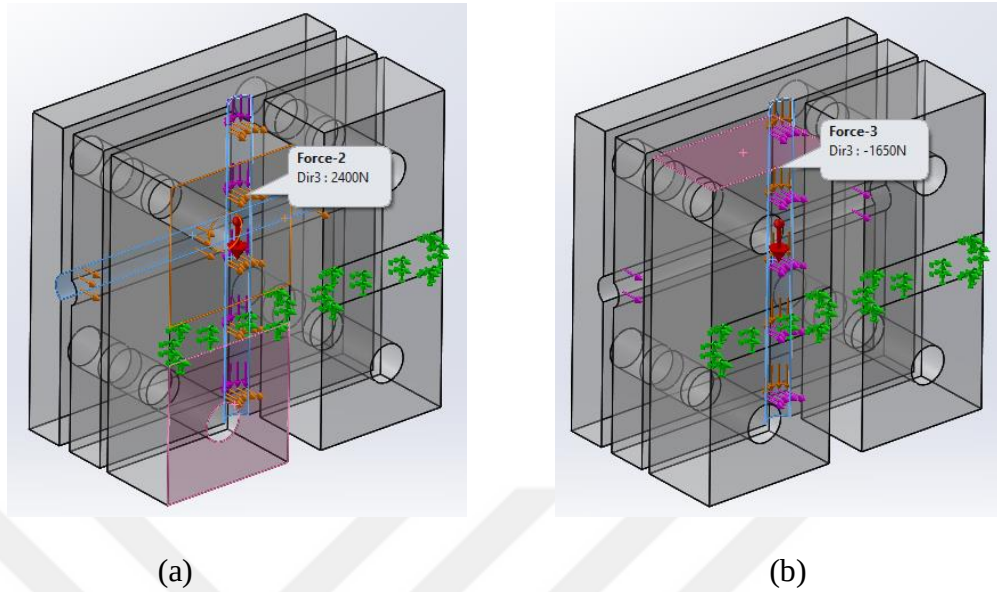


Figure 5.16 : Illustration of applied effective forces, (a) P_w , and (b) P_{sdl} .

While total wind load is applied to glass components as a loading perpendicular to the surface, total dead load is applied as shear force within the plane. After applying the effective loads, 3D structural analysis is carried out and analysis results are shown in Figure 5.17.

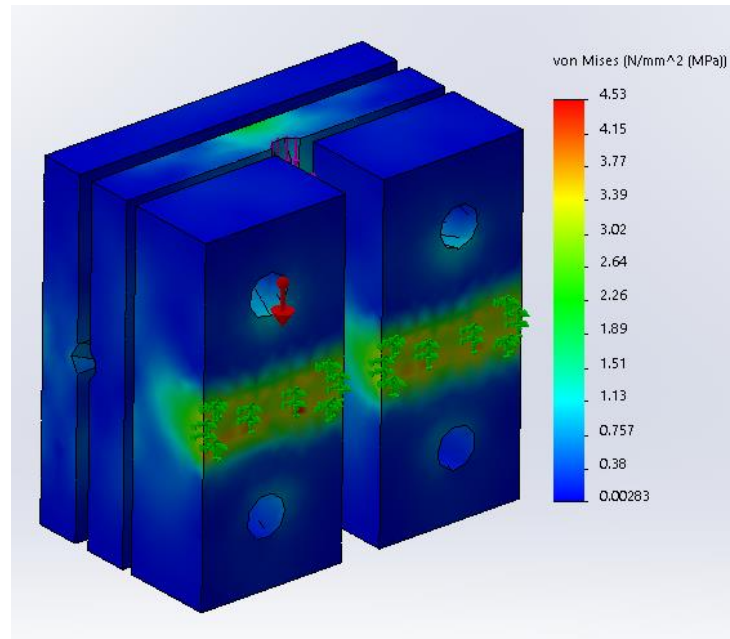


Figure 5.17 : Von Mises strength distribution in TG103-2, TG103-3 and TG103-4.

Maximum tensile stress is obtained to be 5 MPa in the vicinity of the middle zone of TG103-2 due to total wind load (P_w). Dead load as a shear force does not reach critical values. Thus, strength check is carried out regarding maximum tensile stress value due to the wind load effect (P_w). When strength check is executed by using equation 5.3, limit stress of tempered glass value is taken (80 MPa) which is 16 times greater than maximum tensile stress value. Therefore, it is seen that the computing stress far below the maximum allowable stress limit.

$$5 \text{ MPa} < 80 \text{ MPa} \quad \checkmark \quad (5.3)$$

5.3 Prototyping and Manufacturing Process of Glass Node

Prototyping and manufacturing processes are the most important parts of the study which enable to gain enhanced experience about the realization of conceptual designs. There are several prototyping approaches in literature such as traditional and rapid prototyping which are improved in accordance with their study field. Traditional prototyping includes initial idea sketches, technical drawings and physical modeling. However, rapid prototyping mainly focuses on digital modeling, engineering analyses and fabrication by using 3D printings. Both approaches are still in use with regard to the process of design.

According to Gengnagel, Nagy and Stark, in architectural design, prototype and final product are usually the same in that production of one-to one prototyping is quite expensive (2016). However, it is also stated that if certain detail or building component is planned to be prototyped, rapid prototyping procedures can be assessable (Gengnagel et al., 2016). Moreover, prototyping process also consists of the interdependent phases which are design prototyping and engineering prototyping. While design prototyping includes making 3D digital modeling and 3D printing, engineering prototyping consists of structural analyses of design and optimization (Gengnagel et al., 2016). If prototyping process of Glass Node is analyzed with regard to literature reviews, it can be defined as hybrid approach due to be a combination of several types of prototyping processes. For instance, traditional ways and rapid prototyping tools are used during the prototyping and manufacturing process of Glass Node simultaneously because Glass Node is a composite structure consisting of several types of material. Therefore, prototyping and manufacturing process of Glass

Node have been illustrated diagrammatically in order to express the idea of hybrid prototyping and manufacturing approach in Figure 5.18.

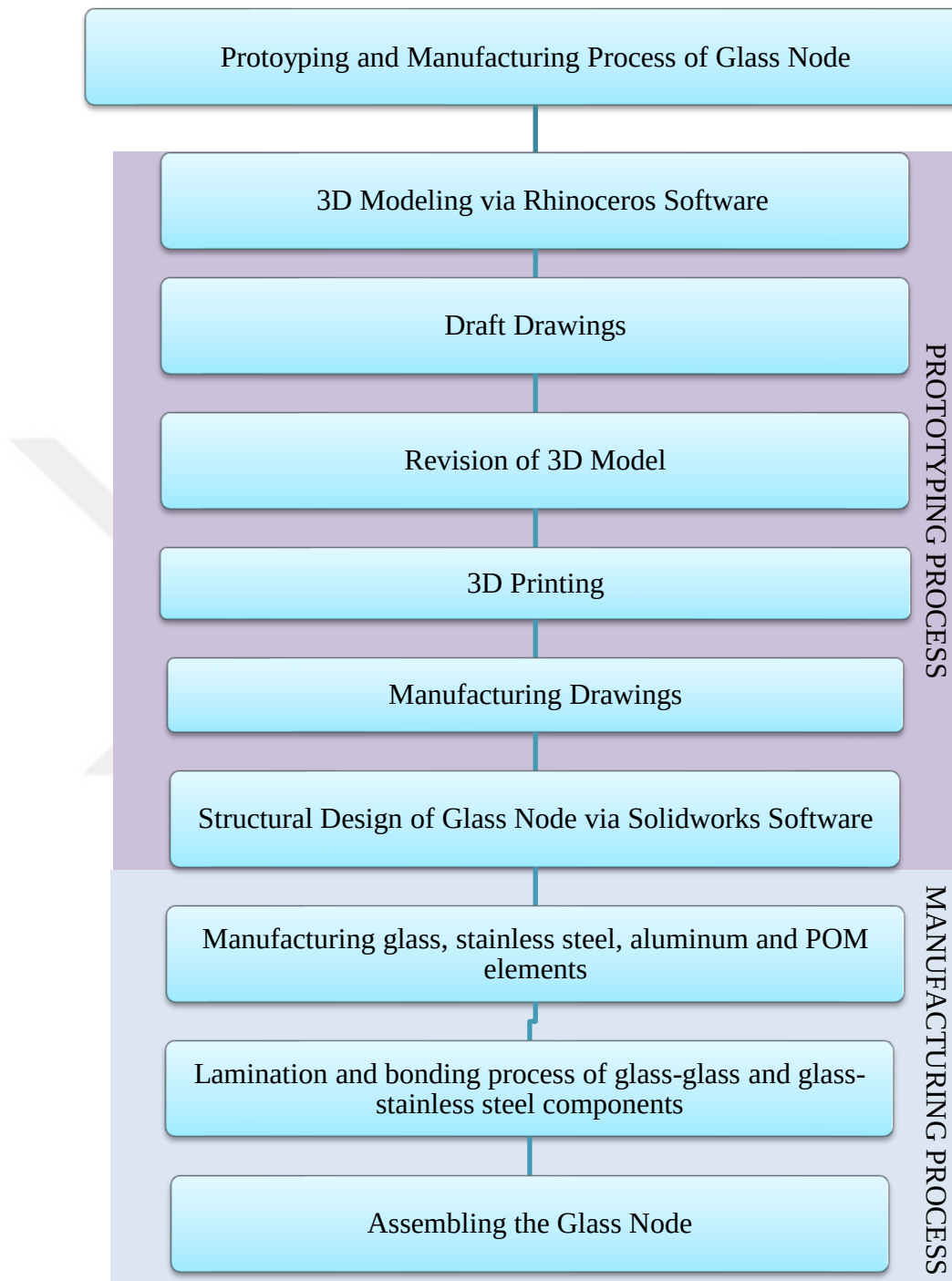


Figure 5.18 : Prototyping process of Glass Node

While prototyping process comprises of making digital 3D modeling, 2D drawings, 3D printing and structural analyzing²¹, manufacturing process includes manufacturing of glass, stainless steel, aluminum and POM elements that bonded them via lamination and structural bonding production of composite components and assembling the Glass Node. 3D digital model of the prototype is performed in Rhinoceros 5 which can be seen in Figure 5.19.

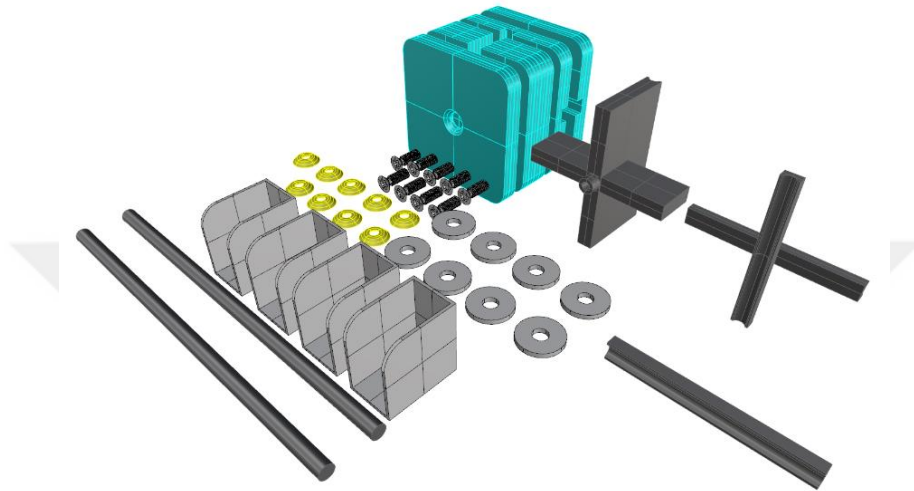


Figure 5.19 : 3D digital model of Glass Node for 3D printing

After all structural components of Glass Node are modeled digitally at Rhinoceros Software, they are printed by using 3D printer (Figure 5.20).



Figure 5.20 : 3D printed components of Glass Node

²¹ While first five parts of the prototyping (Figure 5.18) correspond to design prototyping definition, structural analysis part corresponds to engineering prototyping definition which is explained in Chapters 5.1 and 5.2.

As seen in Figure 5.20, bolts and pins were not preferred to be printed because manufacturing costs of bolts and pins were less than 3D printing of them. Therefore, real materials are also used in prototyping of Glass Node. Afterwards, printed structural elements are assembled in order to check the connections of components (Figure 5.21).

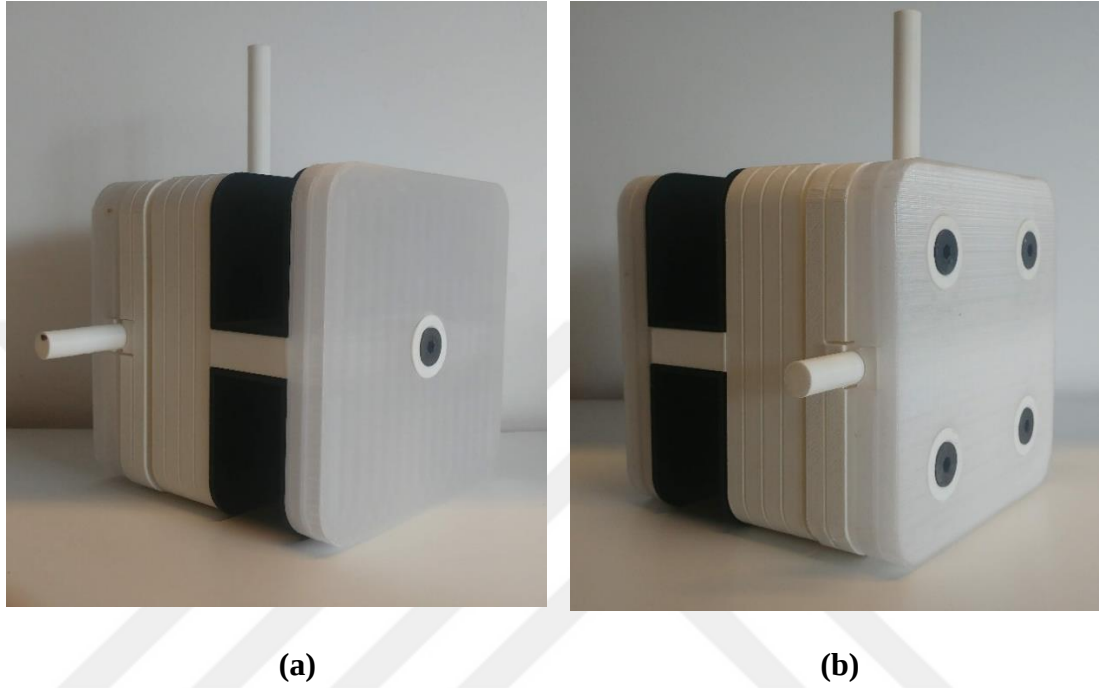


Figure 5.21 : 3D printed prototype (a) Front view of Glass Node, (b) Back view of Glass Node.

3D printed components are assembled successfully. After assembling (connection check), manufacturing process of Glass Node is started. Firstly, while tempered glass elements are cut and drilled according to 2D manufacturing drawings at a glass factory, Dost Cam, stainless steel and POM components are manufactured by Facade Testing Institute (FTI). Afterwards, lamination and bonding processes are executed at two different manufacturers Alcam and Sika in order to produce glass-stainless steel composite components.

There are four types of glass-stainless composite components of Glass Node whose item numbers are TG103-1, TG103-4+SS101, TG103-3+SS103 and $(2 \times (TG103-2) + SS104)^{22}$. TG103-1, TG103-4+SS101, TG103-3+SS103 are bonded via Sentryglass lamination material. The process is carried out in accordance with

²² Please see Chapter 5.1 for explanation of item numbers of composite components.

Sentryglass Application Manual (2012). One of the most important criteria of successful lamination process was to obtain non-bubbled laminated surfaces. Therefore, all instructions in Sentryglass Application Manual illustrated diagrammatically in Figure 5.22 are followed carefully.

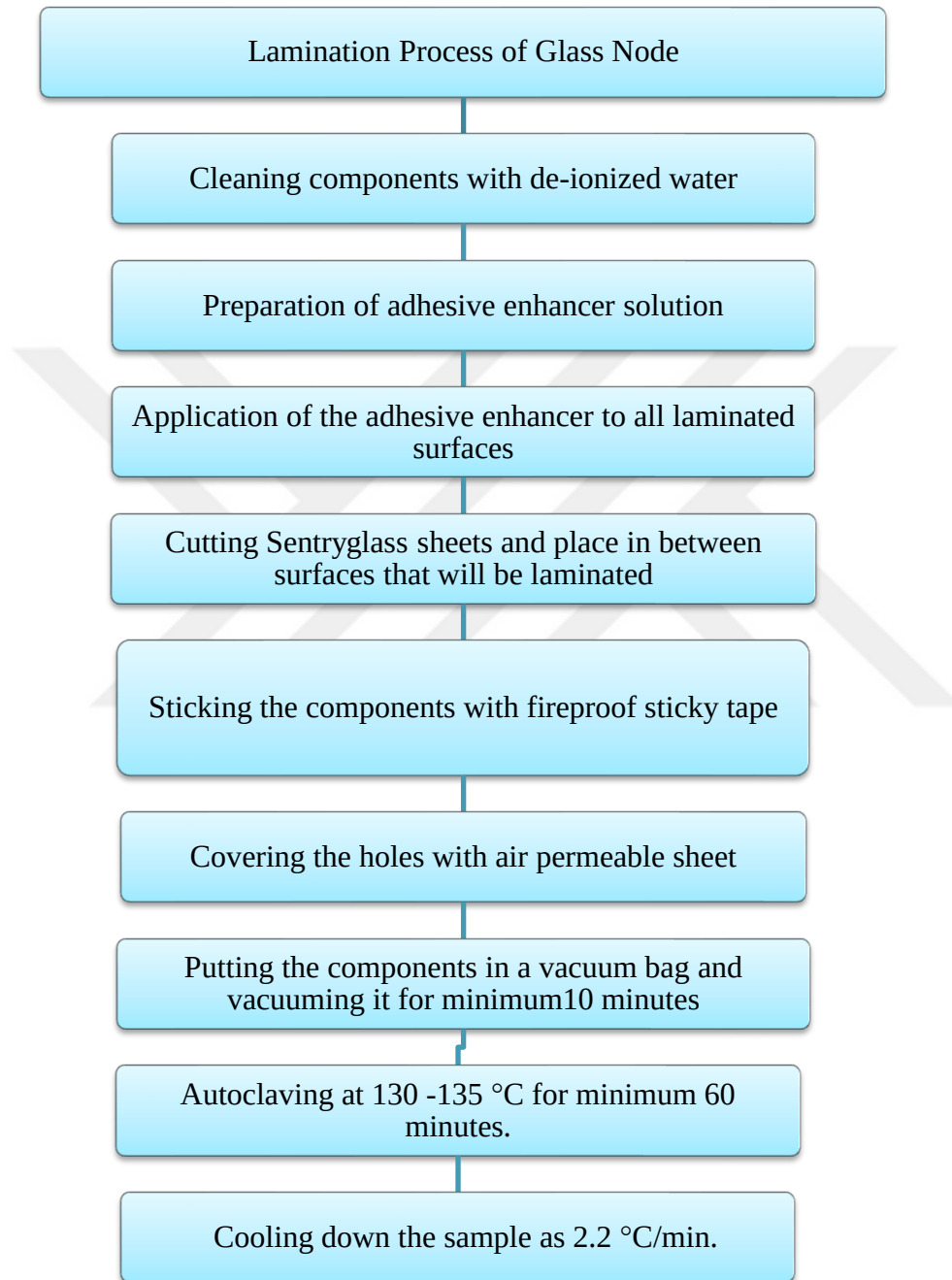


Figure 5.22 : Lamination process of Glass Node composite components, (DuPont, 2012).

Lamination process of Glass Node consists of 9 steps. One of the most important steps is applying adhesion enhancer to surfaces after cleaning them by de-ionized water in order to enable adequate bonding.

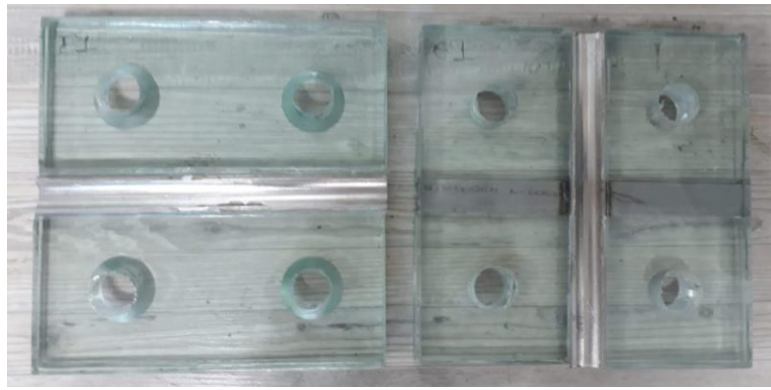
TG103-1 consists of two-layer tempered glass. Therefore, standard lamination process is sustained for it and succeeded. However, adequate autoclave duration and temperature are to be determined for glass-stainless steel composites (TG103-4+SS101, TG103-3+SS103 and $2\times(\text{TG103-2})+\text{SS104}$) experimentally due to differences of heat transmission properties and thermal expansion coefficients of glass and stainless steel materials.

The first experimental manufacturing process could not be successful due to observed air bubbles on laminated surfaces and dislocation of 4-layer glass element during autoclave process which can be seen in Figure 5.23.



Figure 5.23 : Defective laminated glass-stainless steel composite samples, (a) View 1, (b) View 2, (c) View 3.

After the first experiment, autoclave duration of 60 minutes is increased to 90 minutes and cooling process is slowed down. As seen in Figure 5.24, (TG103-4+SS101), (TG103-3+SS103) are laminated successfully.



(a)

(b)

Figure 5.24 : Metal-glass composites, (a) TG103-4+SS101, (b) TG103-3+SS103.

Furthermore bonding of 4-layer glass element and stainless steel solid core ($2 \times (\text{TG103-2}) + \text{SS104}$) are carried out with a different procedure. Firstly, 4-layer glass elements are laminated via Sentryglass. Afterwards, stainless steel core (SS104) is bonded to tempered and laminated glasses via three different adhesives (Sentryglass, Sikasil SG-500, and SikaFast-3131). Moreover, in order to prevent dislocation of 4-layer glass units-steel core composite $2 \times (\text{TG103-2}) + \text{SS104}$, a steel mould is produced as a clamping tool (Appendix H). After the bonding procedure is concluded, 8 units of Glass Node is assembled via screws and roll pins. During the assembling, every glass-metal contact surface is protected by using POM sheets (Figure 5.25)²³.

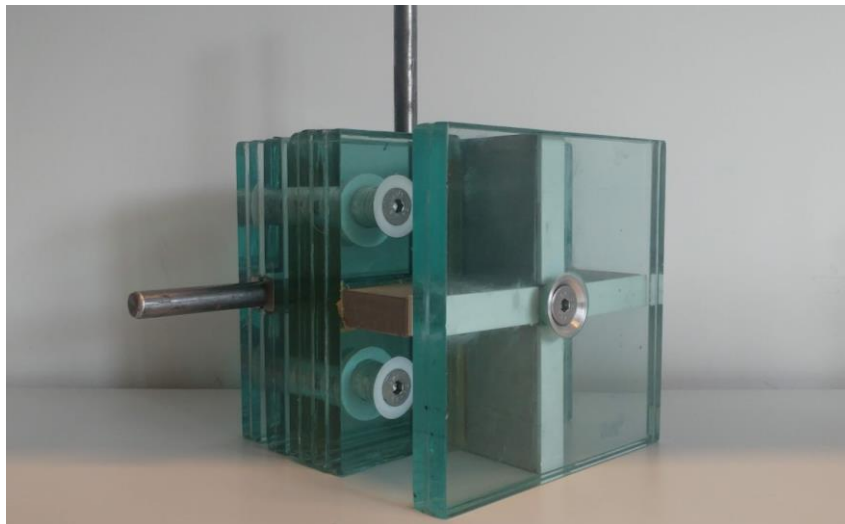


Figure 5.25 : Perspective view of Glass Node.

²³ Please see Appendix I for further images of Glass Node.

5.4 Full Scale Testing of Glass Node

Testing process is the last step of study that enables not only to gain more realistic results about the strength of Glass Node, but also project to compare the experimental results and analysis results which are based on certain assumption. Test process is consisting of four main parts which are designing the test scenario, preparation of test samples and executing preliminary, and main tests. All test procedure is executed at FTI laboratories.

5.4.1 Designing test scenario and preparation of test samples

Designing of test scenario requires a literature review to determine which code or standard is to be used. After literature review, DIN 18008-3 is determined to be used in order to determine load capacity of Glass Node. According to DIN 18008-3, there are three types of loading tests which are normal force bearing capacity, lateral force bearing capacity, and load capacity under moment effect. In this study, only normal force bearing capacity is tested for the developed Glass Node Figure (5.26).

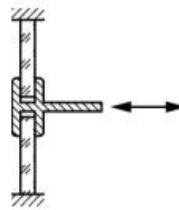


Figure 5.26 : Normal force bearing capacity test illustration (DIN18008-3).

According to DIN18008-3 normal force bearing capacity is tested regarding the procedures below:

- At least five samples should be tested.
- A target value is to be determined.
- The loads shall be applied incrementally in increments of 10% of the target value (F_a).
- The experiments are driven away with a load rate of 0.1 mm /s.
- The load reaches the triple target value (F_t).
- If the triple load of the target value is reached in all tests, may the target value be assumed to be the characteristic carrying capacity.

Target value of the Glass Node is calculated in accordance with the equation 5.6.

$$F_a \geq P_{wd} \quad (5.6)$$

in which;

F_a = Target value of Glass Node capacity under normal force,

P_{wd} = Effective wind load²⁴ (normal force).

When wind load an effective are values put into equation 5.6,

$$F_a \geq 2,4 \text{ kN} \cong 240 \text{ kgf}$$

Triple of target value (F_t) is calculated with equation 5.7

$$F_t = 3F_a \quad (5.7)$$

$$F_t = 3 \times 2,4 \text{ kN}$$

$$F_t = 7,2 \text{ kN} \cong 720 \text{ kgf}$$

After calculation of F_a and F_t values, failure scenarios are determined which are;

- Failure of adhesive
- Failure of glass components
- Bolt stripping.

After preliminary and main tests are re-observed regarding failure scenarios, and some improvements are executed according to the test results. Moreover, in order to assemble the Glass Node to test machine, additional steel clamp is designed and applied to test setup which can be seen in Figure 5.27.

²⁴ Please see equation (5.1).

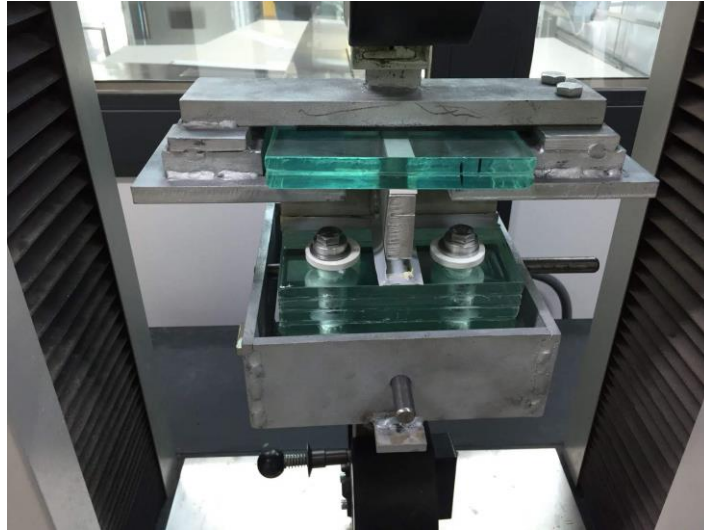


Figure 5.27 : Test setup of Glass Node.

As seen in Figure 5.27, there are some adjustments which are needed to be applied to Glass Node in order to connect it to the tensile test machine. Firstly, to connect Glass Node to the test machine, two-piece stainless steel holder is produced. After that, the test machine is set up according to DIN18008-3. All tests are recorded by video camera. Moreover, software of the test machine collects all the experimental data for the main phase of test process.

5.4.2 Preliminary Tests

Preliminary tests are executed in order to choose adequate adhesive for the connection between $2 \times (TG103-2) + SS104$ which can be seen in Figure 5.28.

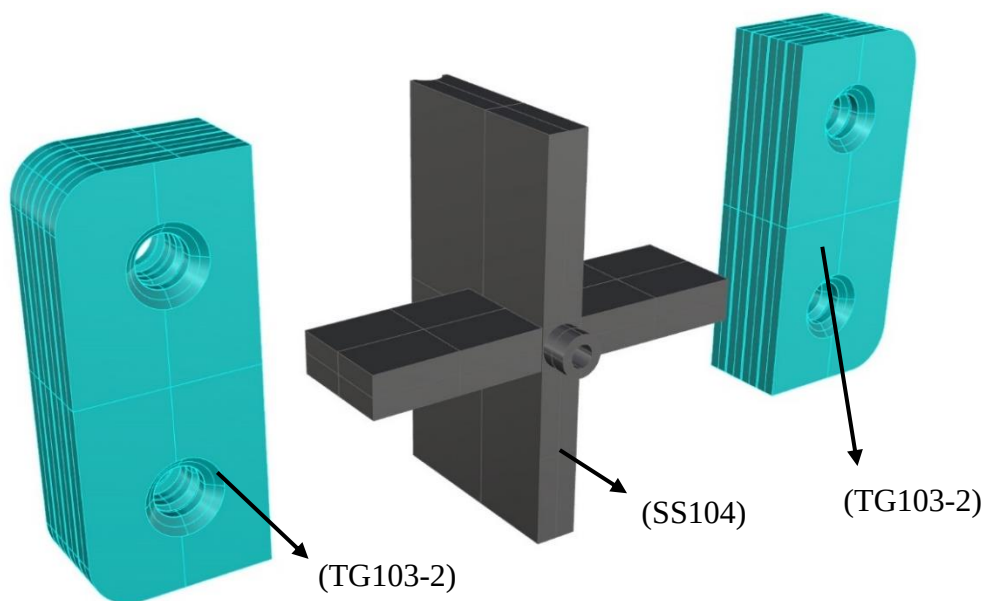


Figure 5.28 : Exploded perspective of glass-steel composite.

Two units of 4-layer laminated glass units are to be adhered to stainless steel cross-shaped core. As mentioned before, three different adhesives are used for the connection which are Sentryglass lamination sheets, Sikasil SG 500 structural silicone, and SikaFast 3131. 3 setups are prepared for the three different adhesives and tests are executed according to DIN18008-3.

The first sample of Glass Node is bonded with Sikasil SG500 structural silicone. Failure mode is observed as an adhesive failure. The first damage is observed at 4,6 kN tension force (yield strenght), and ultimate failure is observed at 6,84 kN tension force. These values show that Sikasil SG500 is satisfied with the target value (F_a), but not enough for triple of the target value (F_t) as mentioned before. These relations are also shown in equation 5.8.

$$F_a < F_{sg500} < F_{sg500max} < F_t \quad (5.8)$$

$$2,4 \text{ kN} < 4,60 \text{ kN} < 6,84 \text{ kN} < 7,2 \text{ kN}$$

where is;

F_{sg500} = Yield strength of Sikasil SG-500

F_a = Target value

$F_{sg500max}$ = Ultimate breaking strength of Sikasil SG-500

F_t = Triple of target value.

As seen in Equation (5.4), ultimate design load can be determined as 6,84 kN which is the value in between F_a and F_t values. Furthermore, the first damage and ultimate failure are documented by photos which can be seen in Figure 5.29.

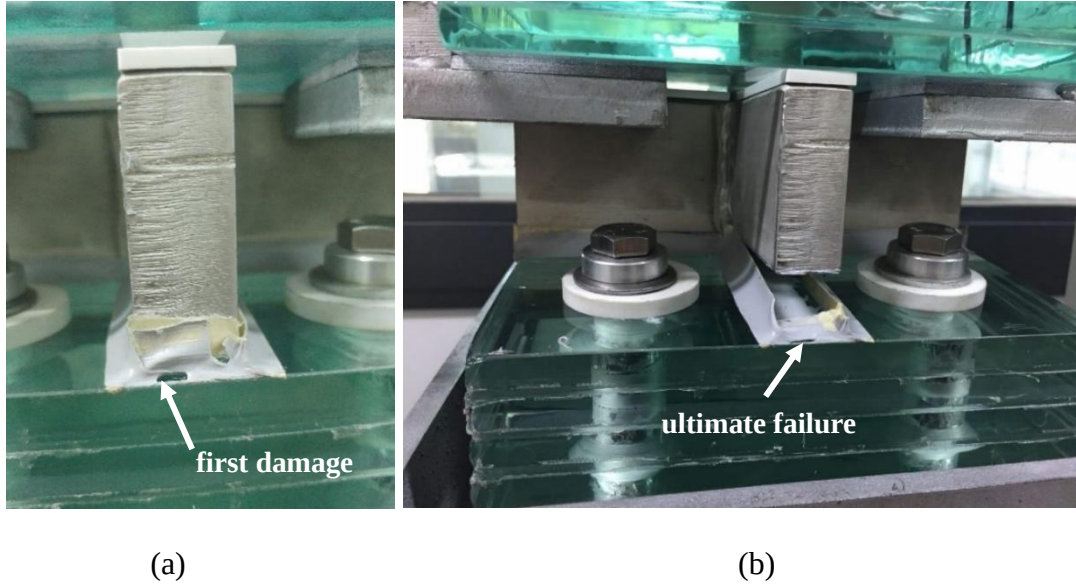


Figure 5.29 : First sample; (a) First damage of Sikasil SG500, (b) Ultimate failure of Sikasil SG500.

As seen in Figure 5.29, while failure is observed at structural silicone, plastic deformation is observed at pom gasket used at cap of Glass Node given in Figure 5.30. Other components of the Glass are not affected by tension force that has been applied.



Figure 5.30 : First sample, deformed POM gasket of Glass Node.

The second sample of Glass Node is bonded with Sentryglass ionomer based lamination material. Failure is observed as an adhesive failure. The first damage is observed at 1,1 kN (yield strength), and ultimate failure is observed at 4,48 kN tension force. These values are quite less than the target value of Glass Node (2,4 kN, F_a) which are also shown in equation 5.9.

$$F_{sgl} < F_a < F_{sglmax} < F_t \quad (5.9)$$

$$1,1 \text{ kN} < 2,4 \text{ kN} < 4,48 \text{ kN} < 7,2 \text{ kN}$$

where;

F_{sgl} = Yield strength of Sentryglass

F_a = Target value

F_{sglmax} = Ultimate breaking strength of Sentryglass

F_t = Triple of target value.

As seen in Equation 5.5, yield load of Sentryglass is lower than determined target value. Therefore, Sentryglass is not adequate adhesive for Glass Node. Furthermore, ultimate failure of Sentryglass and plastic deformation of POM gasket of cap of Glass Node can be seen in Figure 5.31.

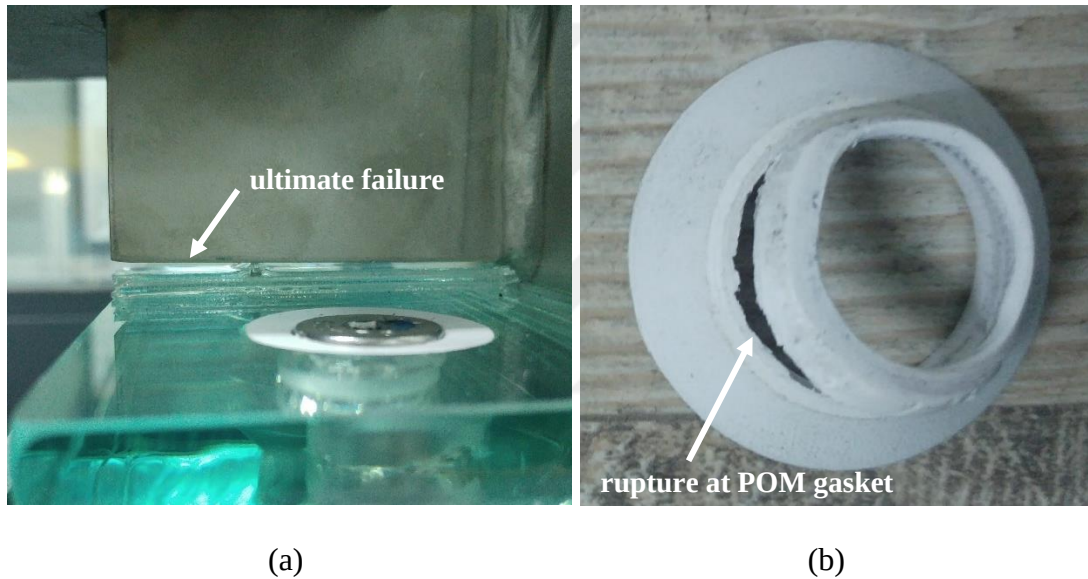


Figure 5.31 : Second Sample; (a) Ultimate failure of Sentryglass, (b) plastic deformation of POM gasket.

The third sample of Glass Node is bonded with SikaFast-3131, methacrylate based adhesive. Failure is observed as screw stripping. The first damage is observed at 10,36 kN (yield load), and ultimate failure is observed at 11,54 kN (ultimate breaking strength). These values ensure target value and triple target value of Glass Node (2,4 kN; F_a , 7,2 kN; F_t) which can be also seen in Equation 5.10.

$$F_a < F_t < F_{sf} < F_{sfmax} \quad (5.10)$$

$$2,4 \text{ kN} < 7,2 \text{ kN} < 10,36 \text{ kN} < 11,54 \text{ kN} \quad \checkmark$$

where is;

F_{sf} = Yield strenght of SikaFast-3131

F_a = Target value

F_{sfmax} = Ultimate breaking strenght of Sikafast-3131

F_t = Triple of target value.

As seen in equation 5.10 SikaFast-3131 is adequate adhesive for Glass Node. Besides, except POM gasket of cap of Glass Node, there is not any deformation observed (Figure 5.32).



Figure 5.32 : Sample 3, plastic deformation of POM gasket of Glass Node.

As seen in Figure 5.32, bolt stripping causes plastic deformation at POM gaskets. Therefore, the design of gaskets and diameter of bolts are revised in order to obtain higher ultimate breaking load. Gaskets of cap of Glass Node is reproduced as aluminum and M12 bolts are applied to Glass Node, instead of M10 bolts²⁵. As a result, structural performance of SikaFast is greater than Sikasil SG500 and Sentryglass which is also shown in Table 5.5.

Table 5.5 : Structural Performance of adhesive materials according to preliminary tests.

Material	Yield Strength	Breaking Strength
Sikasil SG500	4,60 kN	6,84 kN
Sentryglass	1,10 kN	4,48 kN
SikaFast-3131	10,36 kN	11,54 kN

²⁵ These revisions are also stated in Chapters 5.1.3 and 5.1.5.

From this table, structural performance of SikaFast-3131 is deemed to be quite satisfying in order to bond steel core (SS104) to 2 units 4 layered glass elements (2xTG103-2). Therefore, main test is executed by using SikaFast-3131 adhesive material which is explained in the next chapter.

5.4.3 Main tests of Glass Node

Full-scale tests of Glass Node are executed in accordance with DIN18008-3. According to DIN18008-3, minimum 5 samples should be tested in order to determine ultimate load of Glass Node. Therefore 5 units of sample are tested, and all test data are collected by software of tension machine. Except the overlapped graphs, all graphs related with each testing results are added to Appendix J. Additionally, all testing preparations and procedures that are followed during preliminary tests are also done during the main test procedure. Moreover, environmental conditions are also recorded during the test procedures. The temperature is recorded as 30 °C and environmental humidity is determined as 80%. Testing 5 samples takes approximately 104 minutes.

After Sample 1 is tested, cap of Glass Node (TG103-1) fails at 20,38 kN. Moreover, maximum displacement of Glass Node is measured to be 12,68 mm according the software of test machine. As seen in Figure 5.33, by means of lamination of tempered layers of TG103-1, the glass component can still preserve its integrity which is quite substantial in order to ensure safety performance of Glass Node. Moreover, there is not any observed fail of other components of Glass Node.

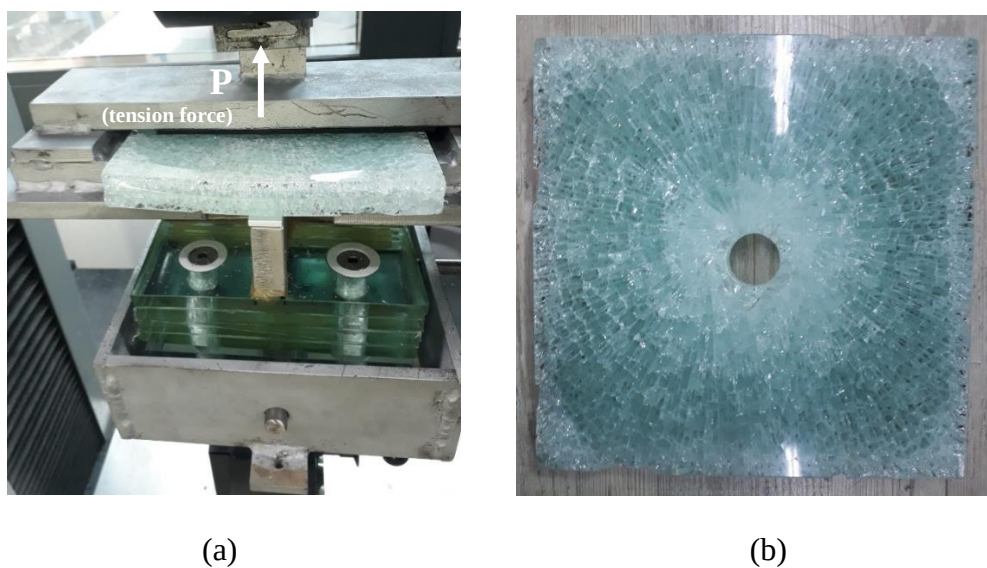


Figure 5.33 : First sample after test process, (a) Glass Node under ultimate tension force, (b) fragmentation of tempered laminated cap.

Sample 2 is also observed and recorded in order to specify breaking load of the glass Node. According to the second test results, breaking strength is 16,30 kN when the maximum displacement Glass Node is 7,93 mm. Failure type is the same type as the first test sample of Glass Node; post testing image of (TG103-1) which can be seen in Figure 5.34.

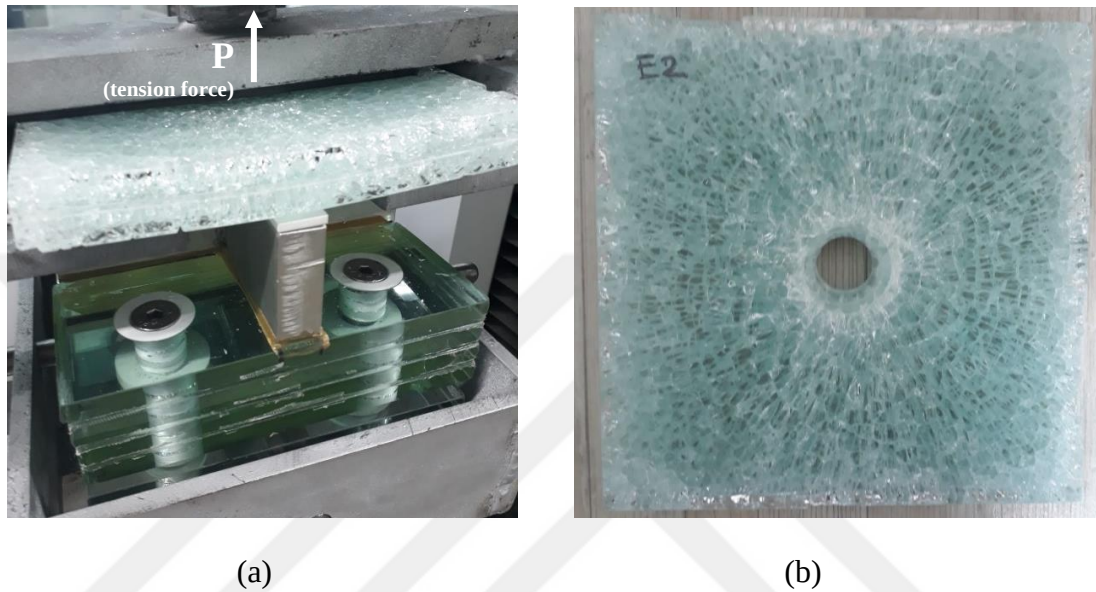


Figure 5.34 : Second sample after test process, (a) Glass Node under ultimate tension force, (b) fragmentation of tempered laminated cap.

After testing Sample 1 and Sample 2, remaining test samples (i.e. Sample 3, Sample 4 and Sample 5) are also tested, and the results are recorded in the same way as the first two experiments. While glass breakage failures are observed upon the investigation of glass failure in Sample 3 and Sample 5, there is no deformation detected at cap of the Sample 4 (Figure 5.35).



Figure 5.35 : Caps of Glass Node test samples.



Figure 5.35 (continued): Caps of Glass Node test samples.

Fragmentation of breakage is observed around the bolt connection. Moreover, fragmentation of the all glass breakages is detected as quite small but curved edge. However, except the Sample 5, all broken glass caps have preserved their integrity by means of lamination layer. As seen in Figure 5.35, cap of Sample 4 did not fail on the contrary to the other test samples. However, bolt stripping failure was observed in Sample 4, which can be seen in Figure 5.36.



Figure 5.36 : Bolt stripping failure in Sample 4.

Bolt stripping failure was observed in the bolts that connect wire strands to Glass Node. Moreover, gaskets of the bolts were also deformed due to this stripping effect. In addition to differences in failure types, measured test results of the samples of Glass Node can be seen at Table 5.

Experiment number	Breaking strength (ultimate force), F_u^{av} (kN)	Yield strength, F_y (kN)	Maximum displacement, Δ_{max} (mm)	Yield displacement, Δ_y (kN)	Failure type/ Mode
Experiment 1	20,38	17,69	12,68	8,73	Glass breakage
Experiment 2	16,30	0	7,93	7,93	Glass breakage
Experiment 3	19,14	18,25	7,93	7,20	Glass breakage
Experiment 4	19,26	17,72	11,18	7,01	Bolt stripping
Experiment 5	21,04	18,00	11,36	7,46	Glass breakage
Average value	19,22	17,92	10,22	7,67	-

Table 5.6 : Measured test results of Glass Node

According to Table 5.6, breaking loads were measured to be 19,14 kN for Sample 3, 19,26 kN for Sample 4 and 21,04 kN for Sample 5. Yield forces were also measured to be 17,69 kN for Sample 1, 18,25 kN for Simple 3, 17,72 kN for Sample 4, and 18,00 kN for Sample 5. Maximum displacements were also determined to be 7,93 mm for the Sample 3, 11,18 mm for Sample 4, and 11,36 mm for Sample 5. Yield displacements were measured to be 8,73 mm for Sample 1, 7,93 mm for Sample 3, 7,01 mm for Sample 4, and 7,46 mm for Sample 5. As a result, maximum breaking and yield load, the highest maximum and yield displacements were determined to be 20,38 kN (Sample 1), 18.00 kN (Sample 5), 12,68 mm (Sample 1), 8,73 mm (Sample 1) respectively. However, during to test process of Sample 2, Glass Node directly reached to the collapse mode. Therefore, there were not any yield load and yield displacement obtained.

As seen in Table 5.6, average breaking load (F_u^{av}) is 19,22 kN which is 8 times greater than the target value of Glass Node (F_a) and 2,7 times greater than triple of Target Value (F_t). The relationship between breaking load of Glass Node F_u^{av} and target values are expressed in Equation 5.6.

$$F_a < F_t < F_u^{av} \quad (5.11)$$

$$2,4 \text{ kN} < 7,2 \text{ kN} < 19,22 \text{ kN} \quad \checkmark$$

where;

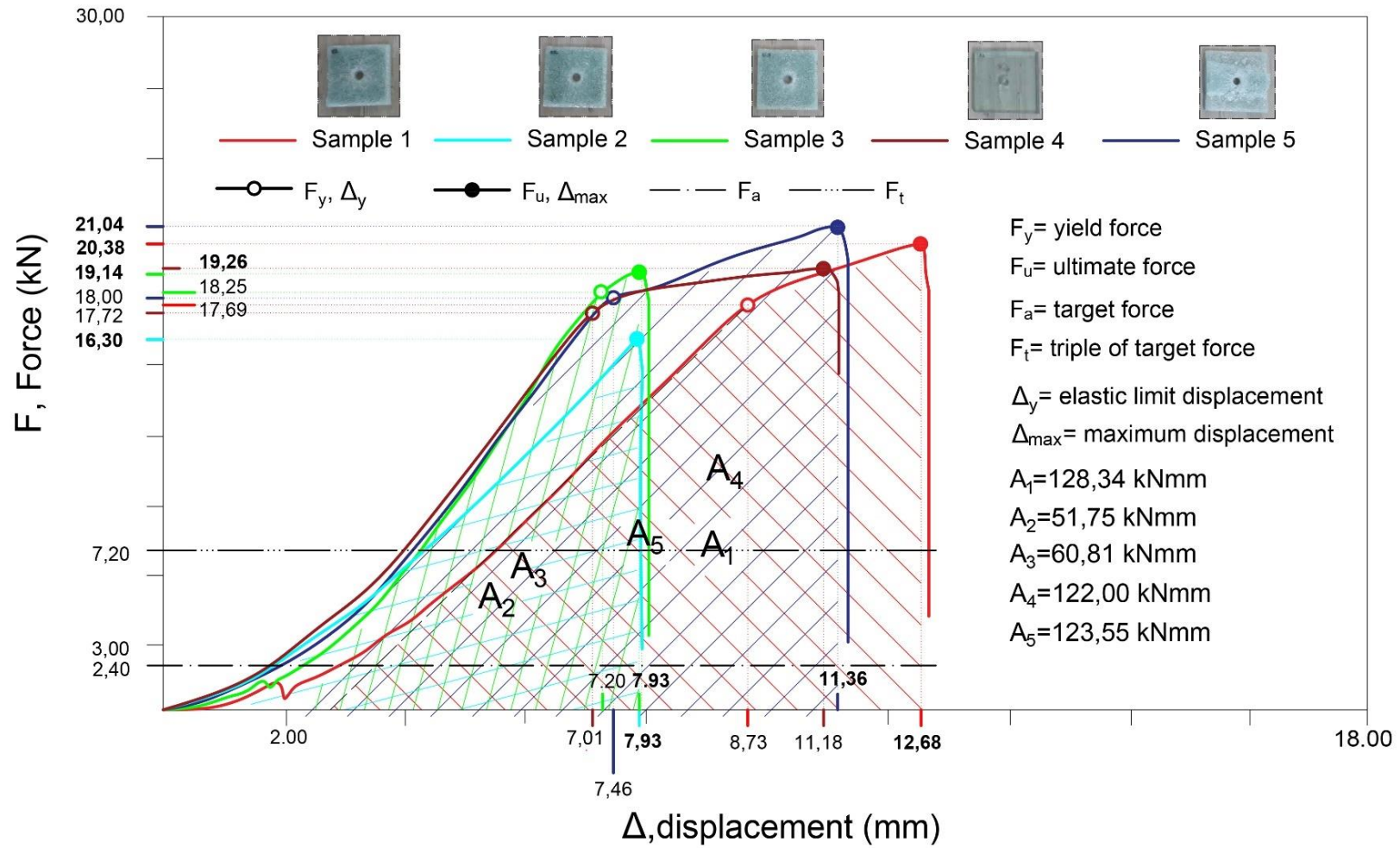
F_u^{av} = Average breaking strength (i.e. ultimate force) of Glass Node

F_a = Target value

F_t = Triple of target value.

As seen in equation 5.11 structural performance of Glass Node is sufficient for the determined effective design loads. Moreover, structural behavior of the Glass Node is also illustrated by using overlapped test data obtained by tension test machine software (Figure 5.37). Samples 1,3,4 and 5 fail at similar breaking load (i.e. ultimate force, F_u) values. However, the lowest structural performance is observed for Sample 2 and the highest one is obtained for Sample 5.

Figure 5.37 : Overlapped Force-Displacement diagram of the test samples.



Moreover, if structural behavior is analyzed with regard to displacement values, it can be said that while the most ductile sample is Sample 1, the most nonductile (i.e. brittle) one is Sample 2. Furthermore, ductility levels of all test samples are also calculated according to equation 5.12 and listed at Table 5.7;

$$ductility\ ratio = \Delta_{max} / \Delta_y \quad (5.12)$$

where is,

Δ_{max} : Maximum displacement,

Δ_y : Yield displacement.

Experiment number	Maximum displacement, Δ_{max} (mm)	Displacement at yield force, Δ_y (mm)	Ductility ratio	Failure Type/ Mode
Experiment 1	12,68	8,73	1,45	Glass breakage
Experiment 2	7,93	7,93	1,00	Glass breakage
Experiment 3	7,93	7,20	1,10	Glass breakage
Experiment 4	11,18	7,01	1,59	Bolt stripping
Experiment 5	11,36	7,46	1,52	Glass breakage
Average Value	10,22	7,67	1,33	-

Table 5.7 : Displacement ductility ratios of test samples.

As a result, while, the best structural performance is observed with Sample 1, the lowest one is observed in Sample 2 in terms of load bearability and ductility. Furthermore, even though the lowest structural performance observed at Sample 2, it is also sufficient with regard to the target values stated at DIN18008-3.

According to all process of the study, literature review, design processes, prototyping and manufacturing process and as a last step testing procedure, Glass Node is able to reach the objectives of the study. Therefore, it can be said that Glass Node is an approved cable-net facade component which can enhance transparency of building envelopes without any structural handicaps.

6. CONCLUSIONS

This chapter includes a general evaluation of the conceptual basis of the study, literature review, design, prototyping and testing processes of the Cable-Net Facade with a proposal Novel Glass Node. Moreover, the test results and technological potentials of Glass Node in terms of building technology are also discussed as a conclusion.

6.1 Summary

Facade as a technical term which is etymologically derived from “face”, meaning front. This definition also can be integrated to the building technology field as an architectural discourse. Facades can be defined as the faces of buildings which enable to establish a conceptual interconnection between inner and outer, spaces. This interconnection generates itself as many different architectural articulations such as re-configuring the definition of inner, outer and in-between spaces. With that discourse, facade is not a separating component but a building element which enables to establish ambiguous relationships between urban and building scales. These unclear connections present themselves as a transformation of form, meaning and technological development of the facade, which is quite substantial for creating high-quality architectural productions and these transformations are based on philosophical and technological developments in modern architectural history.

In the modern history of architecture, the transformation concept has embodied itself as architectural movements such as Modernism, Post-Modernism, Deconstructivism, and High-Tech Architecture. From Modernism to High-Tech Architecture, the architectural movements of the 20th and 21st centuries do not have only a holistic approach towards the built environment as they also investigate the conceptual and technical features of the building facades and search for its potentials. With the Modernism Movement, minimalistic approaches arose, and structural system of the buildings became a part of conceptual discourse of architectural productions such as

“freedom the facade” discourse by Le Corbusier. After Modernism, the Post-Modernism movement evaluated “facade” as an independent building component which can reference the history. With that aspect, Post-Modernism perceived facade as a reflection of imaginariness.

Besides the Post-Modernism, technological developments and philosophical discourses carried on feeding each other mutually. For instance, the “dimensions of body” concept by Deleuze and Guattari, tectonic studies in architecture and High-Tech Movement are related to each other in several ways. One of the intersections between them focuses on decomposition and recomposition of a system which provides an understanding of the component tectonics. This approach can be used at any part of the building design such as facade design. Therefore, cable-net facade and novel Glass Node design procedure was carried out based on the decomposition and recomposition method. All the technical evaluations, designing, prototyping and testing processes were executed in order to reconfigure an innovative facade component.

Cable-net facades are the most transparent and lightweight structural facades designed by means of innovative building technology studies. Nevertheless, point fixing components of the cable-net facades cause a dramatic decrease on transparency ratio. Therefore, comprehending of the cable-net facade components and a focus on increasing the transparency ratio is a substantial move for the reconfiguration of cable-net facades.

Cable-net facades consist of steel wire ropes, anchors, glass units, point fixings and sealants. If all the components are separated from each other and analyzed in terms of the decomposition and recomposition method, it can be seen that, the most promising innovation is developing a new point fixing component which is more transparent from the existing ones. In order to do that, the lightweight structures and their design principles were investigated and determined. The literature research on lightweight structures focused especially on Frei Otto’s design principles which provides a precise design path diagram that still in use. Frei Otto’s design approach of cable-net structural systems consists of conceptual design of the system, draft drawings, preliminary numerical structural analyses, physical modeling and a final design (Figure 2.13). By means of the literature review, based on Frei Otto’s design approach, cable-net facade is designed, analyzed and detailed in order to develop innovative point fixing

component. Additionally, a classification of structural glass facades was also specified in the scope of this study and the cable-net facades components were examined in detail.

Design of the cable-net facade, the steps of which are illustrated diagrammatically at Figure 4.1, is sustained as three interdependent parts: Architectural design of the cable-net facade, structural design of the cable-net facade, and structural design of the steel frame. Architectural and structural design of the cable-net facade were executed simultaneously in order to provide an effective optimization. The cable-net facade structure was designed as 5,136 m x 8,812 m according to FTI's reinforced concrete test stand, which has the dimensions of 7,009 m x 11,986 m. The cable-net facade consists of 20 insulated glass units (1m x 2m), $\Phi 14$ mm steel wire ropes, adjustable and non-adjustable anchors, the Glass Node as a point fixing component and sealants. All components are analyzed according to their applicability in regard to the international standards and regulations, and the application drawing of cable-net facade was made. Furthermore, while the structural design of the cable-net facade was carried out according to the Allowable Stress / Strength Design Principles (ASD), the design limits of the cable-net were determined according to ASCE19-16 and AISC 360-10²⁶. Structural analyses were carried out by using SAP2000 software and all computational design steps are illustrated in Figure 4.1. Firstly, the effective design loads were determined as $(\pm 8 \times 10^{-7})$ kN/mm² for wind load (W $\pm$), $(\pm 6 \times 10^{-7})$ kN/mm² for dead load of IGU (SDL), dead load of structure (D)²⁷, $(\pm 30^\circ\text{C})$ for temperature load (T $\pm$) and -35 kN for prestress load (PR)²⁸ and earthquake loads²⁹ (EQX, EQY). Furthermore, the load combinations were determined according to ASCE 7-10. Following the determination of the test inputs, material properties of the cable-net elements were assigned, and the cable-net structure was analyzed with the help of SAP2000. After the cable-net structure analysis and optimization processes, the maximum reaction forces and deflection were observed for combination LC04³⁰. According to the analysis results, the maximum reaction force is 43,29 kN at the pin

²⁶ All theoretical references are also based on Cable Catenary Theory by Peyrot & Goulois and Hooke Law.

²⁷ Dead load of the structure is calculated by SAP2000 automatically.

²⁸ For determining the PR value, see p.62 and p.63.

²⁹ Earthquake loads are calculated by SAP2000 automatically.

³⁰ LC04 corresponds to (W+)+(T+)+PR+SDL+D.

connection located at the middle of the cable-net structure. Furthermore, 43,29 kN is less than strength design limits of the $\Phi 14$ mm steel wire ropes (59,95 kN), which means that the strength of the structure is adequate. In addition to the strength check, the deflection limit of the cable-net facade was determined as $L/50$ which corresponds to 110,36 mm for this study. During the deflection check, the maximum deflection was observed as 97,95 mm at point fixing joint located at middle of the structure. Therefore, the maximum deflection also ensures the deflection limit of the structure. After the structural analysis of the cable-net, the steel frame design, which enables the connection of the cable-net structure to the reinforced concrete test stand, was performed according to ASD and ASCE 360-10. SAP2000 was also used for the analysis and design of the steel frame. During the design process, maximum reaction forces obtained for the cable-net facade was applied to the steel supporting frame structure and a dimensioning process was performed with all the effective loads. Afterwards, the analysis was run, and the optimization process was completed. While the steel frame design was being performed, the section of structural elements was also determined in consideration to the existing steel profiles that were integrated to the reinforced concrete test stand. Afterwards, a stress check of the insulated glass units (IGU) was executed by using SJ Mepla. The stress and deflection limits of the IGU was determined according to DIN18008, which are 80 MPa and 10 mm, respectively. According to the SJ Mepla analysis; the maximum stress was observed nearby the point fixing components as 33,34 MPa, the maximum deflection was observed in the joint located at the center of the IGU to be 9,20 mm. As seen in the maximum stress and deflection values, IGU's structural performance is satisfactory according to assumed loads.

After the architectural and structural design of cable-net facade and structural frame, the design, development, prototyping and testing process of the Glass Node was performed. The design process of the Glass Node was divided into three main part which are initial architectural design, final architectural design, and structural design. Initial design of the Glass Node focuses on realization of the conceptual ideas about developing a transparent point-fixing element with regard to the designed cable-net facade. Some primary decisions were made in terms of material, structural behavior, structural prototyping, and testing processes of the Glass Node in order to establish a reasonable structure in the study.

The decisions are listed below:

- Glass is determined as the main element in order to provide transparency,
- In addition to the glass elements, steel material is to be used in order to enhance the strength of Glass Node,
- Glass components should be tempered and laminated to comply with the design loads of the cable-net structure,
- Bonding procedures of metal glass elements are to be investigated in detail in terms of structural performance,
- Design and engineering prototyping processes should be executed in order to check the component in terms of architectural detailing and structural performance,
- All procedures are to be carried on accordance with international standards and regulations, especially for DIN18008-3.

After determining the structure of the development procedure of the Glass Node, a conceptual 3D model was made as the initial design of the Glass Node. Afterwards, architectural 2D drawings were completed with some revisions according to dimensional properties of cable-net facades. The Glass Node was designed as a 170 mm x 170 mm prismatic point fixing component. Furthermore, the Glass Node consists of 2 layers of laminated and tempered glass caps (TG103-1), a cross shaped stainless steel core (SS104), 4 layers of tempered and laminated glass, (TG103-3), 2 layers of tempered and laminated glass in two types (TG103-3 and TG103-4), two types of stainless steel bedding element (SS101 and SS103), 4 units of stainless steel roll pins (SS102), 6 units of M12 countersunk bolts (SS105) and POM bedding elements (PM101-1, PM 101-2, PM 101-3, PM 101-4, PM 101-5, PM 101-6). All the elements and their relations to each other are illustrated at final renders of Glass Node (Figure 5.4 and Figure 5.5). As seen in the final renders, TG103-1 and SS101, TG103-3 and SS103, 2 units TG103-2 and SS104 are planned to be bonded. Sentryglass, Sikasil SG500 and SikaFast-3131 were specified as prospective bonding materials for this study in order to determine the most adequate one for connections. Nevertheless, before the bonding procedures, the structural performance of the Glass Node was analyzed in Solidworks Software. Firstly, effective loads were determined to be 2,4 kN wind load and 1,65 kN dead load of IGU for 1 unit of the Glass Node. Afterwards,

the structural analysis was executed as three sub-analyses which are the analysis of exterior cap (TG103-1), the stainless steel core (SS104) and the glass-stainless steel composites. According to analysis results the maximum stresses were determined as 29 MPa for the exterior cap, 4 MPa for the stainless steel core and 5 MPa for the glass-stainless steel composites. All the stress values are less than the design strength of the components, which are 80 MPa, 195,45 MPa and 80 MPa, respectively. These results show that the maximum stresses are observed at the exterior cap of the Glass Node. Therefore, the exterior cap is the most critical element of the Glass node in terms of structural performance. However, structural analysis does not comprise of the bonding performance between glass-stainless steel element. Therefore, the structural performance of the bonding materials is to be experimentally determined. In order to proceed to the experimental processes, prototyping and manufacturing processes are to be performed (Figure 5.18). The prototyping process is divided into two main parts: Design prototyping and engineering prototyping. While the design prototyping process includes conceptual design, architectural drawings and 3D printing of the design with unrealistic materials, the engineering prototyping includes structural simulations and analyses which has been already explained above. Thus, the 3D printing of the Glass Node was performed by using 3D printers in order to check the connection details of the component. After 3D printing the Glass Node, some revisions were added to the architectural design such as increasing the number of bedding materials. Afterwards, the manufacturing process was executed. Except bonding the stainless steel core (SS104) to 4 layers tempered glass (SS103-2), all glass-stainless steel composite elements were laminated by Sentryglass lamination according to the Sentryglass Application Manual. However, Sikasil SG500, SikaFast-3131 and Sentryglass lamination sheet were used in order to bond stainless steel core (SS104) to 2 units of tempered glass (TG 103-2).

After the bonding processes, test was conducted in two phases: The primality test for determining the appropriate bonding materials for SS104 and 2 units TG103-2 and the main tests of the Glass Node. During the preliminary test process, 3 samples were tested by using Sikasil SG500, Sentryglass and SikaFast-3131, respectively. The test procedure was determined according to DIN18008-3. The limit strength values were calculated as 2,4 kN (F_a) as a target value (yield strength limit) and 7,2 kN (F_t) as triple of target value (ultimate breaking strength limit) by referencing DIN18008-3 and

effective wind load of the Glass Node. Furthermore, probable failure types were determined as; failure of adhesive, failure of glass components, and bolt stripping failure. Test was performed by using tension test machine at FTI's laboratory. According to the test results, while the most advanced structural performance was observed with SikaFast-3131 with 10,36 kN yield strength and 11,54 ultimate breaking strength, other bonding materials yield, and ultimate breaking strengths measured to be 4,60 kN (F_a), 6,84 (F_u) for Sikasil SG500, 1,10 kN (F_a), 4,48 (F_u) for Sentryglass (Table 5.5). Therefore, SikaFast-3131 was selected in order to perform the main tests of the Glass Node. Beside the strength of the bonding materials, failure types of the materials were determined as bolt stripping for Sikasil-3131 and adhesive failure for the rest. Therefore, in order to enhance the strength of the Glass Node, bolts were revised as M12 and main tests were executed with five samples bonded with SikaFast-3131.

Main test procedure is also based on DIN18008-3. Five samples were tested by using tension test machine located at FTI's laboratories. Test results were gathered as numerical data and the force-displacement graphs which illustrate the structural behaviors of the Glass Node test samples. According to the results, while the average ultimate breaking strength of Glass Node is determined to be 19,22 kN, the average deflection was measured to be 10,22 mm. Moreover, while the maximum breaking strength and the maximum displacement was observed to be 21,04 kN for Sample 5 and 12,68 mm for Sample 1, minimum breaking strength and lowest maximum displacement were observed to be 16,30 kN and 7,93 mm for Sample 2 and Sample 3. As a result, the determined average breaking strength is 8 times greater than F_a value and 2,7 times greater than F_t value. Moreover, maximum and minimum yield strengths were observed to be 18,25 kN for Sample 3 and 17,69 kN for Sample 1 respectively. According to ductility ratios of the test samples, when the average ductility ratio was measured to be 1,33, the most ductile sample is determined to be Sample 1 (ductility ratio: 1,59) and the most nonductile (i.e. brittle) one is determined to be Sample 2 (ductility ratio: 1). Furthermore, while the Sample 1, Sample 2, Sample 3 and Sample 5 fail by breakage of exterior cap of Glass Node (glass failure), Sample 4 fails from bolt stripping.

6.2 Conclusion

The overall process of design, development, prototyping and testing of the Glass Node shows that:

- Reconfiguration of the cable-net facade is embodied as a Glass Node by means of tectonic studies.
- It is approved that structural performance of Glass Node ensures the design limits determined by international standards.
- Strength of Sika-Fast-3131 is quite satisfactory for the glass-metal bonding of Glass Node
- Strength of the Glass Node is approximately 8 times greater than limit yield strength (F_a) and 2,7 times greater than the ultimate breaking strength (F_u) of the Glass Node. Beside the ensuring the design limits, these results also refer that Glass Node structurally overdesigned due to architectural requisites.
- When highest ductility ratio is observed to be 1,59 at Sample 4 of which failure type is bolt stripping, Sample 2 fails with glass breakage and has minimum ductility ratio; 1.00 (non-ductile). Therefore, it can be presumed that bolt stripping failure is more efficient in terms of ductility of Glass Node.
- Metal-glass lamination with Sentryglass is effective for the composites consisting of up to two layer metal and glass elements.
- Transparency ratio of the designed cable-net facade is %17 percent increased by means of Glass Node design.
- Glass-metal composites have non-negligible potential in order to develop innovative structural systems and components.
- Even the Glass Node is satisfactory in terms of its structural performance, it should be investigated according to other building performance criteria.

6.3 Recommendations for Future Studies

This study fulfills the objectives by means of interdisciplinary research approaches, interdependent literature reviews, detailed architectural designs, structural designs according to the national and international standards, prototyping, manufacturing and

testing processes. Furthermore, executing a full-scale cable-net facade test with Glass Node which is developed as a minimized, lighter and structurally enhanced system can be innovative and qualified research subject for future studies. Thus, the performance of the Glass Node can be investigated in a holistic way.





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APPENDICES

APPENDIX A: Application Drawings of Cable-Net Facade

APPENDIX B: Analysis Report of Cable-Net Structure

APPENDIX C: Analysis Report of Steel Frame

APPENDIX D: SJ Mepla Analysis Report of IGU

APPENDIX E: Structural Design Report of Connections

APPENDIX F: Application Drawings of Glass Node

APPENDIX G: Solidworks Analysis Report of Glass Node

APPENDIX H: Steel Mould for Lamination Process

APPENDIX I: Glass Node as a Final Product

APPENDIX J: Graphs of Test Results

APPENDIX K: Diagrammatic Representation of Thesis Study

APPENDIX A

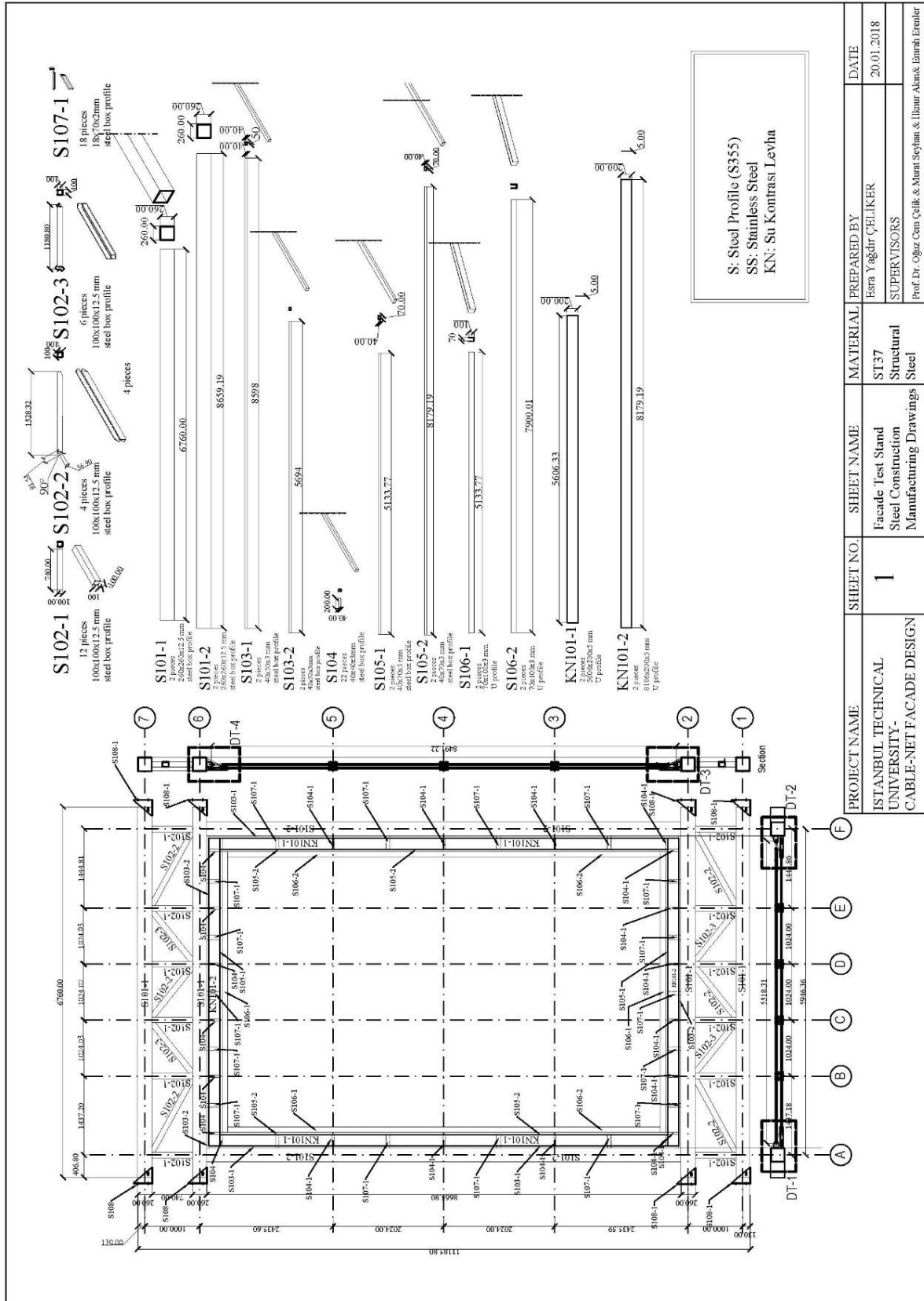


Figure A.1 : Application Drawings of Cable-Net Facade, sheet 1.

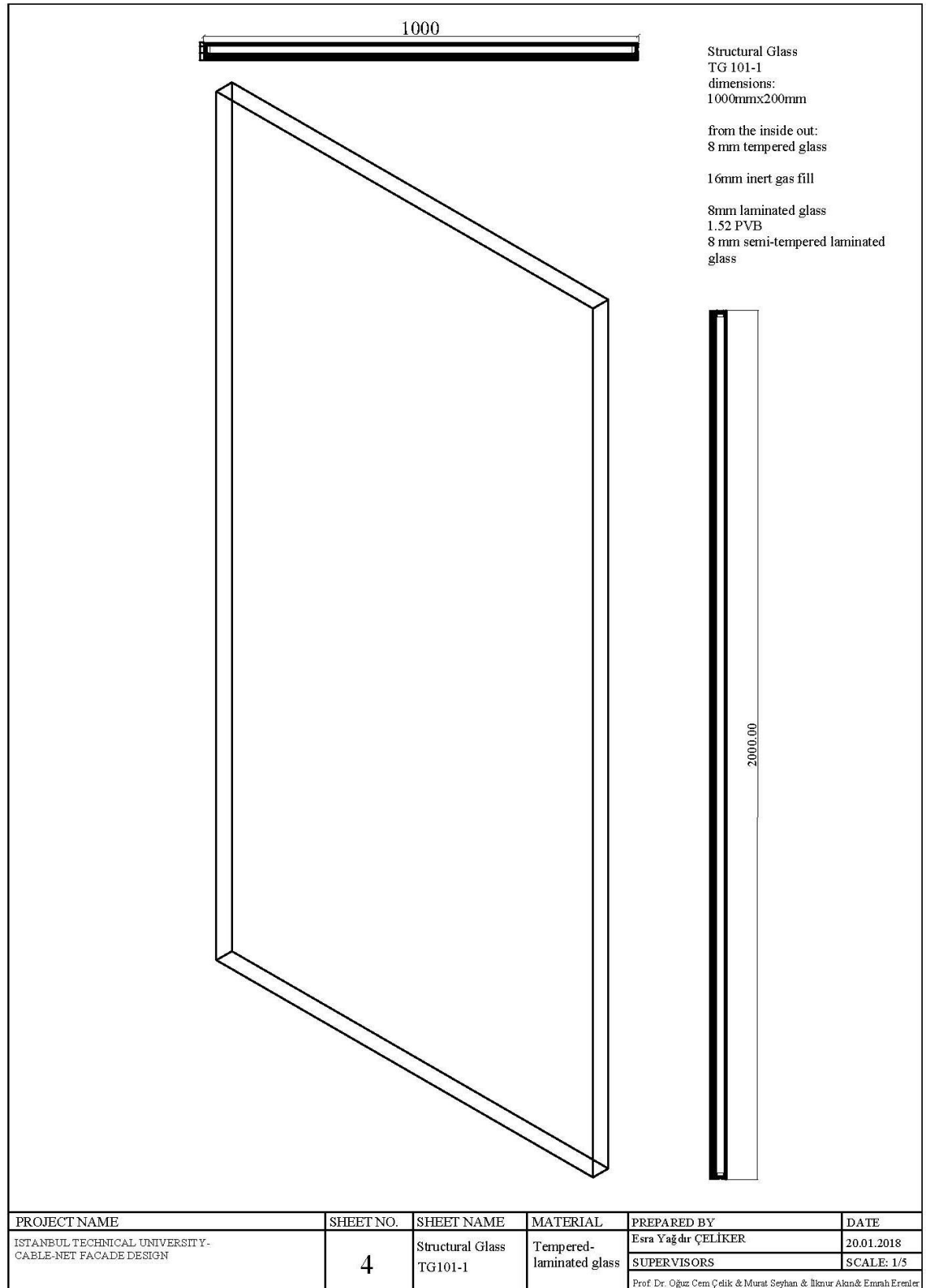


Figure A.4 : Application Drawings of Cable-Net Facade, sheet 4.

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APPENDIX B

CS14.sdb
1. Model geometry

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26 Şubat 2018

1. Model geometry

This section provides model geometry information, including items such as joint coordinates, joint restraints, and element connectivity.

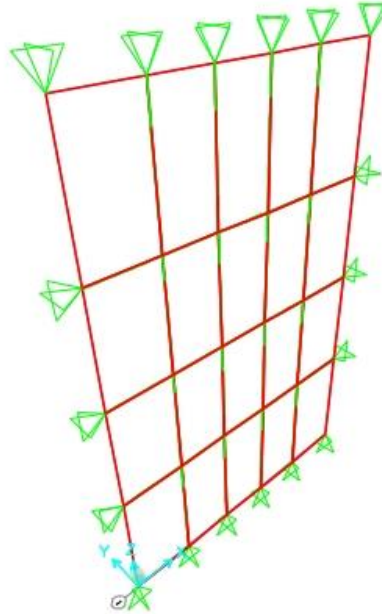


Figure 1: Finite element model

1.1. Joint coordinates

Table 1: Joint Coordinates

Table 1: Joint Coordinates					
Joint	CoordSys	CoordType	GlobalX mm	GlobalY mm	GlobalZ mm
1	GLOBAL	Cartesian	1223,	0,	8543,
2	GLOBAL	Cartesian	1223,	0,	6321,
3	GLOBAL	Cartesian	1223,	0,	4297,
4	GLOBAL	Cartesian	1223,	0,	2273,
5	GLOBAL	Cartesian	1223,	0,	0,
6	GLOBAL	Cartesian	0,	0,	6321,
7	GLOBAL	Cartesian	2247,	0,	6321,
8	GLOBAL	Cartesian	3271,	0,	6321,

Figure A.6 : Analysis Report of Cable-Net Structure, sheet 1.

Table 25: Preferences - Steel Design - AISC-ASD89, Part 2 of 2

Table 25: Preferences - Steel Design - AISC-ASD89, Part 2 of 2						
LLRat	TotalRat	NetRat	CmOption	CmTol	CbOption	CbTol
360,	240,	240,	Program Determined		Program Determined	

12.2. Concrete design

Table 26: Preferences - Concrete Design - ACI 318-14, Part 1 of 2

Table 26: Preferences - Concrete Design - ACI 318-14, Part 1 of 2								
THDesign	NumCurves	NumPoints	MinEccen	PatLLF	UFLimit	SeisCat	Rho	Sds
Envelopes		24	11	Yes	0,75	0,95	D	1, 0,5

Table 26: Preferences - Concrete Design - ACI 318-14, Part 2 of 2

Table 26: Preferences - Concrete Design - ACI 318-14, Part 2 of 2					
PhiT	PhiCTied	PhiCSpiral	PhiV	PhiVSeismic	PhiVJoint
0,9	0,65	0,75	0,75	0,6	0,85

12.3. Aluminum design

Table 27: Preferences - Aluminum Design - AA-ASD 2000

Table 27: Preferences - Aluminum Design - AA-ASD 2000			
FrameType	SRatioLimit	LatFact	UseLatFact
Moment Frame	1,	1,333333	No

Figure A.7 : Analysis Report of Cable-Net Structure, sheet 2.

8. Joint results

This section provides joint results, including items such as displacements and reactions.

9. Frame results

This section provides frame force results.

10. Area results

This section provides area results, including items such as forces and stresses.

11. Material take-off

This section provides a material take-off.

Table 24: Material List 2 - By Section Property

Table 24: Material List 2 - By Section Property				
Section	ObjectType	NumPieces	TotalLength mm	TotalWeight KN
CS14	Cable	31	50726,	0,457
FICT	Area			0,

12. Design preferences

This section provides the design preferences for each type of design, which typically include material reduction factors, framing type, stress ratio limit, deflection limits, and other code specific items.

12.1. Steel design

Table 25: Preferences - Steel Design - AISC-ASD89, Part 1 of 2

Table 25: Preferences - Steel Design - AISC-ASD89, Part 1 of 2						
FrameType	PatLLF	SRatioLimit	LatFactWind	LatFactSeis	DLRat	SDLAndLLRat
Braced Frame	0,75	0,95	1,15	1,33	120	120,

Figure A.8 : Analysis Report of Cable-Net Structure, sheet 3.

Table 3: Connectivity - Cable

Cable	JointI	JointJ	Length mm
20	20	21	2024,
21	21	22	2273,
22	23	3	1223,
23	3	12	1024,
24	12	16	1024,
25	16	20	1024,
26	20	24	1223,
27	25	4	1223,
28	4	13	1024,
29	13	17	1024,
30	17	21	1024,
31	21	26	1223,

Table 4: Cable Section Assignments**Table 4: Cable Section Assignments**

Cable	CableSect	MatProp
1	CS14	Default
2	CS14	Default
3	CS14	Default
4	CS14	Default
5	CS14	Default
6	CS14	Default
7	CS14	Default
8	CS14	Default
9	CS14	Default
10	CS14	Default
11	CS14	Default
12	CS14	Default
13	CS14	Default
14	CS14	Default
15	CS14	Default
16	CS14	Default
17	CS14	Default
18	CS14	Default
19	CS14	Default
20	CS14	Default

Figure A.9 : Analysis Report of Cable-Net Structure, sheet 4.

Table 4: Cable Section Assignments

Cable	CableSect	MatProp
21	CS14	Default
22	CS14	Default
23	CS14	Default
24	CS14	Default
25	CS14	Default
26	CS14	Default
27	CS14	Default
28	CS14	Default
29	CS14	Default
30	CS14	Default
31	CS14	Default

Table 5: Connectivity - Area

Table 5: Connectivity - Area

Area	Joint1	Joint2	Joint3	Joint4
1	27	1	2	6
2	1	11	7	2
3	11	15	8	7
4	15	19	9	8
5	19	28	10	9
6	6	2	3	23
7	2	7	12	3
8	7	8	16	12
9	8	9	20	16
10	9	10	24	20
11	23	25	4	3
12	3	4	13	12
13	12	16	17	13
14	16	20	21	17
15	20	24	26	21
16	25	29	5	4
17	4	5	14	13
18	13	14	18	17
19	17	18	22	21
20	21	26	30	22

Figure A.10 : Analysis Report of Cable-Net Structure, sheet 5.

Table 6: Area Section Assignments

Table 6: Area Section Assignments		
Area	Section	MatProp
1	FICT	Default
2	FICT	Default
3	FICT	Default
4	FICT	Default
5	FICT	Default
6	FICT	Default
7	FICT	Default
8	FICT	Default
9	FICT	Default
10	FICT	Default
11	FICT	Default
12	FICT	Default
13	FICT	Default
14	FICT	Default
15	FICT	Default
16	FICT	Default
17	FICT	Default
18	FICT	Default
19	FICT	Default
20	FICT	Default

2. Material properties

This section provides material property information for materials used in the model.

Table 7: Material Properties 02 - Basic Mechanical Properties

Table 7: Material Properties 02 - Basic Mechanical Properties						
Material	UnitWeight	UnitMass	E1	G12	U12	A1
	KN/mm3	KN-s2/mm4	KN/mm2	KN/mm2		1/C
4000Psi	2,3563E-08	2,4028E-12	24,85558	10,35649	0,2	9,9000E-06
A416Gr270	7,6973E-08	7,8490E-12	196,5006			1,1700E-05
A615Gr60	7,6973E-08	7,8490E-12	199,94798			1,1700E-05
A992Fy50	7,6973E-08	7,8490E-12	199,94798	76,90307	0,3	1,1700E-05
Cable	8,0788E-07	8,2381E-11	210,	80,76923	0,3	1,1700E-05

Figure A.11 : Analysis Report of Cable-Net Structure, sheet 6.

Table 7: Material Properties 02 - Basic Mechanical Properties

Material	UnitWeight KN/mm3	UnitMass KN-s2/mm4	E1 KN/mm2	G12 KN/mm2	U12	A1 1/C
FICTIVE	0,0000E+00	0,0000E+00	1,000E-05	3,846E-06	0,3	1,1700E-05
FLC	7,6973E-08	7,8490E-12	165,	63,46154	0,3	1,1700E-05
FLC2	7,6973E-08	7,8490E-12	130,	50,	0,3	1,1700E-05
Glass	8,8290E-10	9,0031E-14	7,000E-05	2,800E-05	0,25	9,0000E-06
N-355	7,6973E-08	7,8490E-12	199,94798	76,90307	0,3	1,1700E-05
OSS12	7,6973E-08	7,8490E-12	166,	63,84615	0,3	1,1700E-05

Table 8: Material Properties 03a - Steel Data

Table 8: Material Properties 03a - Steel Data

Material	Fy KN/mm2	Fu KN/mm2	FinalSlope
A992Fy50	0,34474	0,44816	-0,1
Cable	0,152	22,727	-0,1

Table 9: Material Properties 03b - Concrete Data

Table 9: Material Properties 03b - Concrete Data

Material	Fc KN/mm2	cFc KN/mm2	FinalSlope
4000Psi	0,02758	0,02758	-0,1

Table 10: Material Properties 03c - Rebar Data

Table 10: Material Properties 03c - Rebar Data

Material	Fy KN/mm2	Fu KN/mm2	FinalSlope
A615Gr60	0,41369	0,62053	-0,1

Figure A.12 : Analysis Report of Cable-Net Structure, sheet 7.

Table 11: Material Properties 03f - Tendon Data

Material	Fy KN/mm2	Fu KN/mm2	FinalSlope
A416Gr270	1,68991	1,86158	-0,1

3. Section properties

This section provides section property information for objects used in the model.

3.1. Frames

Table 12: Frame Section Properties 01 - General, Part 1 of 4

Table 12: Frame Section Properties 01 - General, Part 1 of 4								
SectionName	Material	Shape	t3 mm	t2 mm	tf mm	tw mm	t2b mm	tfb mm
FSEC1	A992Fy50	I/Wide Flange	304,8	127,	9,652	6,35	127,	9,652
RIGID	A992Fy50	Circle	250,					

Table 12: Frame Section Properties 01 - General, Part 2 of 4

Table 12: Frame Section Properties 01 - General, Part 2 of 4							
SectionName	Area mm2	TorsConst mm4	I33 mm4	I22 mm4	I23 mm4	AS2 mm2	AS3 mm2
FSEC1	4264,51	96511,77	65724174,7	3301257,17	0,	1935,48	2043,01
RIGID	49087,39	383495197,	191747598,5	191747598,5	0,	44178,65	44178,65

Table 12: Frame Section Properties 01 - General, Part 3 of 4

Table 12: Frame Section Properties 01 - General, Part 3 of 4						
SectionName	S33 mm3	S22 mm3	Z33 mm3	Z22 mm3	R33 mm	R22 mm
FSEC1	431260,99	51988,3	491187,5	80716,53	124,145	27,823
RIGID	1533980,79	1533980,79	2604166,67	2604166,67	62,5	62,5

Table 12: Frame Section Properties 01 - General, Part 4 of 4

Table 12: Frame Section Properties 01 - General, Part 4 of 4								
SectionName	AMod	A2Mod	A3Mod	JMod	I2Mod	I3Mod	MMod	WMod
FSEC1	1,	1,	1,	1,	1,	1,	1,	1,
RIGID	1000,	1000,	1000,	1000,	1000,	1000,	0,	0,

Figure A.13 : Analysis Report of Cable-Net Structure, sheet 8.

3.2. Cables

Table 13: Cable Section Definitions, Part 1 of 2

Table 13: Cable Section Definitions, Part 1 of 2						
CableSect	Material	Diameter mm	Area mm2	TorsConst mm4	I mm4	AS mm2
CAB1	Cable	16,	201,06	6433,98	3216,99	180,96
CS12	FLC2	10,461	85,95	1175,74	587,87	77,36
CS14	FLC2	12,205	116,99	2178,3	1089,15	105,29
FLC16	FLC	14,712	170,	4599,58	2299,79	153,
OSS12	FLC	10,585	88,	1232,5	616,25	79,2

Table 13: Cable Section Definitions, Part 2 of 2

Table 13: Cable Section Definitions, Part 2 of 2								
CableSect	AMod	A2Mod	A3Mod	JMod	I2Mod	I3Mod	MMod	WMod
CAB1	16,	1,	1,	1,	1,	1,	0,014	0,14
CS12	1,	1,	1,	1,	1,	1,	1,	1,
CS14	1,	1,	1,	1,	1,	1,	1,	1,
FLC16	1,	1,	1,	1,	1,	1,	1,	1,
OSS12	1,	1,	1,	1,	1,	1,	1,	1,

3.3. Areas

Table 14: Area Section Properties, Part 1 of 3

Table 14: Area Section Properties, Part 1 of 3							
Section	Material	AreaType	Type	DrillDOF	Thickness mm	BendThick mm	F11Mod
ASEC1	4000Psi	Shell	Shell-Thin	Yes	250,	250,	1,
CAM	Glass	Shell	Shell-Thin	Yes	250,	250,	1,
FICT	FICTIVE	Shell	Shell-Thin	Yes	0,1	0,1	1,

Figure A.14 : Analysis Report of Cable-Net Structure, sheet 9.

Table 14: Area Section Properties, Part 2 of 3

Table 14: Area Section Properties, Part 2 of 3							
Section	F22Mod	F12Mod	M11Mod	M22Mod	M12Mod	V13Mod	V23Mod
ASEC1	1,	1,	1,	1,	1,	1,	1,
CAM	1,	1,	1,	1,	1,	1,	1,
FICT	1,	1,	1,	1,	1,	1,	1,

Table 14: Area Section Properties, Part 3 of 3

Table 14: Area Section Properties, Part 3 of 3		
Section	MMod	WMod
ASEC1	1,	1,
CAM	1,	1,
FICT	1,	1,

3.4. Solids

Table 15: Solid Property Definitions

Table 15: Solid Property Definitions				
SolidProp	Material	MatAngleA Degrees	MatAngleB Degrees	MatAngleC Degrees
Solid1	4000Psi	0,	0,	0,

4. Load patterns

This section provides loading information as applied to the model.

4.1. Definitions

Table 16: Load Pattern Definitions

Table 16: Load Pattern Definitions			
LoadPat	DesignType	SelfWtMult	AutoLoad
DEAD	Dead	1,	
WIND+	Wind	0,	None
EQX	Quake	0,	USER COEFF

Figure A.15 : Analysis Report of Cable-Net Structure, sheet 10.

Table 18: Load Case Definitions, Part 1 of 2

Case	Type	InitialCond	ModalCase	BaseCase	MassSource	DesActOpt
WIND-	NonStatic	Zero				Prog Det
SDL	NonStatic	Zero				Prog Det
PR+D	NonStatic	Zero				Prog Det
LC01	NonStatic	Zero				Prog Det
LC02	NonStatic	Zero				Prog Det
LC03	NonStatic	Zero				Prog Det
LC04	NonStatic	Zero				Prog Det
LC05	NonStatic	Zero				Prog Det
LC06	NonStatic	Zero				Prog Det
LC07	NonStatic	Zero				Prog Det
LC08	NonStatic	Zero				Prog Det
LC09	NonStatic	Zero				Prog Det
LC10	NonStatic	Zero				Prog Det
LC11	NonStatic	Zero				Prog Det
LC12	NonStatic	Zero				Prog Det
LC13	NonStatic	Zero				Prog Det
LC14	NonStatic	Zero				Prog Det
LC15	NonStatic	Zero				Prog Det

Table 18: Load Case Definitions, Part 2 of 2

Table 18: Load Case Definitions, Part 2 of 2

Case	DesignAct
DEAD	Non-Composite
MODAL	Other
WIND	Short-Term Composite
EQX	Short-Term Composite
EQY	Short-Term Composite
TEMP+	Short-Term Composite
PR	Long-Term Composite
TEMP-	Short-Term Composite
WIND-	Short-Term Composite
SDL	Long-Term Composite
PR+D	Non-Composite
LC01	Non-Composite
LC02	Non-Composite

Figure A.16 : Analysis Report of Cable-Net Structure, sheet 11.

Table 16: Load Pattern Definitions

LoadPat	DesignType	SelfWtMult	AutoLoad
EQY	Quake	0,	USER COEFF
TEMP+	Temperature	0,	
PR	Prestress	0,	
TEMP-	Temperature	0,	None
WIND-	Wind	0,	
SDL	Super Dead	0,	

4.2. Auto seismic loading

Table 17: Auto Seismic - User Coefficient

Table 17: Auto Seismic - User Coefficient

LoadPat	Dir	PercentEcc	C	K	WeightUsed KN	BaseShear KN
EQY	Y	0,05	0,25	1,	0,343	0,086
EQX	X	0,05	0,25	1,	0,376	0,094

5. Load cases

This section provides load case information.

5.1. Definitions

Table 18: Load Case Definitions, Part 1 of 2

Table 18: Load Case Definitions, Part 1 of 2

Case	Type	InitialCond	ModalCase	BaseCase	MassSource	DesActOpt
DEAD	NonStatic	Zero				Prog Det
MODAL	LinModal	PR+D				Prog Det
WIND	NonStatic	Zero				Prog Det
EQX	NonStatic	Zero				Prog Det
EQY	NonStatic	Zero				Prog Det
TEMP+	NonStatic	Zero				Prog Det
PR	NonStatic	Zero				Prog Det
TEMP-	NonStatic	Zero				Prog Det

Figure A.17 : Analysis Report of Cable-Net Structure, sheet 12.

Table 18: Load Case Definitions, Part 2 of 2

Case	DesignAct
LC03	Non-Composite
LC04	Non-Composite
LC05	Non-Composite
LC06	Non-Composite
LC07	Non-Composite
LC08	Non-Composite
LC09	Non-Composite
LC10	Non-Composite
LC11	Non-Composite
LC12	Non-Composite
LC13	Non-Composite
LC14	Non-Composite
LC15	Non-Composite

5.2. Static case load assignments

Table 19: Case - Static 1 - Load Assignments

Table 19: Case - Static 1 - Load Assignments			
Case	LoadType	LoadName	LoadSF
DEAD	Load pattern	DEAD	1,
WIND	Load pattern	WIND+	1,
EQX	Load pattern	EQX	1,
EQY	Load pattern	EQY	1,
TEMP+	Load pattern	TEMP+	1,
PR	Load pattern	PR	1,
TEMP-	Load pattern	TEMP-	1,
WIND-	Load pattern	WIND-	1,
SDL	Load pattern	SDL	1,
PR+D	Load pattern	DEAD	1,
PR+D	Load pattern	SDL	1,
PR+D	Load pattern	PR	1,
LC01	Load pattern	DEAD	1,
LC01	Load pattern	SDL	1,
LC01	Load pattern	PR	1,

Figure A.18 : Analysis Report of Cable-Net Structure, sheet 13.

Table 19: Case - Static 1 - Load Assignments

Case	LoadType	LoadName	LoadSF
LC02	Load pattern	DEAD	1,
LC02	Load pattern	SDL	1,
LC02	Load pattern	PR	1,
LC02	Load pattern	TEMP+	1,
LC03	Load pattern	DEAD	1,
LC03	Load pattern	SDL	1,
LC03	Load pattern	PR	1,
LC03	Load pattern	TEMP-	1,
LC04	Load pattern	DEAD	1,
LC04	Load pattern	SDL	1,
LC04	Load pattern	PR	1,
LC04	Load pattern	WIND+	1,
LC04	Load pattern	TEMP+	1,
LC05	Load pattern	DEAD	1,
LC05	Load pattern	SDL	1,
LC05	Load pattern	PR	1,
LC05	Load pattern	WIND+	1,
LC05	Load pattern	TEMP-	1,
LC06	Load pattern	DEAD	1,
LC06	Load pattern	SDL	1,
LC06	Load pattern	PR	1,
LC06	Load pattern	WIND-	1,
LC06	Load pattern	TEMP+	1,
LC07	Load pattern	DEAD	1,
LC07	Load pattern	SDL	1,
LC07	Load pattern	PR	1,
LC07	Load pattern	WIND-	1,
LC07	Load pattern	TEMP-	1,
LC08	Load pattern	DEAD	1,
LC08	Load pattern	SDL	1,
LC08	Load pattern	PR	1,
LC08	Load pattern	EQX	1,
LC08	Load pattern	EQY	0,3
LC09	Load pattern	DEAD	1,
LC09	Load pattern	SDL	1,
LC09	Load pattern	PR	1,
LC09	Load pattern	EQX	1,

Table 19: Case - Static 1 - Load Assignments

Case	LoadType	LoadName	LoadSF
LC09	Load pattern	EQY	-0,3
LC10	Load pattern	DEAD	1,
LC10	Load pattern	SDL	1,
LC10	Load pattern	PR	1,
LC10	Load pattern	EQX	-1,
LC10	Load pattern	EQY	0,3
LC11	Load pattern	DEAD	1,
LC11	Load pattern	SDL	1,
LC11	Load pattern	PR	1,
LC11	Load pattern	EQX	-1,
LC11	Load pattern	EQY	-0,3
LC12	Load pattern	DEAD	1,
LC12	Load pattern	SDL	1,
LC12	Load pattern	PR	1,
LC12	Load pattern	EQX	0,3
LC12	Load pattern	EQY	1,
LC13	Load pattern	DEAD	1,
LC13	Load pattern	SDL	1,
LC13	Load pattern	PR	1,
LC13	Load pattern	EQX	-0,3
LC13	Load pattern	EQY	1,
LC14	Load pattern	DEAD	1,
LC14	Load pattern	SDL	1,
LC14	Load pattern	PR	1,
LC14	Load pattern	EQX	0,3
LC14	Load pattern	EQY	-1,
LC15	Load pattern	DEAD	1,
LC15	Load pattern	SDL	1,
LC15	Load pattern	PR	1,
LC15	Load pattern	EQX	-0,3
LC15	Load pattern	EQY	-1,

Figure A.19 : Analysis Report of Cable-Net Structure, sheet 14.

5.3. Response spectrum case load assignments

Table 20: Function - Response Spectrum - User

Table 20: Function - Response Spectrum - User

Name	Period Sec	Accel	FuncDamp
UNIFRS	0,	1,	0,05
UNIFRS	1,	1,	

6. Load combinations

This section provides load combination information.

Table 21: Combination Definitions

Table 21: Combination Definitions

ComboName	ComboType	CaseName	ScaleFactor
LC-01	Linear Add	LC01	1,
LC-02	Linear Add	LC02	1,
LC-03	Linear Add	LC03	1,
LC-04	Linear Add	LC04	1,
LC-05	Linear Add	LC05	1,
LC-06	Linear Add	LC06	1,
LC-07	Linear Add	LC07	1,
LC-08	Linear Add	LC08	1,
LC-09	Linear Add	LC09	1,
LC-10	Linear Add	LC10	1,
LC-11	Linear Add	LC11	1,
LC-12	Linear Add	LC12	1,
LC-13	Linear Add	LC13	1,
LC-14	Linear Add	LC14	1,
LC-15	Linear Add	LC15	1,

Figure A.20 : Analysis Report of Cable-Net Structure, sheet 16.

7. Structure results

This section provides structure results, including items such as structural periods and base reactions.

7.1. Mass summary

Table 22: Assembled Joint Masses, Part 1 of 2

Table 22: Assembled Joint Masses, Part 1 of 2								
Joint	MassSource	U1	U2	U3	R1	R2	R3	CenterX
		KN-s2/mm	KN-s2/mm	KN-s2/mm	KN-mm-s2	KN-mm-s2	KN-mm-s2	mm
1	MSSSRC1	1,020E-06	1,020E-06	1,020E-06	0,	0,	0,	1223,
2	MSSSRC1	2,981E-06	2,981E-06	2,981E-06	0,	0,	0,	1223,
3	MSSSRC1	2,890E-06	2,890E-06	2,890E-06	0,	0,	0,	1223,
4	MSSSRC1	3,005E-06	3,005E-06	3,005E-06	0,	0,	0,	1223,
5	MSSSRC1	1,044E-06	1,044E-06	1,044E-06	0,	0,	0,	1223,
6	MSSSRC1	5,615E-07	5,615E-07	5,615E-07	0,	0,	0,	0,
7	MSSSRC1	2,890E-06	2,890E-06	2,890E-06	0,	0,	0,	2247,
8	MSSSRC1	2,890E-06	2,890E-06	2,890E-06	0,	0,	0,	3271,
9	MSSSRC1	2,981E-06	2,981E-06	2,981E-06	0,	0,	0,	4295,
10	MSSSRC1	5,615E-07	5,615E-07	5,615E-07	0,	0,	0,	5518,
11	MSSSRC1	1,020E-06	1,020E-06	1,020E-06	0,	0,	0,	2247,
12	MSSSRC1	2,799E-06	2,799E-06	2,799E-06	0,	0,	0,	2247,
13	MSSSRC1	2,913E-06	2,913E-06	2,913E-06	0,	0,	0,	2247,
14	MSSSRC1	1,044E-06	1,044E-06	1,044E-06	0,	0,	0,	2247,
15	MSSSRC1	1,020E-06	1,020E-06	1,020E-06	0,	0,	0,	3271,
16	MSSSRC1	2,799E-06	2,799E-06	2,799E-06	0,	0,	0,	3271,
17	MSSSRC1	2,913E-06	2,913E-06	2,913E-06	0,	0,	0,	3271,
18	MSSSRC1	1,044E-06	1,044E-06	1,044E-06	0,	0,	0,	3271,
19	MSSSRC1	1,020E-06	1,020E-06	1,020E-06	0,	0,	0,	4295,
20	MSSSRC1	2,890E-06	2,890E-06	2,890E-06	0,	0,	0,	4295,
21	MSSSRC1	3,005E-06	3,005E-06	3,005E-06	0,	0,	0,	4295,
22	MSSSRC1	1,044E-06	1,044E-06	1,044E-06	0,	0,	0,	4295,
23	MSSSRC1	5,615E-07	5,615E-07	5,615E-07	0,	0,	0,	0,
24	MSSSRC1	5,615E-07	5,615E-07	5,615E-07	0,	0,	0,	5518,
25	MSSSRC1	5,615E-07	5,615E-07	5,615E-07	0,	0,	0,	0,
26	MSSSRC1	5,615E-07	5,615E-07	5,615E-07	0,	0,	0,	5518,
27	MSSSRC1	0,	0,	0,	0,	0,	0,	0,
28	MSSSRC1	0,	0,	0,	0,	0,	0,	5518,

Figure A.21 : Analysis Report of Cable-Net Structure, sheet 17.

Table 22: Assembled Joint Masses, Part 1 of 2

Joint	MassSource	U1 KN-s2/mm	U2 KN-s2/mm	U3 KN-s2/mm	R1 KN-mm-s2	R2 KN-mm-s2	R3 KN-mm-s2	CenterX mm
29	MSSSRC1	0,	0,	0,	0,	0,	0,	0,
30	MSSSRC1	0,	0,	0,	0,	0,	0,	5518,
SumAccelUX	MSSSRC1	0,000047	0,	0,	0,	0,	0,	2759,
SumAccelUY	MSSSRC1	0,	0,000047	0,	0,	0,	0,	2759,
SumAccelUZ	MSSSRC1	0,	0,	0,000047	0,	0,	0,	2759,

Table 22: Assembled Joint Masses, Part 2 of 2

Table 22: Assembled Joint Masses, Part 2 of 2

Joint	MassSource	CenterY mm	CenterZ mm
1	MSSSRC1	0,	8543,
2	MSSSRC1	0,	6321,
3	MSSSRC1	0,	4297,
4	MSSSRC1	0,	2273,
5	MSSSRC1	0,	0,
6	MSSSRC1	0,	6321,
7	MSSSRC1	0,	6321,
8	MSSSRC1	0,	6321,
9	MSSSRC1	0,	6321,
10	MSSSRC1	0,	6321,
11	MSSSRC1	0,	8543,
12	MSSSRC1	0,	4297,
13	MSSSRC1	0,	2273,
14	MSSSRC1	0,	0,
15	MSSSRC1	0,	8543,
16	MSSSRC1	0,	4297,
17	MSSSRC1	0,	2273,
18	MSSSRC1	0,	0,
19	MSSSRC1	0,	8543,
20	MSSSRC1	0,	4297,
21	MSSSRC1	0,	2273,
22	MSSSRC1	0,	0,
23	MSSSRC1	0,	4297,
24	MSSSRC1	0,	4297,
25	MSSSRC1	0,	2273,

Figure A.22 : Analysis Report of Cable-Net Structure, sheet 18.

Table 22: Assembled Joint Masses, Part 2 of 2

Joint	MassSource	CenterY mm	CenterZ mm
26	MSSSRC1	0,	2273,
27	MSSSRC1	0,	8543,
28	MSSSRC1	0,	8543,
29	MSSSRC1	0,	0,
30	MSSSRC1	0,	0,
SumAccelUX	MSSSRC1	0,	4279,82
SumAccelUY	MSSSRC1	0,	4279,82
SumAccelUZ	MSSSRC1	0,	4279,82

7.2. Modal results

Table 23: Modal Participating Mass Ratios

Table 23: Modal Participating Mass Ratios								
OutputCase	StepNum	Period Sec	UX	UY	UZ	SumUX	SumUY	SumUZ
MODAL	1,	0,075222	0,	0,94	0,	0,	0,94	0,
MODAL	2,	0,051842	0,	4,476E-05	0,	0,	0,94	0,
MODAL	3,	0,047611	0,	0,	0,	0,	0,94	0,
MODAL	4,	0,040966	0,	1,999E-02	0,	0,	0,96	0,
MODAL	5,	0,039855	0,	0,	0,	0,	0,96	0,
MODAL	6,	0,035359	0,	3,689E-02	0,	0,	1,	0,
MODAL	7,	0,034196	0,	0,	0,	0,	1,	0,
MODAL	8,	0,031893	0,	1,089E-05	0,	0,	1,	0,
MODAL	9,	0,02982	0,	0,	0,	0,	1,	0,
MODAL	10,	0,028672	0,	4,580E-04	0,	0,	1,	0,
MODAL	11,	0,027677	0,	0,	0,	0,	1,	1,243E-2 0
MODAL	12,	0,025411	0,	0,	0,	0,	1,	1,278E-2 0

Figure A.23 : Analysis Report of Cable-Net Structure, sheet 19.

Table 25: Preferences - Steel Design - AISC-ASD89, Part 2 of 2

Table 25: Preferences - Steel Design - AISC-ASD89, Part 2 of 2

LLRat	TotalRat	NetRat	CmOption	CmTol	CbOption	CbTol
360,	240,	240,	Program Determined		Program Determined	

12.2. Concrete design

Table 26: Preferences - Concrete Design - ACI 318-14, Part 1 of 2

Table 26: Preferences - Concrete Design - ACI 318-14, Part 1 of 2

THDesign	NumCurves	NumPoints	MinEccen	PatLLF	UFLimit	SeisCat	Rho	Sds
Envelopes	24	11	Yes	0,75	0,95	D	1,	0,5

Table 26: Preferences - Concrete Design - ACI 318-14, Part 2 of 2

Table 26: Preferences - Concrete Design - ACI 318-14, Part 2 of 2

PhiT	PhiCTied	PhiCSpiral	PhiV	PhiVSeismic	PhiVJoint
0,9	0,65	0,75	0,75	0,6	0,85

12.3. Aluminum design

Table 27: Preferences - Aluminum Design - AA-ASD 2000

Table 27: Preferences - Aluminum Design - AA-ASD 2000

FrameType	SRatioLimit	LatFact	UseLatFact
Moment Frame	1,	1,333333	No

Figure A.24 : Analysis Report of Cable-Net Structure, sheet 20.

8. Joint results

This section provides joint results, including items such as displacements and reactions.

9. Frame results

This section provides frame force results.

10. Area results

This section provides area results, including items such as forces and stresses.

11. Material take-off

This section provides a material take-off.

Table 24: Material List 2 - By Section Property

Table 24: Material List 2 - By Section Property				
Section	ObjectType	NumPieces	TotalLength mm	TotalWeight KN
CS14	Cable	31	50726,	0,457
FICT	Area			0,

12. Design preferences

This section provides the design preferences for each type of design, which typically include material reduction factors, framing type, stress ratio limit, deflection limits, and other code specific items.

12.1. Steel design

Table 25: Preferences - Steel Design - AISC-ASD89, Part 1 of 2

Table 25: Preferences - Steel Design - AISC-ASD89, Part 1 of 2						
FrameType	PatLLF	SRatioLimit	LatFactWind	LatFactSeis	DLRat	SDLAndLLRat
Braced Frame	0,75	0,95	1,15	1,33	120	120,

Figure A.25 : Analysis Report of Cable-Net Structure, sheet 21.

12.4. Cold formed design

Table 28: Preferences - Cold Formed Design - AISI-ASD96

Table 28: Preferences - Cold Formed Design - AISI-ASD96								
FrameType	SRatioLimit	Omega BS	Omega BUS	Omega BLTB	Omega VS	Omega VNS	Omega T	Omega C
Braced Frame	1,	1,67	1,67	1,67	1,67	1,5	1,67	1,8

Figure A.26 : SAP 2000 Analyze Report of Cable-Net Structure, sheet 22.

APPENDIX C

Model geometry

This section provides model geometry information, including items such as joint coordinates, joint restraints, and element connectivity.

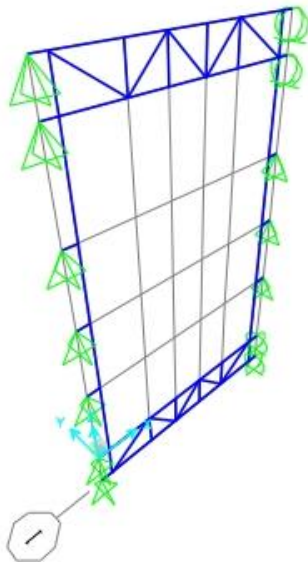


Figure 1: Finite element model

Joint coordinates

Table 1: Joint Coordinates

Table 1: Joint Coordinates					
Joint	CoordSys	CoordType	GlobalX	GlobalY	GlobalZ
		pe	mm	mm	mm
45	GLOBAL	Cartesian	0,	0,	9918,
46	GLOBAL	Cartesian	6664,	0,	9918,
47	GLOBAL	Cartesian	0,	0,	8918,
48	GLOBAL	Cartesian	6664,	0,	8918,
49	GLOBAL	Cartesian	0,	0,	0,
50	GLOBAL	Cartesian	6664,	0,	0,
51	GLOBAL	Cartesian	0,	0,	-1000,
52	GLOBAL	Cartesian	6664,	0,	-1000,
53	GLOBAL	Cartesian	356,	0,	8918,
54	GLOBAL	Cartesian	356,	0,	0,
55	GLOBAL	Cartesian	6308,	0,	8918,
56	GLOBAL	Cartesian	6308,	0,	0,
58	GLOBAL	Cartesian	356,	0,	9918,
59	GLOBAL	Cartesian	1796,	0,	8918,

Figure A.27 : Analysis Report of Steel Frame, sheet 1.

Material properties

This section provides material property information for materials used in the model.

Table 6: Material Properties 02 - Basic Mechanical Properties

Table 6: Material Properties 02 - Basic Mechanical Properties						
Material	UnitWeight	UnitMass	E1	G12	U12	A1
	KN/mm3	KN-s2/mm4	KN/mm2	KN/mm2		1/C
4000Psi	2,3563E-08	2,4028E-12	24,85558	10,35649	0,2	9,9000E-06
A416Gr270	7,6973E-08	7,8490E-12	196,5006			1,1700E-05
A992Fy50	7,6973E-08	7,8490E-12	199,94798	76,90307	0,3	1,1700E-05
FICT	0,0000E+00	0,0000E+00	1,000E-05	3,846E-06	0,3	1,1700E-05
FLC	7,6973E-08	7,8490E-12	166,	63,84615	0,3	1,1700E-05

Table 7: Material Properties 03a - Steel Data

Table 7: Material Properties 03a - Steel Data			
Material	Fy	Fu	FinalSlope
	KN/mm2	KN/mm2	
A992Fy50	0,34474	0,44816	-0,1

Table 8: Material Properties 03b - Concrete Data

Table 8: Material Properties 03b - Concrete Data			
Material	Fc	eFc	FinalSlope
	KN/mm2	KN/mm2	
4000Psi	0,02758	0,02758	-0,1

Table 9: Material Properties 03f - Tendon Data

Table 9: Material Properties 03f - Tendon Data			
Material	Fy	Fu	FinalSlope
	KN/mm2	KN/mm2	
A416Gr270	1,68991	1,86158	-0,1

Figure A.28 : Analysis Report of Steel Frame, sheet 2.

Table 1: Joint Coordinates

Joint	CoordSys	CoordType	GlobalX	GlobalY	GlobalZ
			mm	mm	mm
60	GLOBAL	Cartesian	2820,	0,	9918,
61	GLOBAL	Cartesian	3844,	0,	8918,
62	GLOBAL	Cartesian	4868,	0,	9918,
63	GLOBAL	Cartesian	6308,	0,	9918,
64	GLOBAL	Cartesian	1796,	0,	9918,
65	GLOBAL	Cartesian	3844,	0,	9918,
66	GLOBAL	Cartesian	4868,	0,	8918,
67	GLOBAL	Cartesian	2820,	0,	8918,
68	GLOBAL	Cartesian	356,	0,	-1000,
69	GLOBAL	Cartesian	1796,	0,	0,
70	GLOBAL	Cartesian	2820,	0,	-1000,
71	GLOBAL	Cartesian	3844,	0,	0,
72	GLOBAL	Cartesian	4868,	0,	-1000,
73	GLOBAL	Cartesian	6308,	0,	-1000,
74	GLOBAL	Cartesian	4868,	0,	0,
75	GLOBAL	Cartesian	3844,	0,	-1000,
76	GLOBAL	Cartesian	2820,	0,	0,
77	GLOBAL	Cartesian	1796,	0,	-1000,
78	GLOBAL	Cartesian	356,	0,	6483,
79	GLOBAL	Cartesian	0,	0,	6483,
80	GLOBAL	Cartesian	356,	0,	2435,
81	GLOBAL	Cartesian	0,	0,	2435,
82	GLOBAL	Cartesian	356,	0,	4459,
83	GLOBAL	Cartesian	0,	0,	4459,
84	GLOBAL	Cartesian	6308,	0,	2435,
85	GLOBAL	Cartesian	6664,	0,	2435,
86	GLOBAL	Cartesian	6308,	0,	4459,
87	GLOBAL	Cartesian	6664,	0,	4459,
88	GLOBAL	Cartesian	6308,	0,	6483,
89	GLOBAL	Cartesian	6664,	0,	6483,

Joint restraints**Table 2: Joint Restraint Assignments**

Table 2: Joint Restraint Assignments						
Joint	U1	U2	U3	R1	R2	R3
45	Yes	Yes	Yes	No	No	No

Figure A.29 : Analysis Report of Steel Frame, sheet 3.

Table 2: Joint Restraint Assignments

Joint	U1	U2	U3	R1	R2	R3
46	No	No	Yes	No	No	No
47	Yes	Yes	Yes	No	No	No
48	No	No	Yes	No	No	No
49	Yes	Yes	Yes	No	No	No
50	No	No	Yes	No	No	No
51	Yes	Yes	Yes	No	No	No
52	No	No	Yes	No	No	No
79	Yes	Yes	Yes	No	No	No
81	Yes	Yes	Yes	No	No	No
83	Yes	Yes	Yes	No	No	No
85	Yes	Yes	Yes	No	No	No
87	Yes	Yes	Yes	No	No	No
89	Yes	Yes	Yes	No	No	No

Table 5: Frame Release Assignments 1 - General, Part 1 of 2**Table 5: Frame Release Assignments 1 - General, Part 1 of 2**

Frame	PI	V2I	V3I	TI	M2I	M3I
42	No	No	No	No	Yes	Yes
43	No	No	No	No	Yes	Yes

Table 5: Frame Release Assignments 1 - General, Part 2 of 2**Table 5: Frame Release Assignments 1 - General, Part 2 of 2**

Frame	PJ	V2J	V3J	TJ	M2J	M3J
42	No	No	No	No	Yes	Yes
43	No	No	No	No	Yes	Yes

Figure A.30 : Analysis Report of Steel Frame, sheet 4.

Section properties

This section provides section property information for objects used in the model.

Frames

Table 10: Frame Section Properties 01 - General, Part 1 of 4

Table 10: Frame Section Properties 01 - General, Part 1 of 4

SectionName	Material	Shape	t3	t2	tf	tw	t2b	tfb
			mm	mm	mm	mm	mm	mm
FSEC1	A992Fy50	I/Wide Flange	304,8	127,	9,652	6,35	127,	9,652
TUBO100 X100X10	A992Fy50	Box/Tube	100,	100,	10,	10,		
TUBO100 X100X12.5	A992Fy50	Box/Tube	100,	100,	12,5	12,5		
TUBO100 X100X8	A992Fy50	Box/Tube	100,	100,	8,	8,		
TUBO100 X50X8	A992Fy50	Box/Tube	100,	50,	8,	8,		
TUBO100 X70X8	A992Fy50	Box/Tube	100,	70,	8,	8,		
TUBO120 X120X10	A992Fy50	Box/Tube	120,	120,	10,	10,		
TUBO120 X120X20	A992Fy50	Box/Tube	120,	120,	20,	20,		
TUBO120 X120X22.2	A992Fy50	Box/Tube	120,	120,	22,2	22,2		
TUBO140 X140X12.5	A992Fy50	Box/Tube	140,	140,	12,5	12,5		

Figure A.31 : Analysis Report of Steel Frame, sheet 5.

Load patterns

This section provides loading information as applied to the model.

Table 14: Load Pattern Definitions

Table 14: Load Pattern Definitions			
LoadPat	DesignType	SelfWtM ult	AutoLoad
DEAD	Dead	1,	
TEMP+	Temperature	0,	
TEMP-	Temperature	0,	
LIVE	Live	0,	
WIND+	Wind	0,	None
WIND-	Wind	0,	None

Load cases

This section provides load case information.

Definitions

Table 15: Load Case Definitions, Part 1 of 2

Table 15: Load Case Definitions, Part 1 of 2						
Case	Type	InitialCond	ModalCase	BaseCase	MassSou rce	DesActO pt
DEAD	LinStatic	Zero				Prog Det
MODAL	LinModal	Zero				Prog Det
T+	LinStatic	Zero				Prog Det
T-	LinStatic	Zero				Prog Det
LIVE	LinStatic	Zero				Prog Det
W+	LinStatic	Zero				Prog Det
W-	LinStatic	Zero				Prog Det
CASE01	LinStatic	Zero				Prog Det
CASE02	LinStatic	Zero				Prog Det
CASE03	LinStatic	Zero				Prog Det
CASE04	LinStatic	Zero				Prog Det
CASE05	LinStatic	Zero				Prog Det

Figure A.32 : Analysis Report of Steel Frame, sheet 6.

Table 15: Load Case Definitions, Part 2 of 2

Table 15: Load Case Definitions, Part 2 of 2

Case	DesignAct
DEAD	Non-Composite
MODAL	Other
T+	Short-Term Composite
T-	Short-Term Composite
LIVE	Short-Term Composite
W+	Short-Term Composite
W-	Short-Term Composite
CASE01	Non-Composite
CASE02	Non-Composite
CASE03	Non-Composite
CASE04	Non-Composite
CASE05	Non-Composite

Static case load assignments

Table 16: Case - Static 1 - Load Assignments

Table 16: Case - Static 1 - Load Assignments

Case	LoadType	LoadName	LoadSF
DEAD	Load pattern	DEAD	1,
T+	Load pattern	TEMP+	1,
T-	Load pattern	TEMP-	1,
LIVE	Load pattern	LIVE	1,
W+	Load pattern	WIND+	1,
W-	Load pattern	WIND-	1,
CASE01	Load pattern	DEAD	1,
CASE01	Load pattern	LIVE	1,
CASE02	Load pattern	DEAD	1,
CASE02	Load pattern	LIVE	1,
CASE02	Load pattern	WIND+	1,
CASE02	Load pattern	TEMP+	1,
CASE03	Load pattern	DEAD	1,
CASE03	Load pattern	LIVE	1,
CASE03	Load pattern	WIND-	1,
CASE03	Load pattern	TEMP+	1,
CASE04	Load pattern	DEAD	1,
CASE04	Load pattern	LIVE	1,

Figure A.33 : Analysis Report of Steel Frame, sheet 7.

Table 16: Case - Static 1 - Load Assignments

Case	LoadType	LoadName	LoadSF
CASE04	Load pattern	WIND+	1,
CASE04	Load pattern	TEMP-	1,
CASE05	Load pattern	DEAD	1,
CASE05	Load pattern	LIVE	1,
CASE05	Load pattern	WIND-	1,
CASE05	Load pattern	TEMP-	1,

Response spectrum case load assignments**Table 17: Function - Response Spectrum - User****Table 17: Function - Response Spectrum - User**

Name	Period Sec	Accel	FuncDamp
UNIFRS	0,	1,	0,05
UNIFRS	1,	1,	

Load combinations

This section provides load combination information.

Table 18: Combination Definitions**Table 18: Combination Definitions**

ComboName	ComboType	CaseName	ScaleFactor
D	Linear Add	DEAD	1,
DL	Linear Add	DEAD	1,
DL		LIVE	1,
COMB01	Linear Add	CASE01	1,
COMB02	Linear Add	CASE02	1,
COMB03	Linear Add	CASE03	1,
COMB05	Linear Add	CASE05	1,
COMB04	Linear Add	CASE04	1,
DSTL1	Linear Add	DEAD	1,
DSTL1		CASE01	1,
DSTL2	Linear Add	DEAD	1,

Figure A.34 : Analysis Report of Steel Frame, sheet 8.

Table 18: Combination Definitions

ComboName	ComboType	CaseName	ScaleFactor
DSTL2		LIVE	1,
DSTL2		CASE01	1,
DSTL3	Linear Add	DEAD	1,
DSTL3		LIVE	1,
DSTL3		CASE01	1,
DSTL3		W+	1,
DSTL4	Linear Add	DEAD	1,
DSTL4		LIVE	1,
DSTL4		CASE01	1,
DSTL4		W+	-1,
DSTL5	Linear Add	DEAD	1,
DSTL5		LIVE	1,
DSTL5		CASE01	1,
DSTL5		W-	1,
DSTL6	Linear Add	DEAD	1,
DSTL6		LIVE	1,
DSTL6		CASE01	1,
DSTL6		W-	-1,
DSTL7	Linear Add	DEAD	1,
DSTL7		CASE01	1,
DSTL7		W+	1,
DSTL8	Linear Add	DEAD	1,
DSTL8		CASE01	1,
DSTL8		W+	-1,

Design summary

This section provides the design summary for each type of design, which highlights the controlling demand/capacity ratio and it's associated combination and location in each member.

13.1. Steel design

Table 31: Steel Design 1 - Summary Data - AISC-ASD89, Part 1 of 2

Table 31: Steel Design 1 - Summary Data - AISC-ASD89, Part 1 of 2

Frame	Location	Combo	DesignSect	DesignType	Ratio	RatioType
	mm					
38	356,	COMB04	TUBO260X 260X12	Beam	0,44575	PMM

Figure A.35 : Analysis Report of Steel Frame, sheet 9.

Table 31: Steel Design 1 - Summary Data - AISC-ASD89, Part 1 of 2

Frame	Location	Combo	DesignSect	DesignType	Ratio	RatioType
	mm					
39	356,	COMB05	TUBO260X 260X12	Beam	0,39001	PMM
40	356,	COMB03	TUBO260X 260X12	Beam	0,361483	PMM
41	356,	COMB04	TUBO260X 260X12	Beam	0,423043	PMM
42	6483,	COMB03	TUBO260X 260X12	Column	0,312581	PMM
43	6483,	COMB03	TUBO260X 260X12	Column	0,435532	PMM
45	0,	COMB05	TUBO100X 100X10	Brace	0,539932	PMM
46	0,	DSTL2	TUBO100X 100X10	Brace	0,344621	PMM
47	1431,28	DSTL2	TUBO100X 100X10	Brace	0,108502	PMM
48	1431,28	DSTL2	TUBO100X 100X10	Brace	0,185338	PMM
49	1753,17	COMB04	TUBO100X 100X10	Brace	0,391065	PMM
50	1000,	COMB05	TUBO100X 100X10	Column	0,683433	PMM
51	0,	COMB04	TUBO100X 100X10	Column	0,665085	PMM
52	1000,	DSTL2	TUBO100X 100X10	Column	0,209797	PMM
53	1000,	DSTL2	TUBO100X 100X10	Column	0,072558	PMM
54	0,	DSTL2	TUBO100X 100X10	Column	0,209097	PMM
55	0,	DSTL2	TUBO100X 100X10	Column	0,209815	PMM
56	1000,	COMB04	TUBO100X 100X10	Column	0,64108	PMM
57	0,	COMB05	TUBO100X 100X10	Brace	0,503907	PMM
58	0,	DSTL2	TUBO100X 100X10	Brace	0,315132	PMM
59	1431,28	DSTL2	TUBO100X 100X10	Brace	0,112836	PMM
60	1431,28	DSTL2	TUBO100X 100X10	Brace	0,17608	PMM

Figure A.36 : Analysis Report of Steel Frame, sheet 10.

Table 31: Steel Design 1 - Summary Data - AISC-ASD89, Part 1 of 2

Frame	Location	Combo	DesignSect	DesignType	Ratio	RatioType
	mm					
61	1753,17	COMB04	TUBO100X 100X10	Brace	0,359917	PMM
62	1000,	COMB05	TUBO100X 100X10	Column	0,655742	PMM
63	0,	DSTL2	TUBO100X 100X10	Column	0,188188	PMM
64	1000,	DSTL2	TUBO100X 100X10	Column	0,081205	PMM
65	0,	DSTL2	TUBO100X 100X10	Column	0,204514	PMM
66	0,	DSTL2	TUBO100X 100X10	Column	0,196235	PMM
67	0,	COMB05	TUBO100X 100X10	Beam	0,440278	PMM
68	0,	COMB05	TUBO100X 100X10	Beam	0,388235	PMM
69	0,	DSTL2	TUBO100X 100X10	Beam	0,300637	PMM
70	0,	DSTL2	TUBO100X 100X10	Beam	0,607985	PMM
71	0,	DSTL2	TUBO100X 100X10	Beam	0,403815	PMM
72	0,	DSTL2	TUBO100X 100X10	Beam	0,716021	PMM

Figure A.37 : Analysis Report of Steel Frame, sheet 11.

APPENDIX D

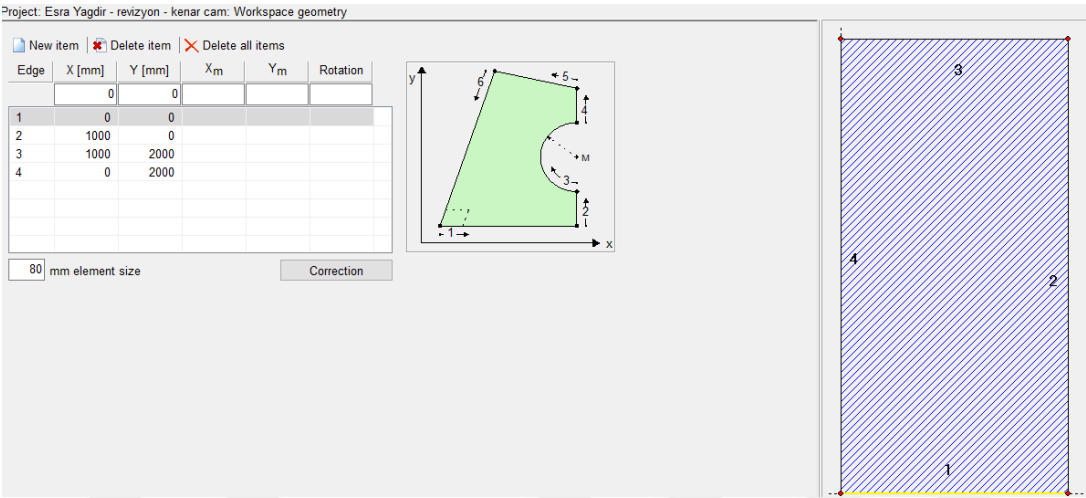


Figure A.38 : FJ Mepla Analysis Report of IGU, sheet 1.

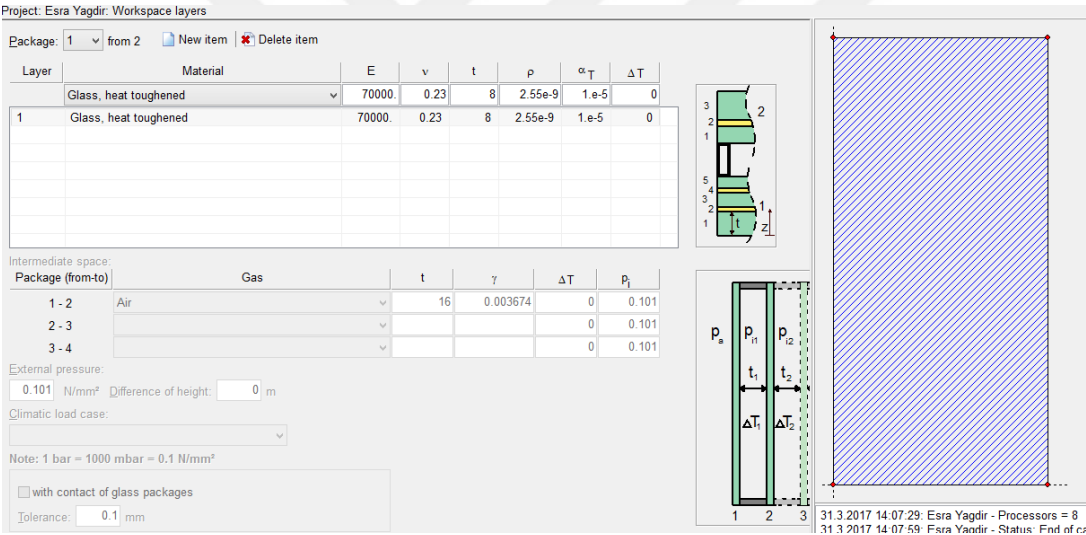


Figure A.39 : FJ Mepla Analysis Report of IGU, sheet 2.

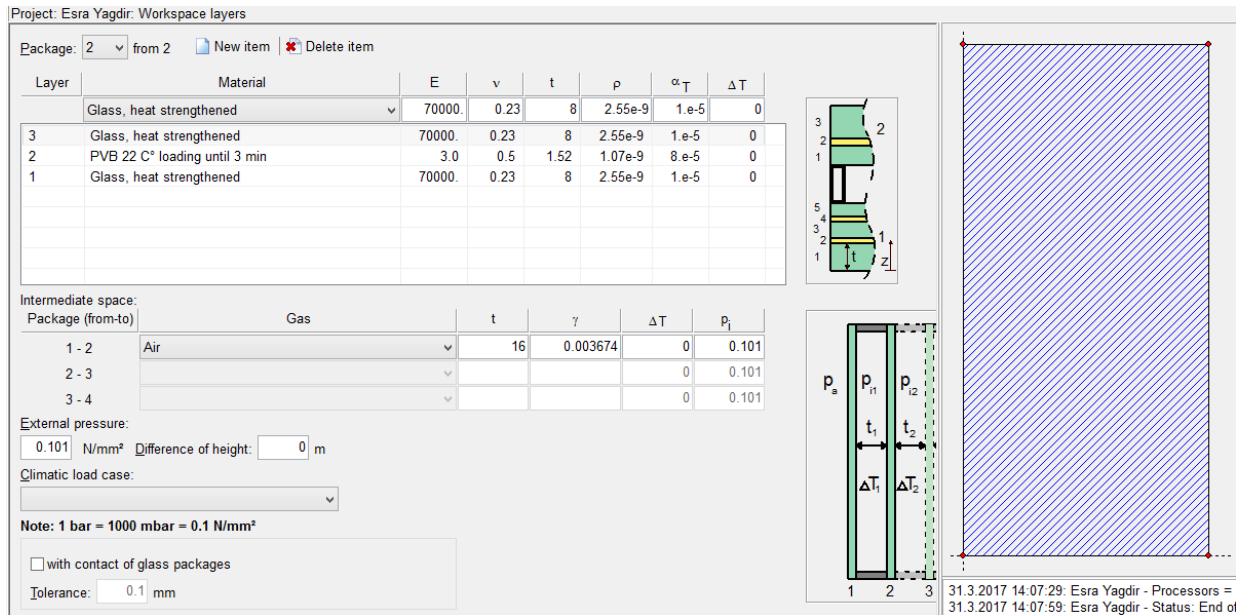
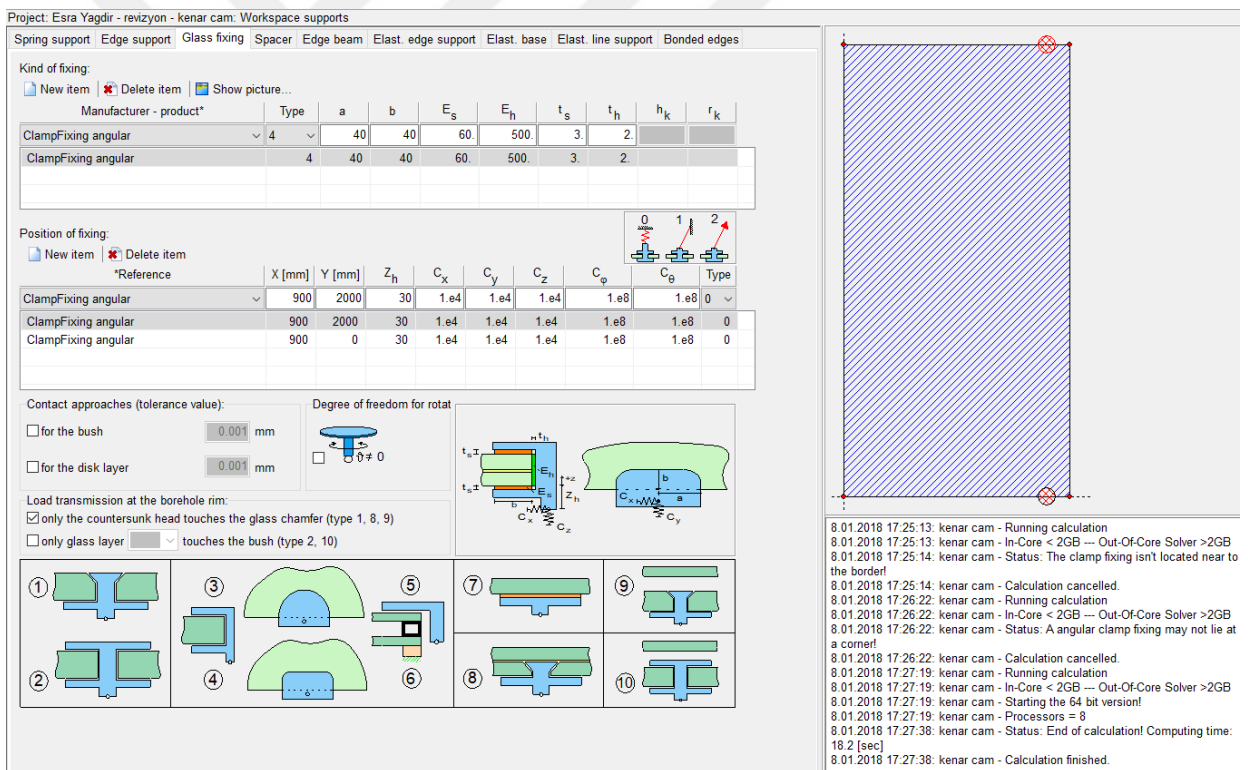


Figure A.40 : FJ Mepla Analysis Report of IGU, sheet 3.



Project: Esra Yagdir: Workspace loads

Face load Concentrated load Pendulum Pressure hit Line load Load cases Border loads

☒ Use load cases

Please choose a Standard/Code. only combination - no proof

New item Delete item Delete all items Open file... Save file...

LC	DW	Wind		Snow		Line		Point		Climate		Shear	Description
		1	2	1	2	1	2	1	2	1	2		
☐	1	1	1	0	0	0	0	1	1	1	1	1	D+Wp+C(Winter)
☐ 12													
☐ 1	1	1	1	0	0	0	0	1	1	1	1	1	D+Wp+C(Winter)
☐ 2	1	1	1	0	0	0	0	1	1	1	1	1	D+Wp+C(Summer)
☐ 3	1	1	1	0	0	0	0	1	1	1	1	1	D+Ws+C(Winter)
☐ 4	1	1	1	0	0	0	0	1	1	1	1	1	D+Ws+C(Summer)
☐ 5	1	0	0	1	0	0	0	0	0	1	1	1	D+L
☐ 6	1	0	0	0	0	1	0	0	0	1	1	1	D+P
☒ 7	1.35	1.5	0	0	0	0	0.9	0.9	1	1.35D+1.5Wp+0.6x1.5C(Winter)			
☒ 8	1.35	1.5	0	0	0	0	0.9	0.9	1	1.35D+1.5Wp+0.6x1.5C(Summer)			
☒ 9	1.35	1.5	0	0	0	0	0.9	0.9	1	1.35D+1.5Ws+0.6x1.5C(Winter)			
☒ 10	1.35	1.5	0	0	0	0	0.9	0.9	1	1.35D+1.5Ws+0.6x1.5C(Summer)			
☒ 11	1.35	0	0	1.5	0	0	0	0	1	1.35D+1.5L			
☒ 12	1.35	0	0	0	0	1.5	0	0	1	1.35D+1.5P			

Wind

☒ Pressure -0.0008

☐ Suction 0.0008

☐ without

☐ Suction 0

☐ Pressure 0

☒ without

Snow

☐ P: 0

☐

P_0 : 0 P_1 : 0

Y_0 : 0 Y_1 : 0

P_0 P_1

Y_0 Y_1

Climate

☒ Winter (default)

☐ Summer (default)

☐ self-defined

☐ without

Proof/Verification:

☐ No proof - only combination

☐ Ultimate Limit State ULS

☒ Servability Limit State SLS

Figure A.42 : FJ Mepla Analysis Report of IGU, sheet 5.

Project: Esra Yagdir: Workspace options

General Verification

Calculation approach:

☐ geometrically non-linear

☒ linear calculation

Convergence settings:

0.1 N force tolerance

☐ Disable automatic

☐ Apply loads in how many steps:

3

Local result outputs:

Package: 1 from 2

New item Delete item

X [mm]	Y [mm]

Equation Solver:

☐ In-Core, IC ☐ Out-of-Core, OOC ☒ IC <2GB or OOC >2GB

Stress results (max. values):

☒ Max. principal stress

☒ Min. principal stress

☐ Von Mises stress

Reaction forces:

☒ Spacer

☒ Elastic line supports

☒ Elastic edge supports

☒ Springs

☒ Beams

☒ Point fixings

☒ Interspace of double-glazing

☒ Bonded edges

Output:

☐ calculate formed volume

Messages: English Protocol: English

Figure A.43 : FJ Mepla Analysis Report of IGU, sheet 6.

Project: Esra Yagdir: Workspace options

General Verification

Preset Code:

DIN18008 - Germany - Height < 1000m

Type of glass assignment:

Package	Type of Glass	LG	Layer 1	Side 1	Layer 2	Side 2	f_k	$f_{k,b}$	γ_M	$k_{mod, standig}$	$k_{mod, mitte}$
4		☐	-	top	-	top					
3		☐	-	top	-	top					
2	Glass, heat strengthened	☒	-	top	-	top	70.	0.	1.5	1.0	1.
1	Glass, heat toughened	☐	-	top	-	top	120.	0.	1.5	1.0	1.

Free glass borders:

☒ 1 ☒ 2 ☒ 3 ☒ 4

Reset

Type of construction:

☐ Line support according to DIN 18008-2, usage of k_c

Deflection limit, SLS:

25 [mm] (e.g.: L/100)

Chord shortening:

☐ Evaluate chord shortening

P1 (x, y): P2 (x, y):

[mm] max. shortening

Figure A.44 : FJ Mepla Analysis Report of IGU, sheet 7.

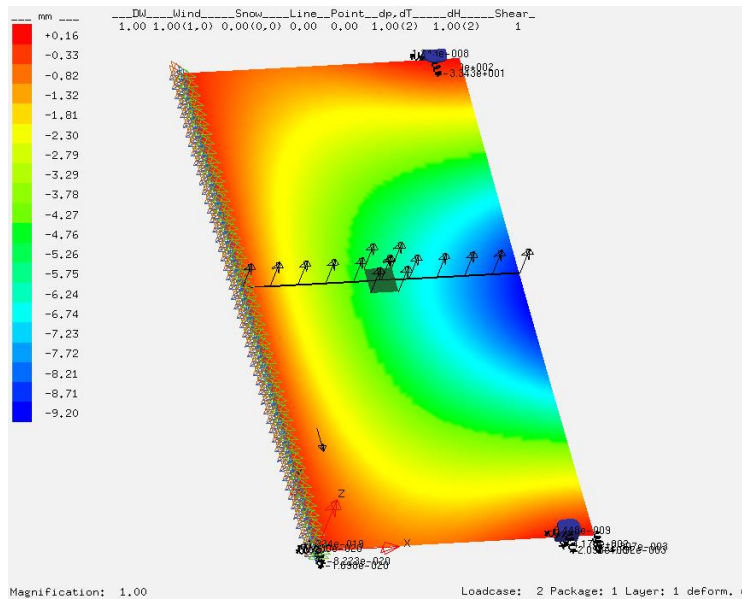


Figure A.45 : FJ Mepla Analysis Report of IGU, sheet 9.

According to Figure A.48, maximum stress of one layer tempered glass is 33,34 MPa. Which is lower that ultimate design stress of tempered glass.

$$33.34 \text{ MPa} < 80 \text{ MPa}.$$

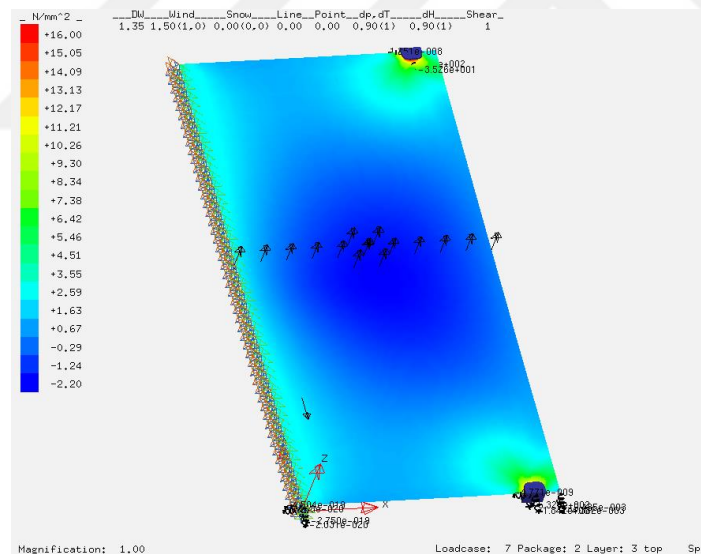


Figure A.46 : FJ Mepla Analysis Report of IGU, sheet 11.

According to Figure A.48, maximum stress of one layer tempered glass is 16.00 MPa. Which is lower that ultimate design stress of tempered glass.

$$16.00 \text{ MPa} < 46.67 \text{ MPa}.$$

Determined Glass Unit Combination:

Outer glass layer + air gap + inner glass layer

8+1.52+8 mm semi-tempered laminated glass + 16 mm air gap + 8 mm tempered glass

APPENDIX E

- Dimensioning the connection plate according to Eurocode 3.

Problem, Sketch, Calculation			Reference	Commentary
Example 3.3.1: No correction 1. System Steel grade: Fe 430 M 30, 6.8 d = 26 mm, $\Delta = 1$ mm $t_1 = 12$ mm, $t = 20$ mm 2. Loading $N_{Ed} = 200.0$ kN (compression force) $M_{Ed} = 1.4(20 \times 6.8 + 2 \times 12) \times 10^3 / 3 = 1.34$ kNm (bending moment in the bolt)				Such a connection is used if no rotation is required.
3. Determination of the pin resistance Geometrical conditions for plate by plate thickness $t = 20$ mm: 3.1 $a = \frac{N_{Ed} \cdot t_{pl}}{2 \cdot f_u \cdot t} = \frac{200 \cdot 10^3 \cdot 20}{2 \cdot 420 \cdot 20} = 52$ mm chequer: $a = 50$ mm $c = \frac{N_{Ed} \cdot t_{pl}}{2 \cdot f_u \cdot t} = \frac{200 \cdot 10^3 \cdot 20}{2 \cdot 420 \cdot 20} = 52$ mm chequer: $c = 40$ mm			[Table 6.5.1]	The bending moment in the bolt is calculated by $M_{Ed} = N_{Ed} \cdot \Delta = 40 + 2(12)/3$
3.2 Shear resistance of the pin $F_{t,Rd} = 0.5 A \cdot \frac{f_u}{\gamma_{M2}} = 0.5 \cdot \frac{200}{1.25} \cdot 10^3 = 80.0$ kN > 250.0 kN			[Table 6.5.1]	Pin connections should be arranged to avoid eccentricity.
3.3 Bearing resistance of plate and pin $F_{b,Rd} = 1.5 \cdot t \cdot d \cdot \frac{f_u}{\gamma_{M2}} = 1.5 \cdot 20 \cdot 26 \cdot \frac{430}{1.25} \cdot 10^{-3} = 237.8$ kN > 200.0 kN			[Table 6.5.1]	
3.4 Bending resistance of pin $M_{t,Rd} = 0.8 W_{pl,y} \cdot \frac{f_u}{\gamma_{M2}} = 0.8 \cdot \frac{200}{1.25} \cdot \frac{430}{1.25} \cdot 10^{-3} = 1.06$ kNm > 1.34 kNm			[Table 6.5.1]	$W_{pl,y} = \pi \cdot d^3 / 32$
3.5 Interaction shear and bending $\left(\frac{M_{Ed}}{M_{t,Rd}} \right)^2 + \left(\frac{F_{t,Ed}}{F_{t,Rd}} \right)^2 = \left(\frac{1.34}{1.06} \right)^2 + \left(\frac{200.0}{80.0} \right)^2 = 0.69 < 1.0$			[Table 6.5.1]	

Figure A.47 : Eurocode 3 DataSheet.

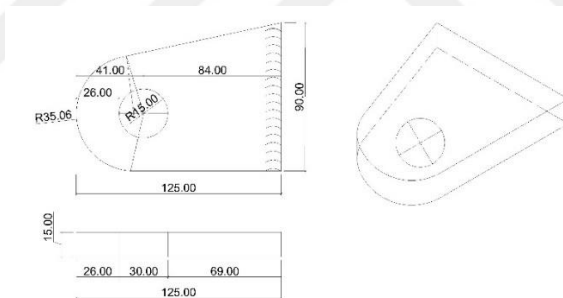


Figure A.48 : Steel plate dimensioning.

$N_{sd} = 49000$ N = 5 t
 M20
 $d_0 = 23$ mm (IKZ605-1400)
 $d = 20$ mm
 $t_1 = 12$ mm (260x260x12mm Box Profile Column)
 $t = 15$ mm (Plate thickness)
 $\Delta = 1$ mm
 Steel Class: S355-J2
 $F_y = 355$ N/mm²
 $F_u = F_y / \Omega$
 $\Omega = 2$ (AISC, 2016)

$$a \geq \frac{N_{sd} * \Omega}{2t * f_y} + \frac{2 * d_0}{3}$$

$$a \geq \frac{49000 * 2}{2 * 15 * 355} + \frac{2 * 23}{3} = 24,53 \text{ mm}$$

$$a = 25 \text{ mm}$$

$$c \geq \frac{N_{sd} * \gamma}{2t * f_y} + \frac{d_0}{3}$$

$$c \geq \frac{49000 * 2}{2 * 15 * 355} + \frac{23}{3} = 16,86 \text{ mm}$$

$$c = 20 \text{ mm}$$

$$L' = 2 * a + c + 20$$

$$L' = 2 * 25 + 20 + 20$$

$$L' = 90 \text{ mm}$$

- **Welding check according to TS648.**

Welding type: Corner welding

Effective welding length = $L = L' - 2a$

L' = Length of steel sheet

a = Thickness of welding

$\sigma_{\text{safety}} = 1,25 \text{ t/cm}^2$

Structural limits:

$$3 \text{ mm} \leq a \leq 0,7 * t_{\text{min}}$$

$$3 \text{ mm} \leq a \leq 0,7 * 12 \text{ mm}$$

$$3 \text{ mm} \leq a \leq 8,4 \text{ mm}$$

$$a = 5 \text{ mm}$$

$$15 * a \leq L \leq 100 * a$$

$$15 * 5 \text{ mm} \leq L \leq 100 * 4 \text{ mm}$$

$$75 \text{ mm} \leq L \leq 400 \text{ mm}$$

$$\text{Welding length} = L = L' - 2a$$

$$L = 90 \text{ mm} - 2 * 5 \text{ mm}$$

$$L = 80 \text{ mm}$$

$$75 \text{ mm} \leq 80 \text{ mm} \leq 400 \text{ mm} \checkmark$$

$$\text{Welding effective} = F_k = \sum a * L$$

$$F_k = 2 * 0,5 * 8 = 8 \text{ cm}^2$$

- **Welding check according to tension stress**

$$\sigma = N / F_k$$

$$\sigma = 5,00 \text{ t} / 8 \text{ cm}^2$$

$$\sigma = 0,625 \text{ t/cm}^2$$

$$\sigma \leq \sigma_s$$

$$\sigma_s = 1,25 \text{ t/cm}^2$$

$$0,625 \text{ t/cm}^2 \leq 1,25 \text{ t/cm}^2 \checkmark$$

- **Welding check according to shear stress**

$$\tau = T / F_k$$

$$\tau = 0,35 \text{ t} / 8 \text{ cm}^2$$

$$\tau = 0,04 \text{ t/cm}^2$$

$$\tau \leq \tau_s$$

$$0,04 \text{ t/cm}^2 \leq 1,1 \text{ t/cm}^2 \checkmark$$

APPENDIX F

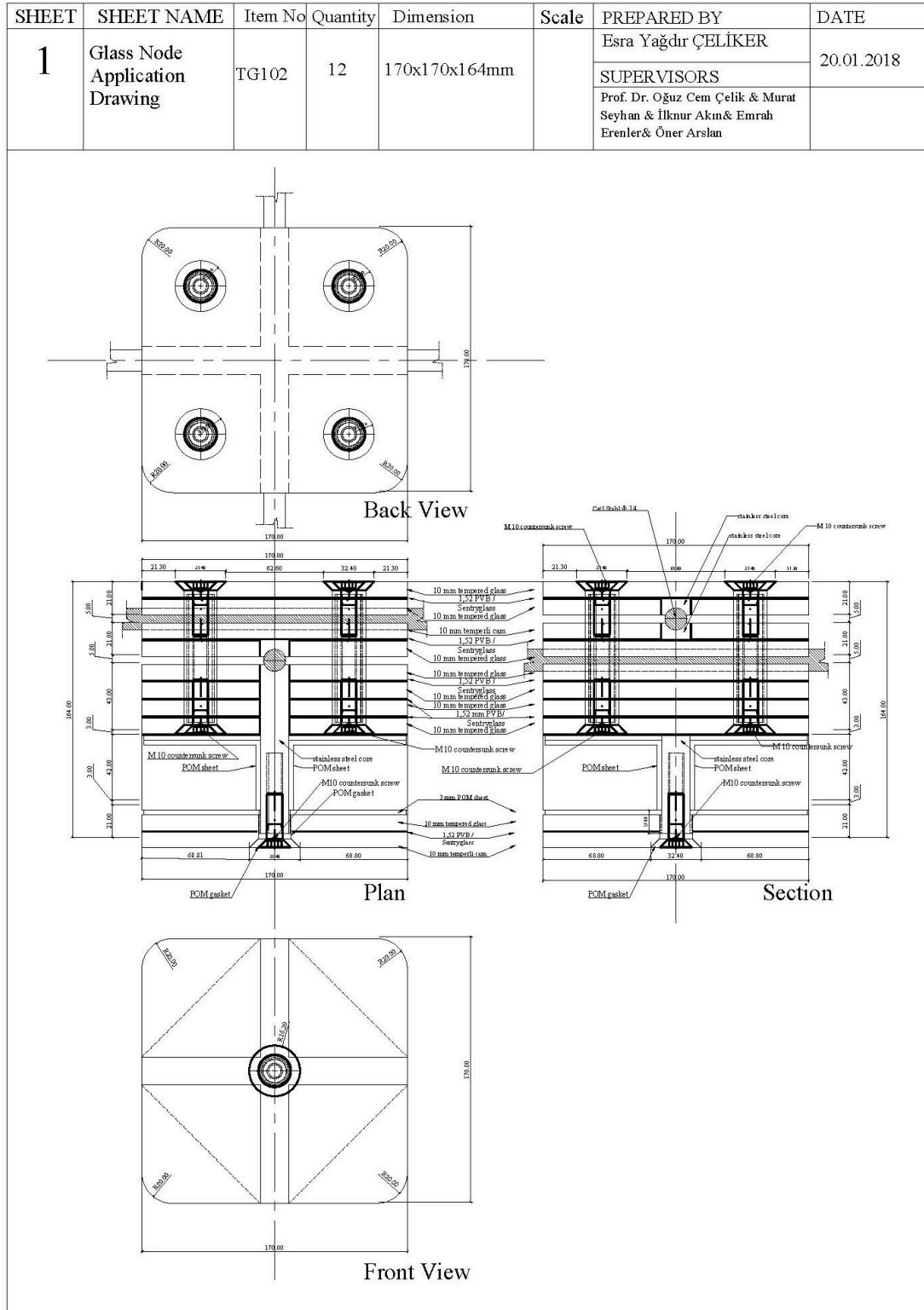


Figure A.49 : Application drawings of Glass Node, sheet 1.

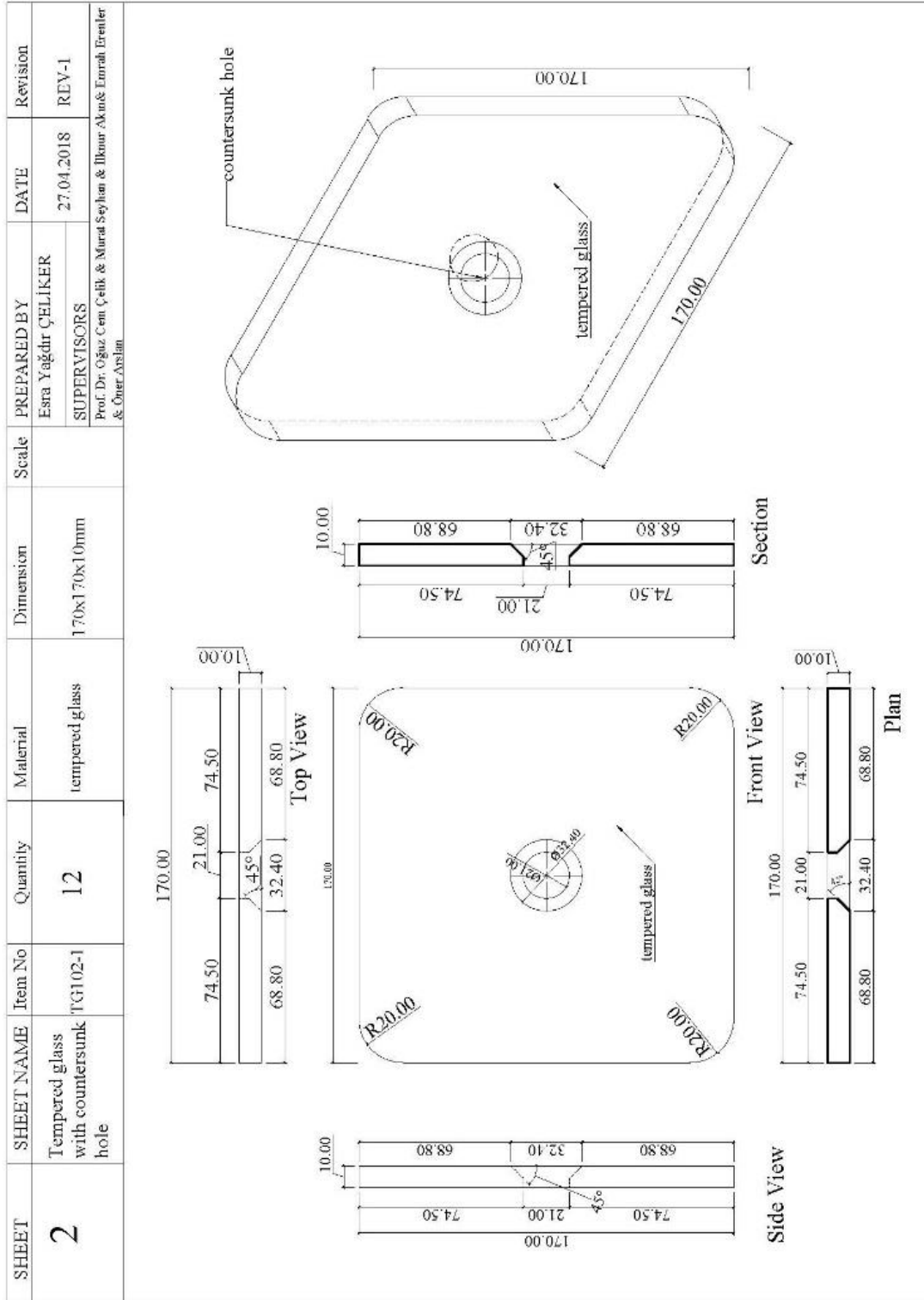


Figure A.50 : Application drawings of Glass Node, sheet 1.

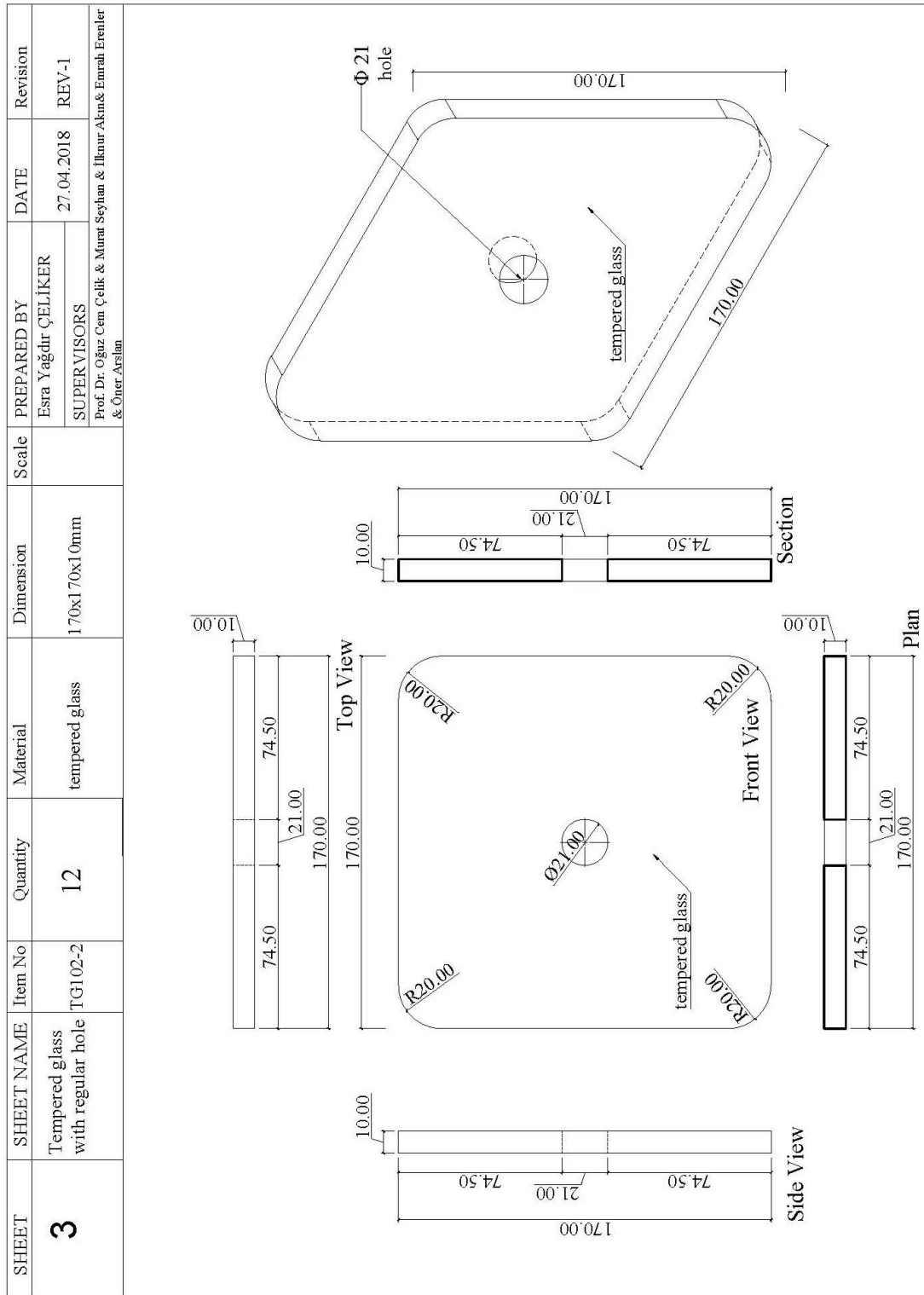


Figure A.51 : Application drawings of Glass Node, sheet 1.

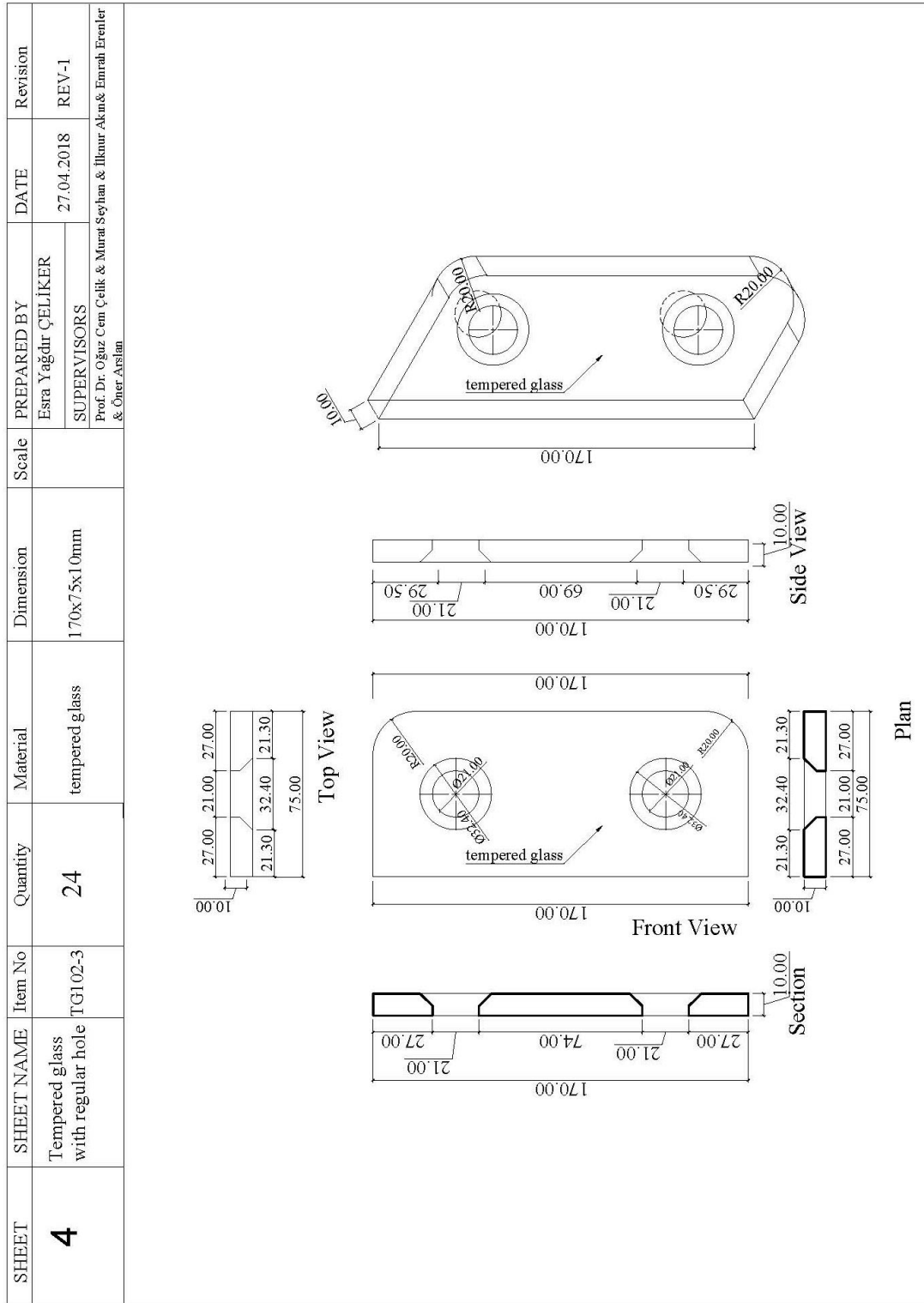


Figure A.52 : Application drawings of Glass Node, sheet 1.

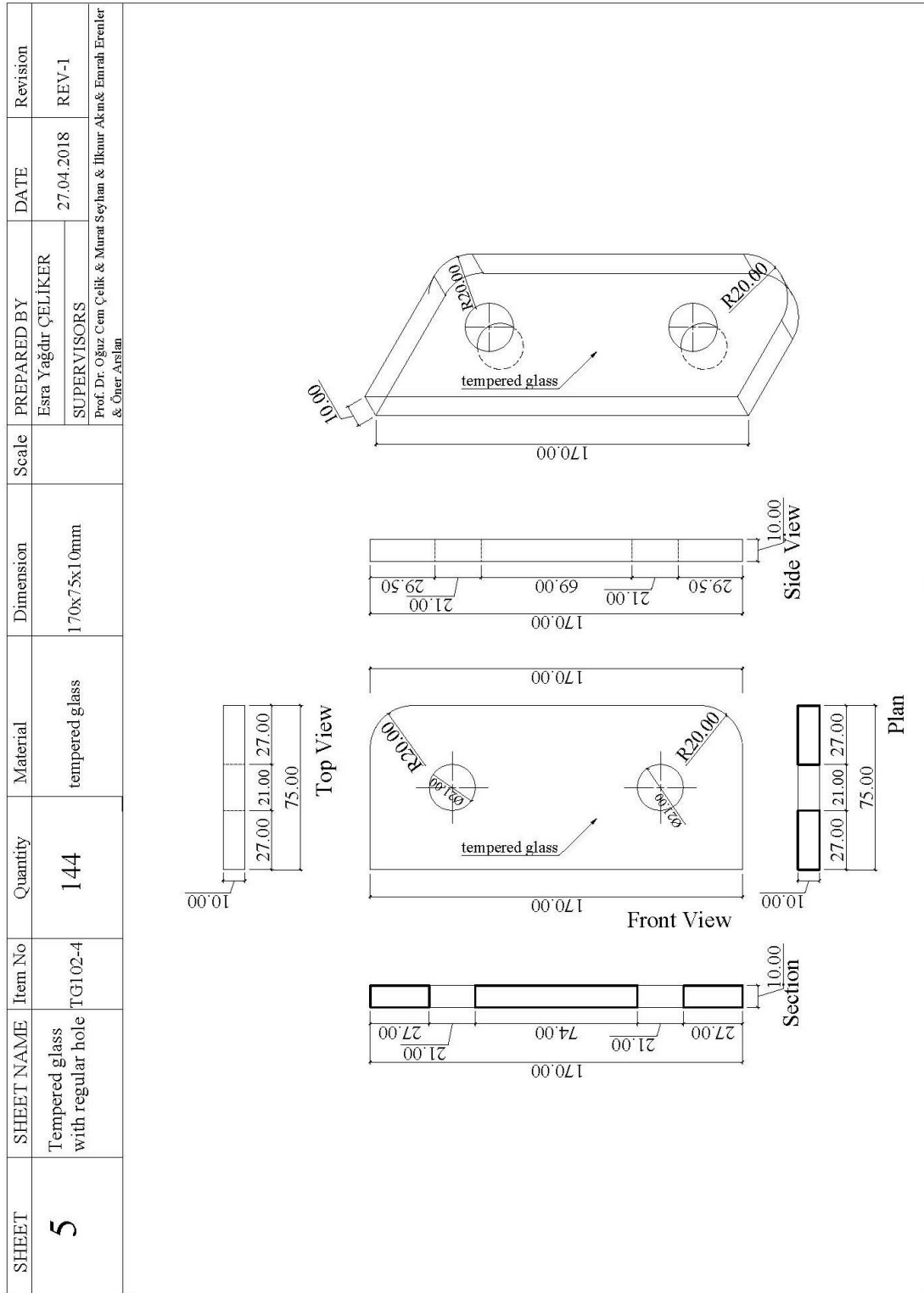


Figure A.53 : Application drawings of Glass Node, sheet 1.

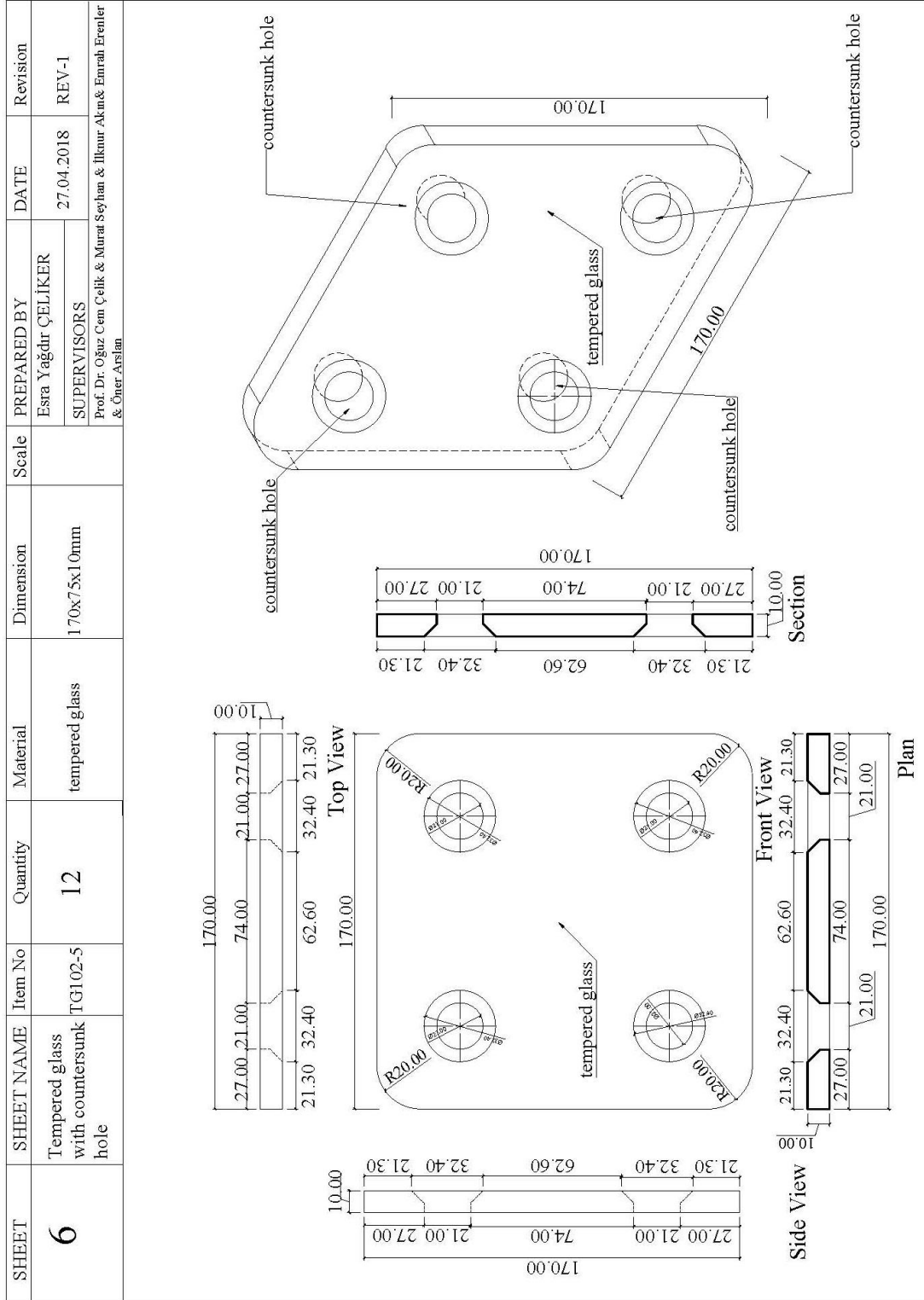


Figure A.54 : Application drawings of Glass Node, sheet 1.

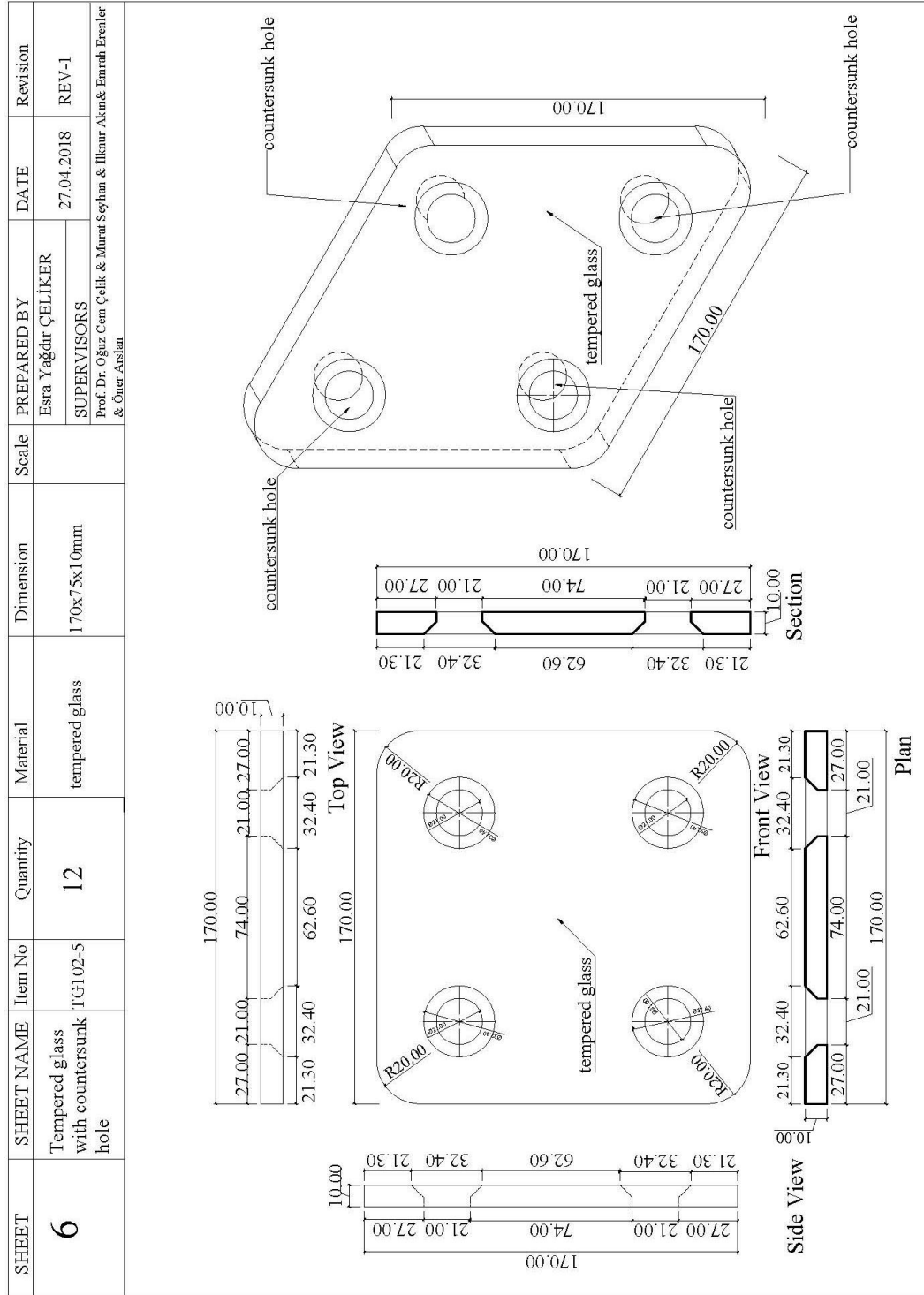


Figure A.55 : Application drawings of Glass Node, sheet 1.

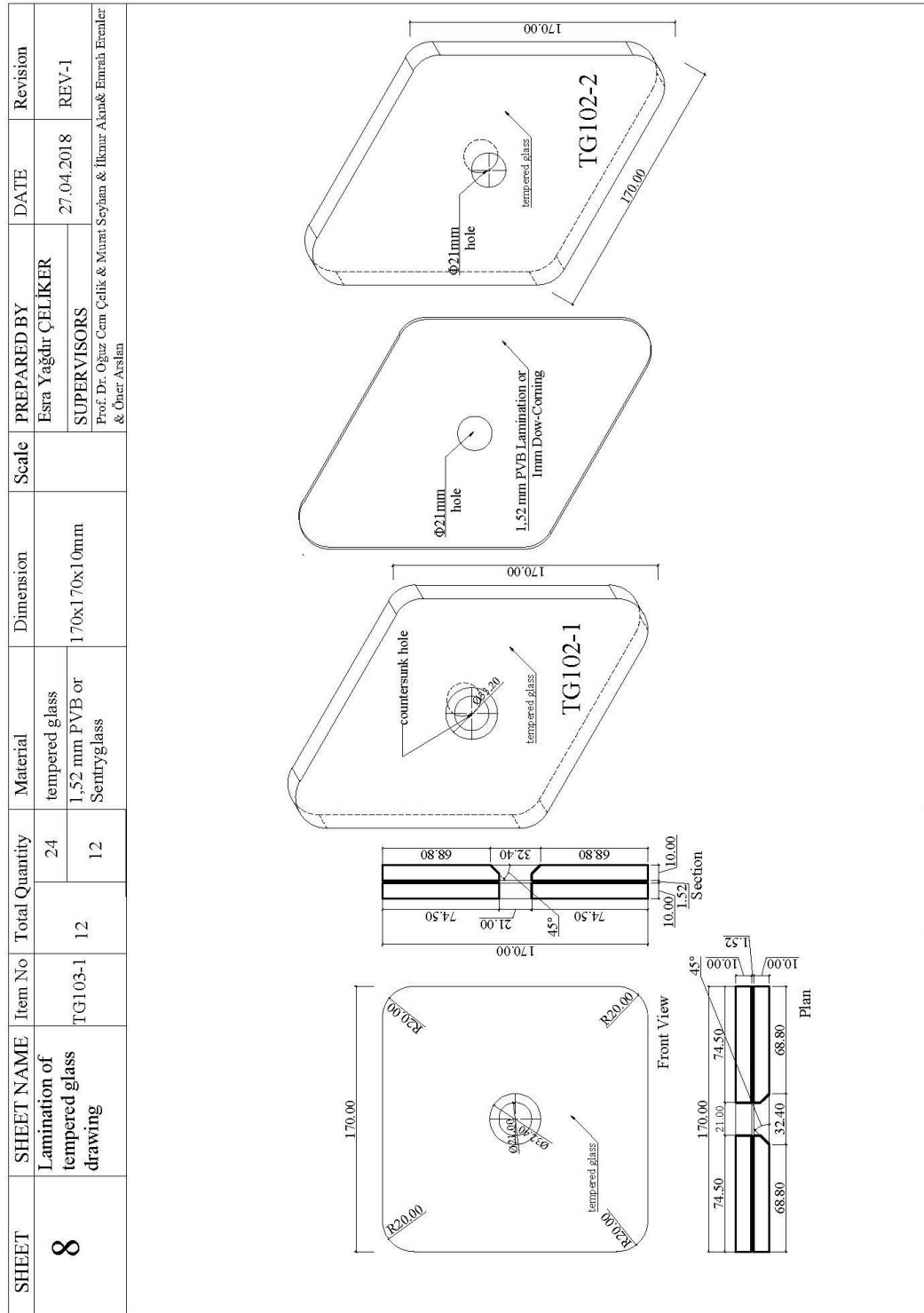


Figure A.57 : Application drawings of Glass Node, sheet 1.

[illegible]

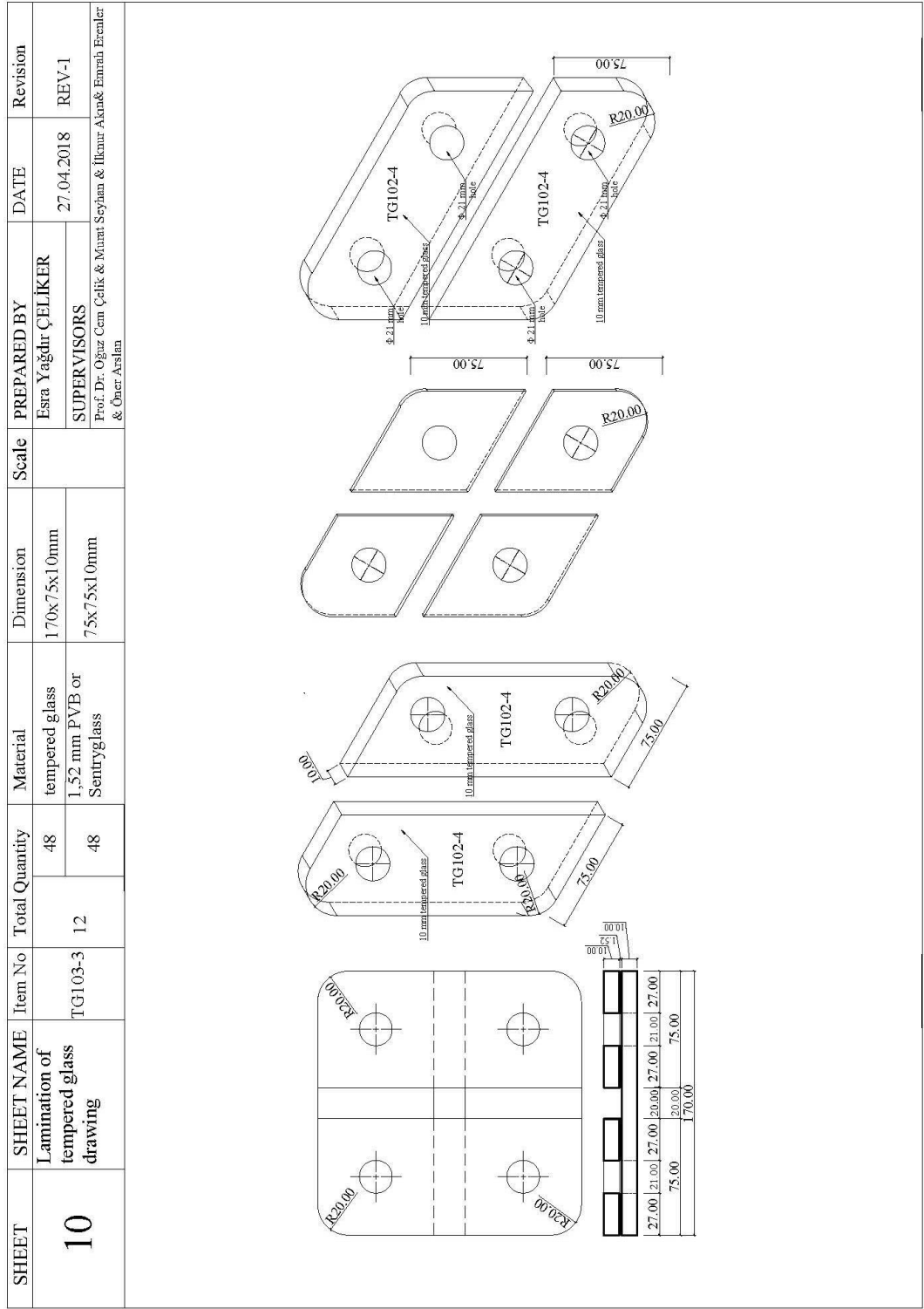


Figure A.59 : Application drawings of Glass Node, sheet 1.

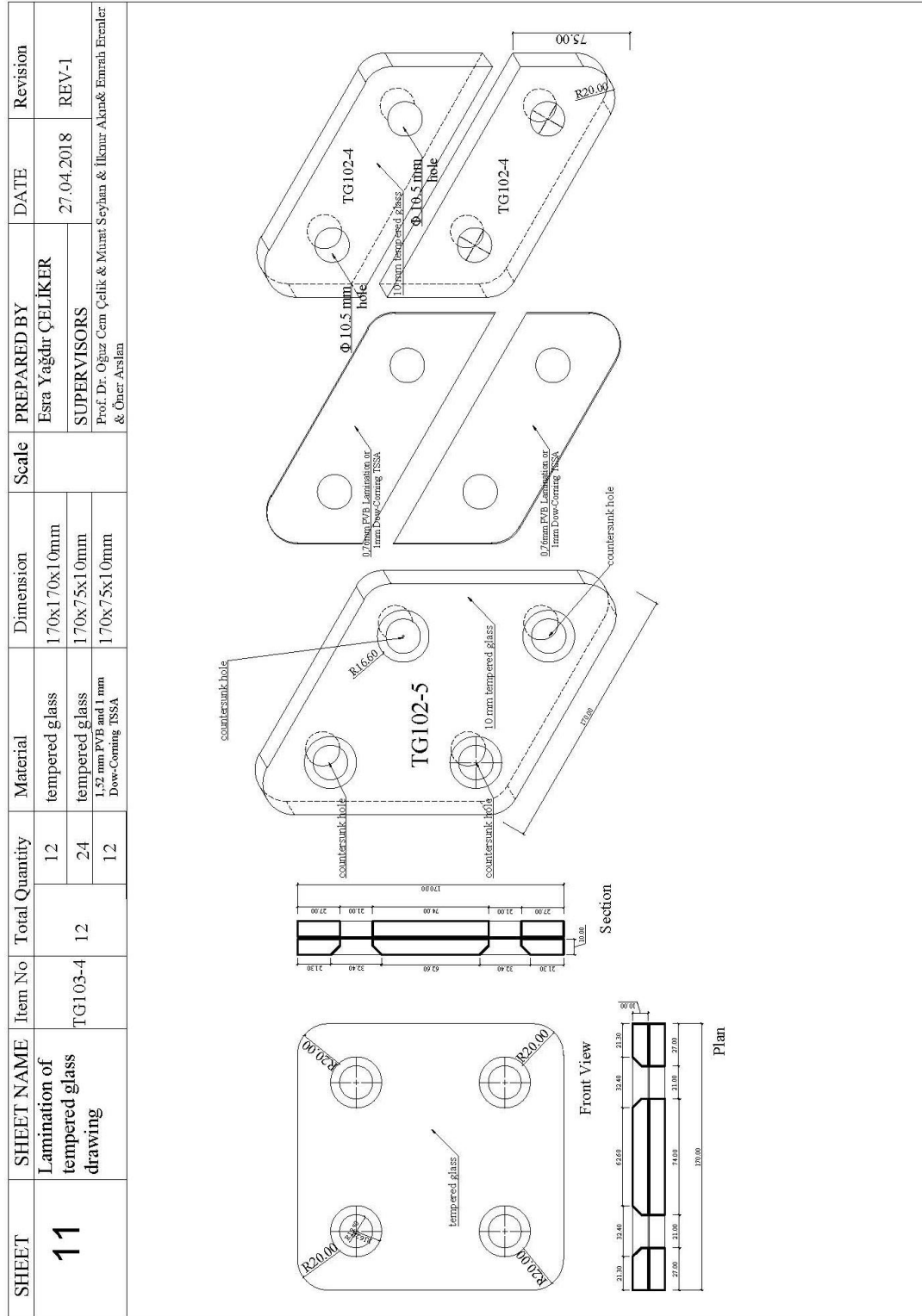


Figure A.60 : Application drawings of Glass Node, sheet 1.

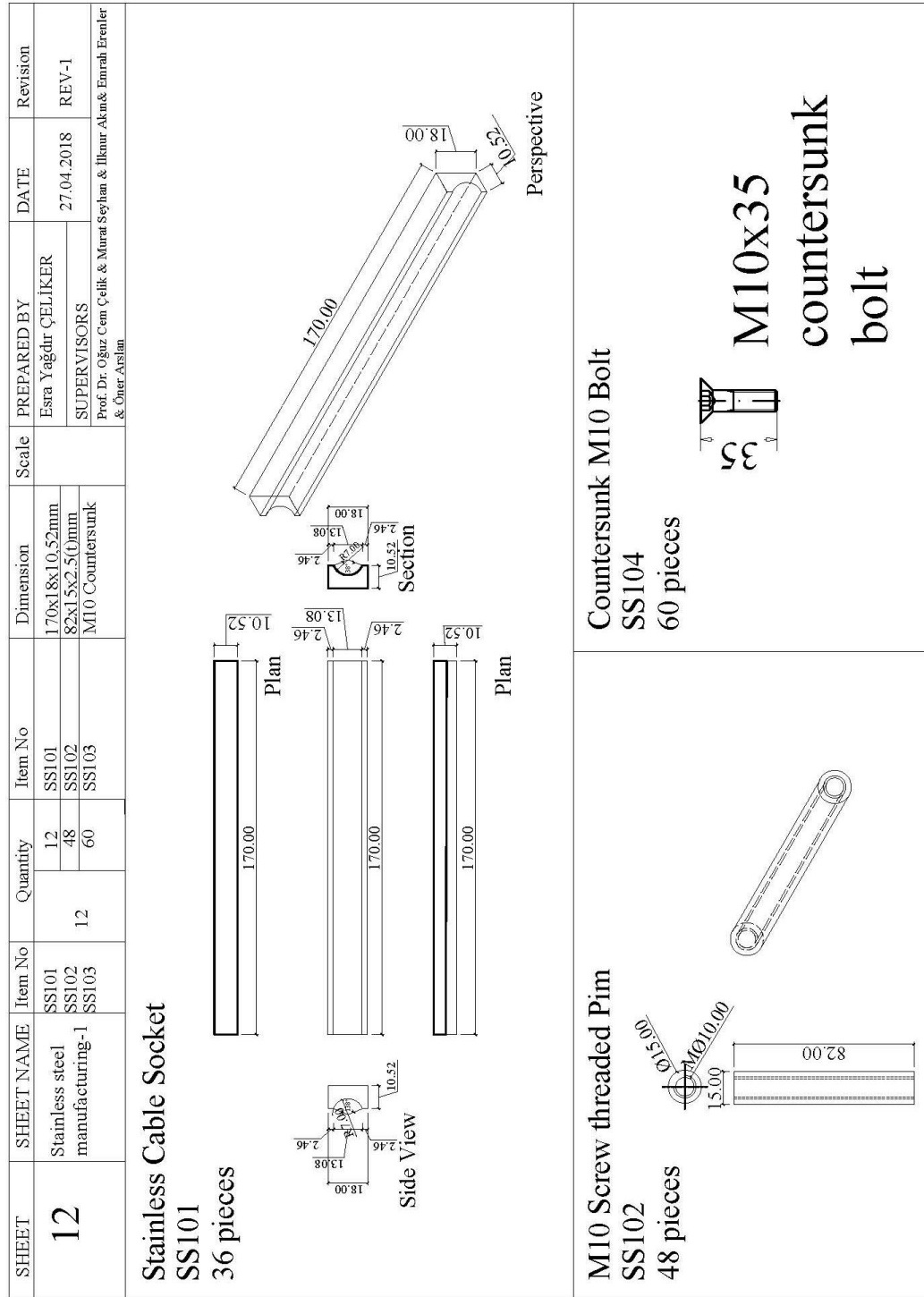


Figure A.61 : Application drawings of Glass Node, sheet 1.

SHEET	SHEET NAME	Item No	Quantity	Item No	Revision
13	Stainless steel manufacturing-2	SS101	24	SS101	REV-1
		SS103	12	2 SS101	
				is to be welded.	

SS101
2 SS101
is to be welded.

Side View

Front View

Section

Perspective

Plan

Figure A.62 : Application drawings of Glass Node, sheet 1.

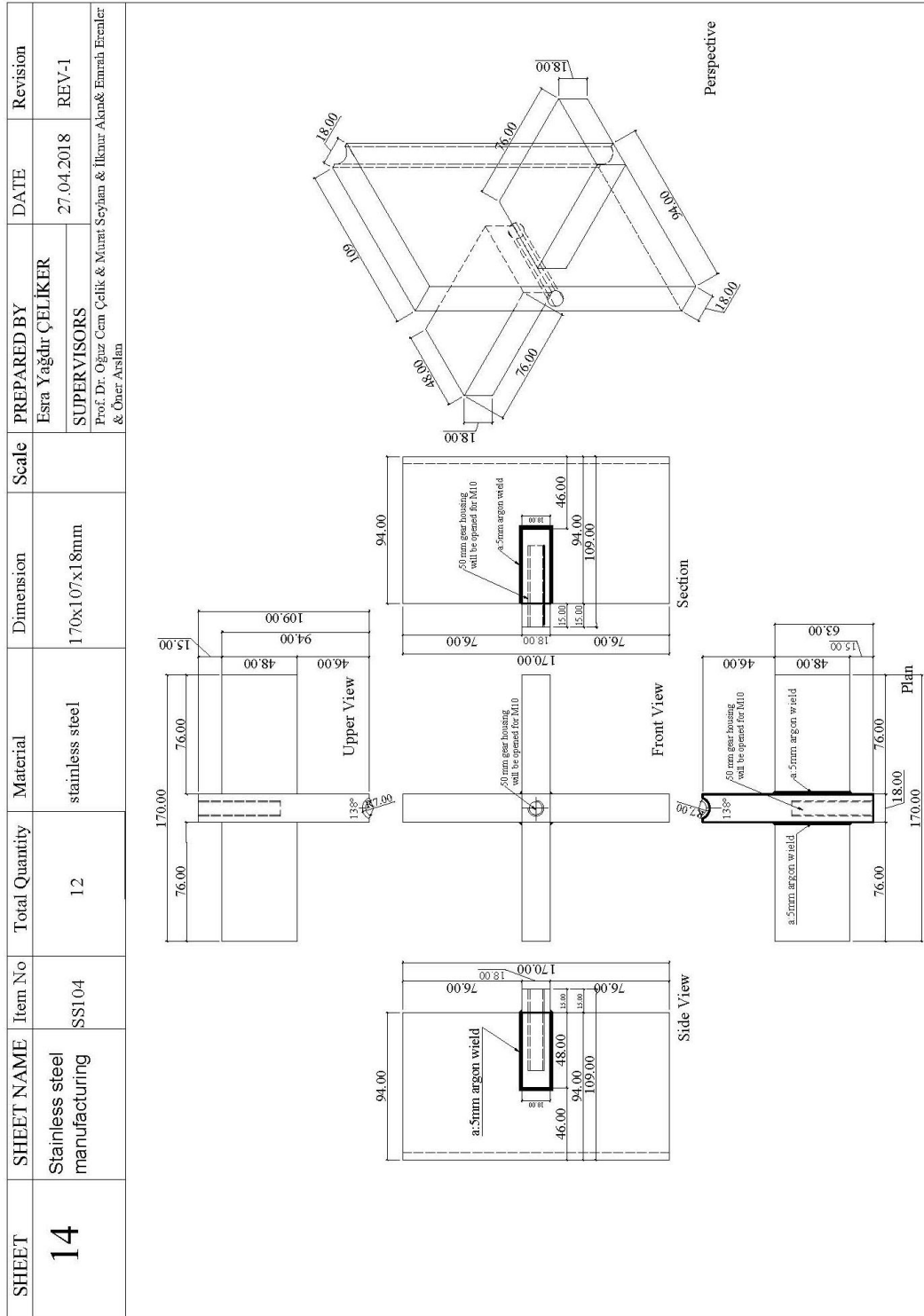


Figure A.63 : Application drawings of Glass Node, sheet 1.

SHEET	SHEET NAME	Item No	Quantity	Item No	Dimension	Scale	Prepared by	DATE	Revision
15	POM/Polycarbonate Production	PM101	12	PM101-1	POM/Polycarbonate Bedding		Esra Yağdır ÇELİKER	27.04.2018	REV-1
				PM101-2	POM Tube				
PM101-1 POM/Polycarbonate bedding 48 pieces				PM101-3	POM Tube		Danışmanlar Prof. Dr. Öğüz Cem Çelik & Murat Seyhan & İlknur Akın & Enrah Erenler & Öner Arslan		
				PM101-4	POM Tube				
				PM101-5	POM/Polycarbonate Sheet				
				PM101-6	POM/Polycarbonate Sheet				
				PM101-7	POM/Polycarbonate Gasket				
				PM101-8	POM/Polycarbonate Gasket				
				PM101-9	POM/Polycarbonate Gasket				
PM101-2 POM Tube 48 pieces									
PM101-3 POM Tube 12 pieces									
PM101-7 POM/Polycarbonate Gasket 96 Pieces									

Figure A.64 : Application drawings of Glass Node, sheet 1.

APPENDIX G

Cap (TG103-1)

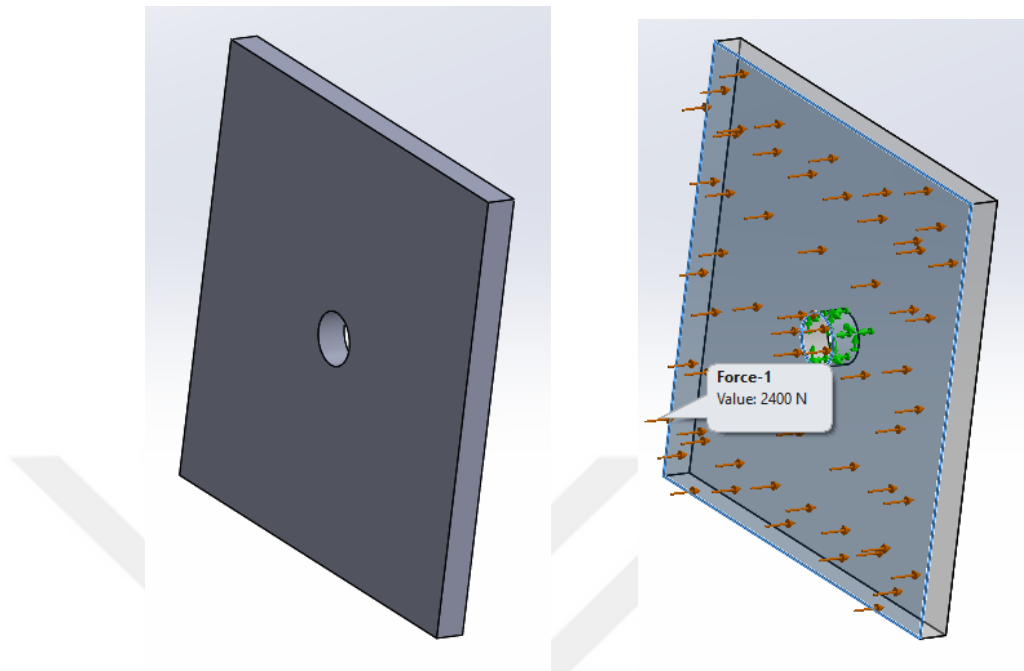


Figure A.65 : Solidworks Analysis Report of Glass Node, sheet1.

$$\text{Wind Load} = 1.5 \times 0.8 \text{ kPa} \times 1\text{m} \times 2\text{m} = 2.4 \text{ kN}$$

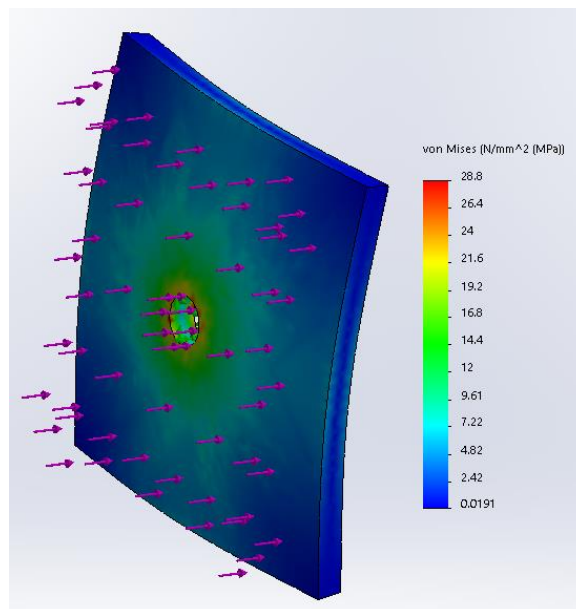


Figure A.66 : Solidworks Analysis Report of Glass Node, sheet2.

$$\text{Tension stress} = 29 \text{ MPa} < 80 \text{ MPa OK}$$

Stainless Steel core (SS104)

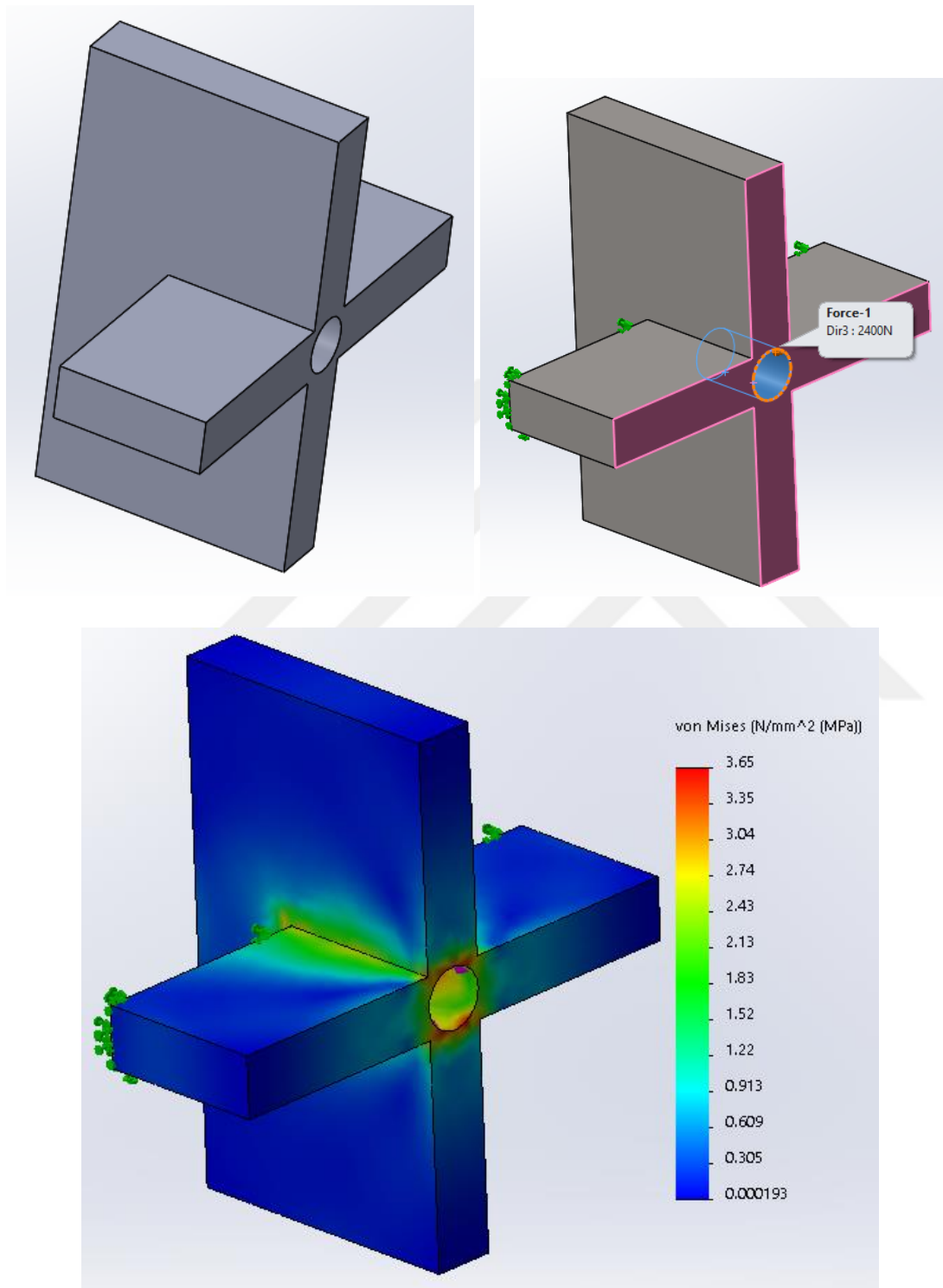


Figure A.67 : Solidworks Analysis Report of Glass Node, sheet3.

Tension stress = 4 MPa < $220/1.1=200$ MPa OK

Node

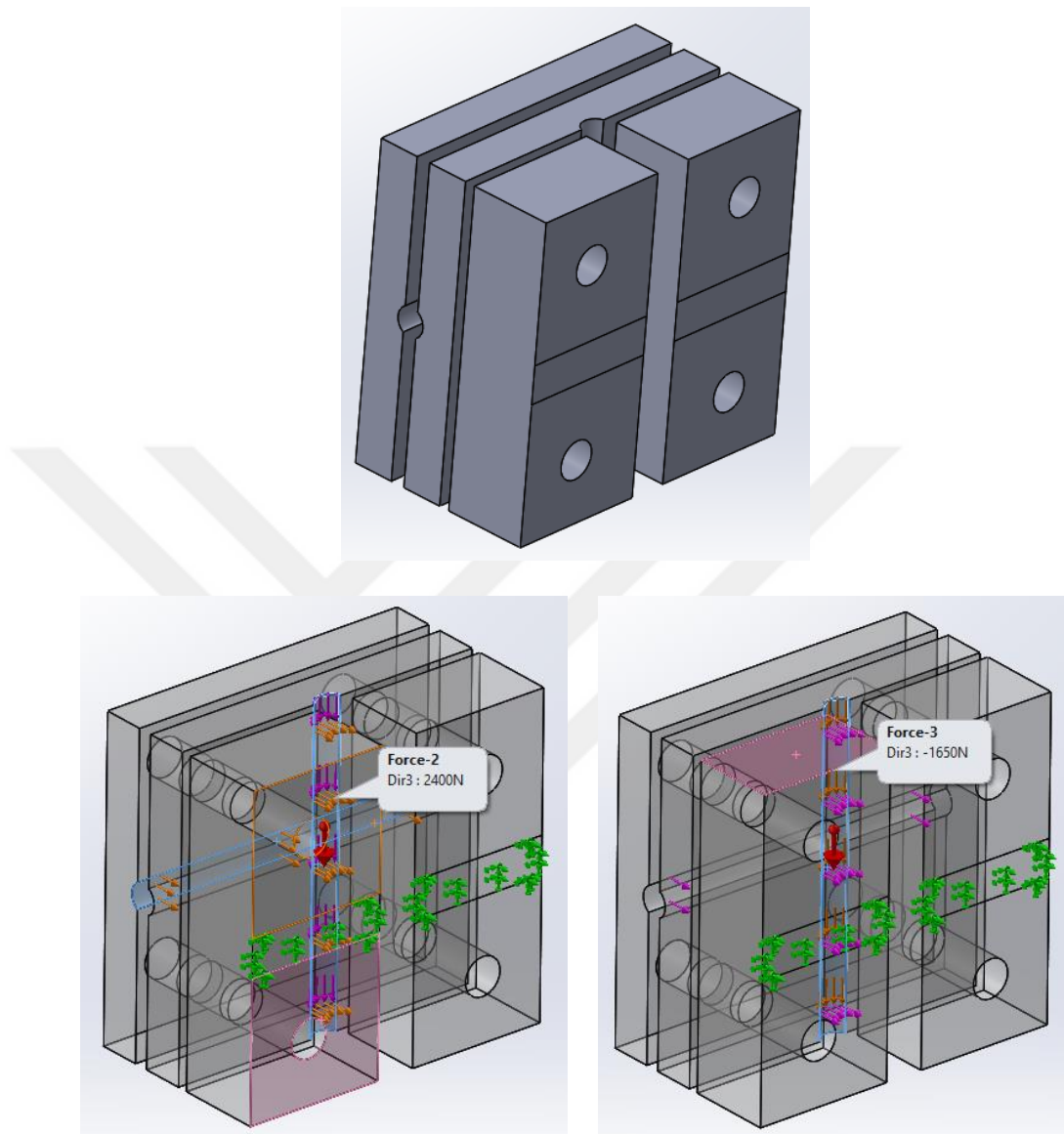


Figure A.68 : Solidworks Analysis Report of Glass Node, sheet 4.

Dead load of IGU = $1.35 \times 0.024 \times 25\text{kN/m}^3 \times 2\text{m} \times 1\text{m} = 1.65 \text{ kN}$

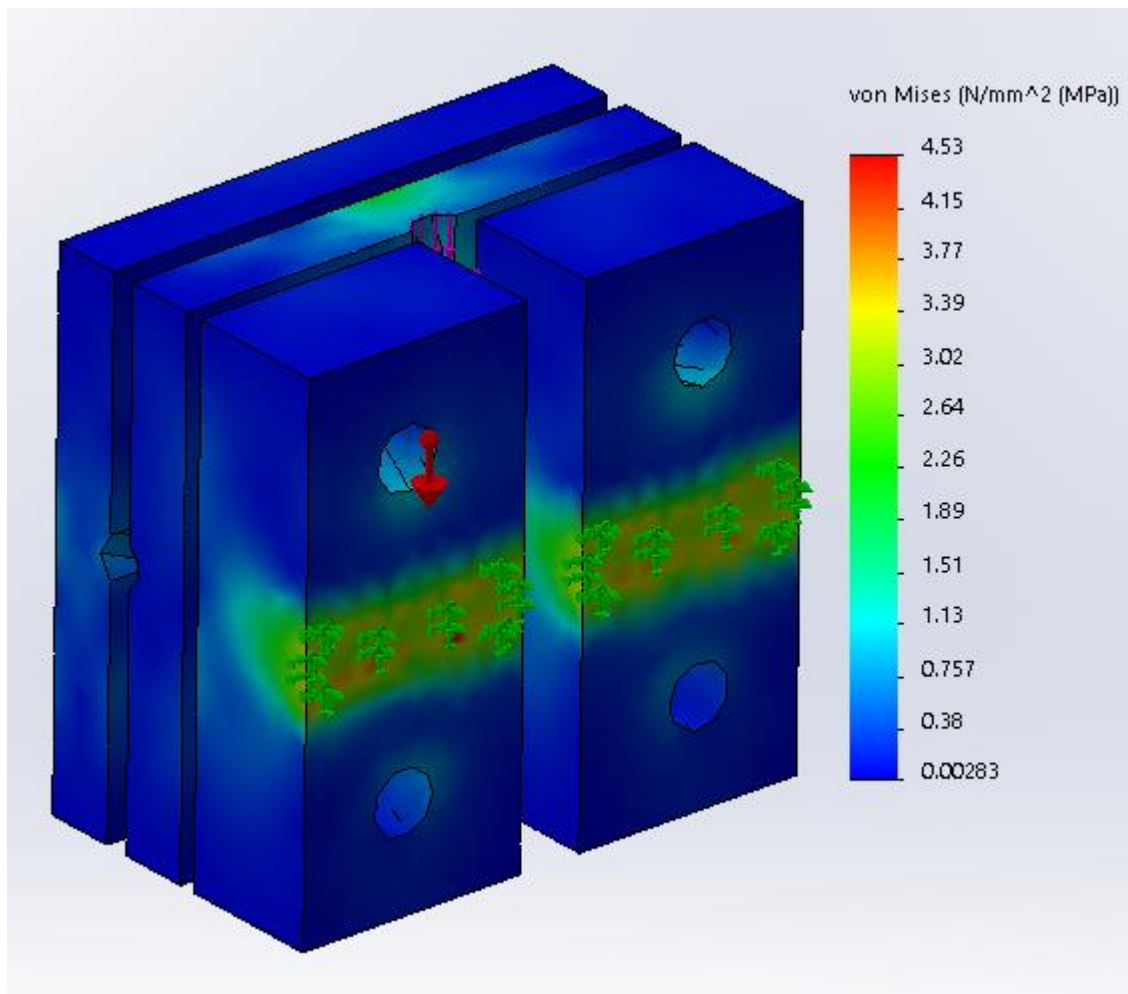


Figure A.69 : Solidworks Analysis Report of Glass Node, sheet 5.

Maximum stress= 5 MPa < 80 MPa OK
(Eurocode3 1993-1-1)

APPENDIX H

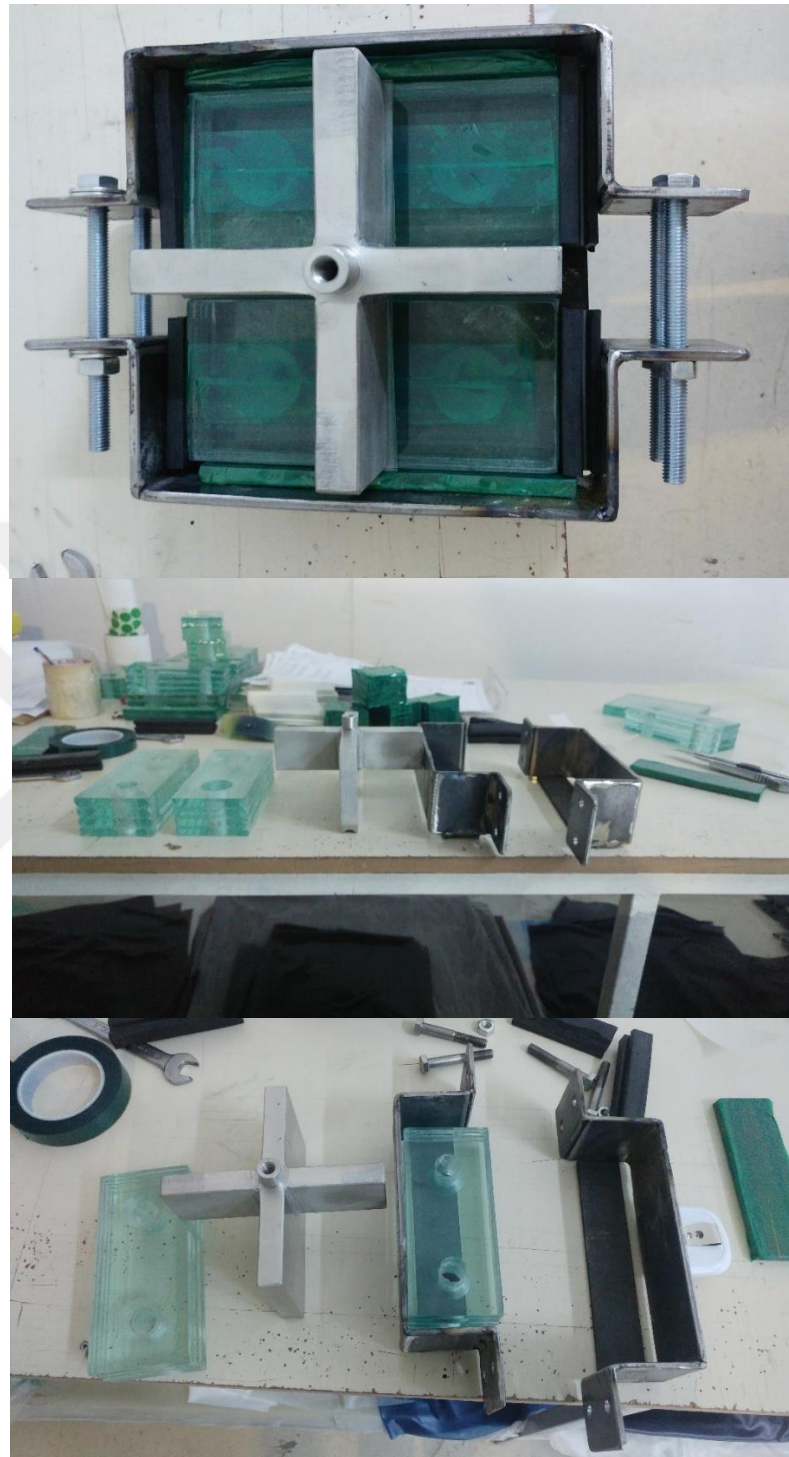


Figure A.70 : Steel mould for lamination process.

APPENDIX I

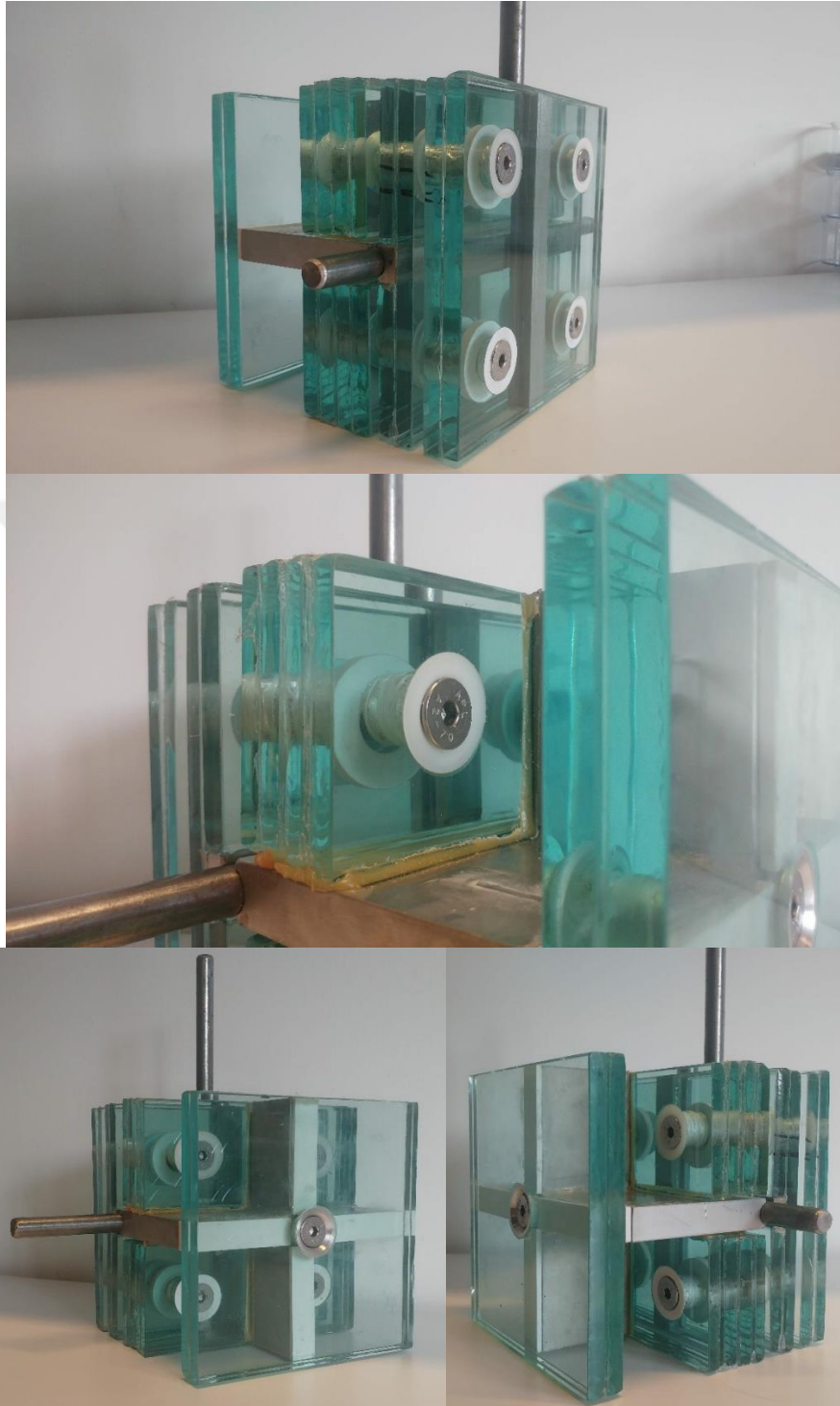


Figure A.71 : Glass Node as a final product.

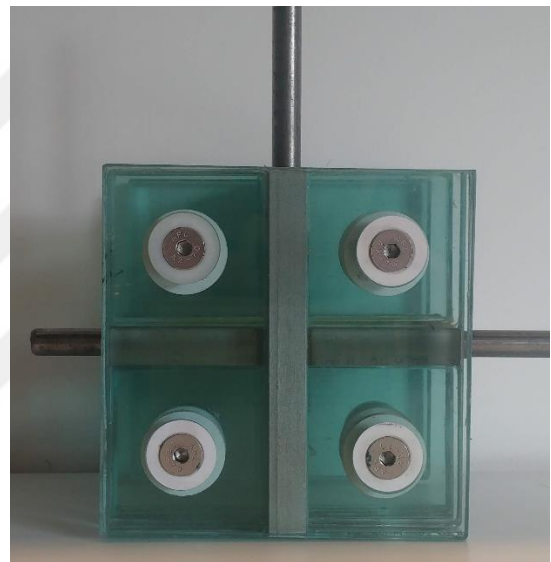
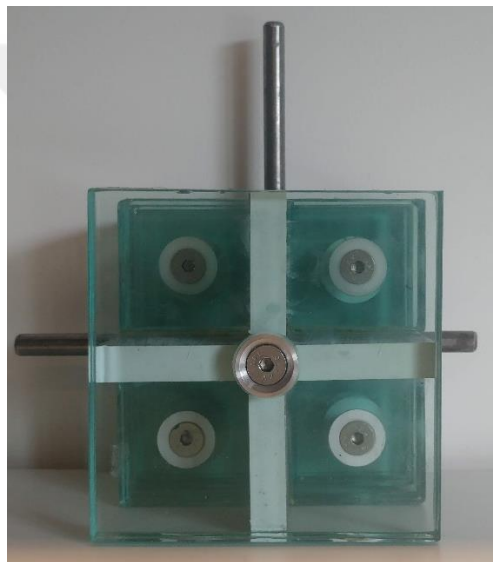
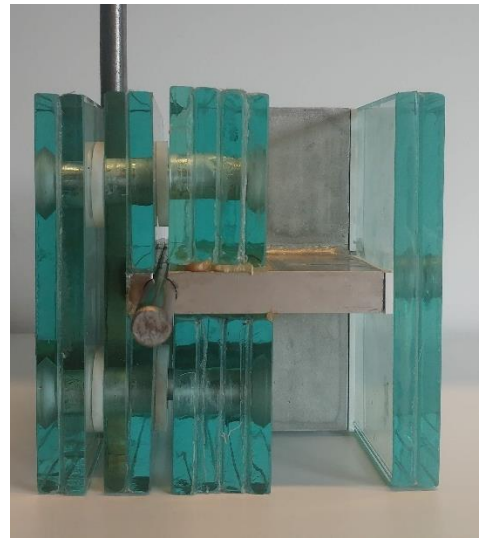
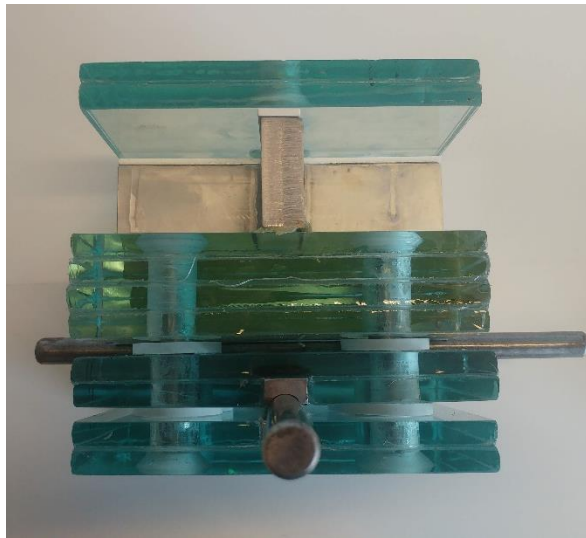


Figure A.72 : Glass Node as a final product.

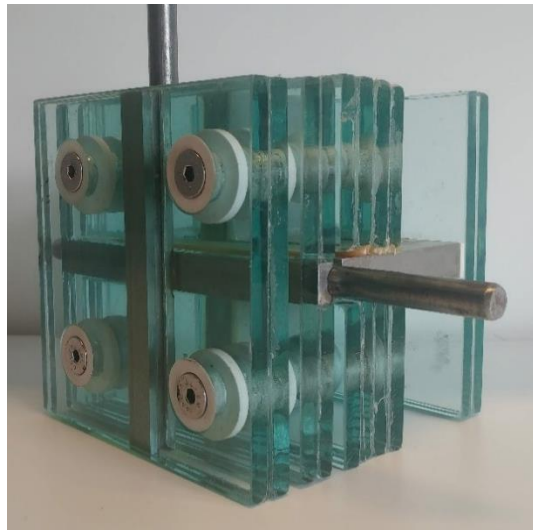
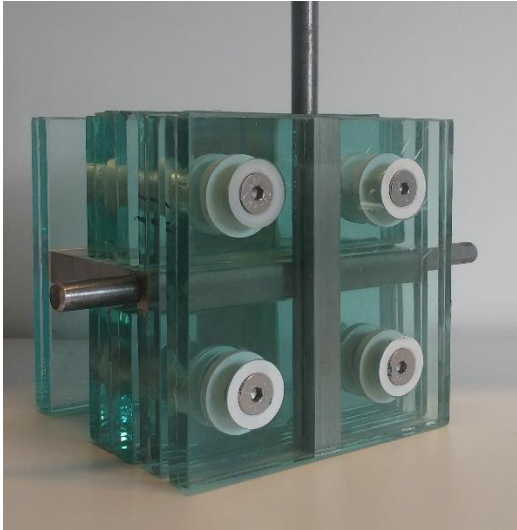


Figure A.73 : Glass Node as a final product.

APPENDIX J

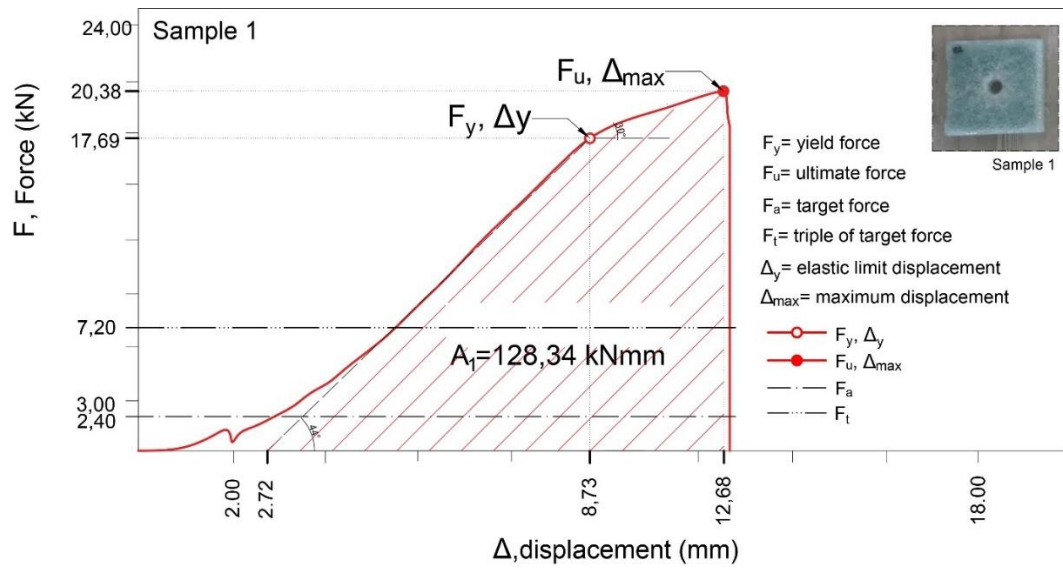


Figure A.74 : Sample 1 Force-Displacement Diagram.

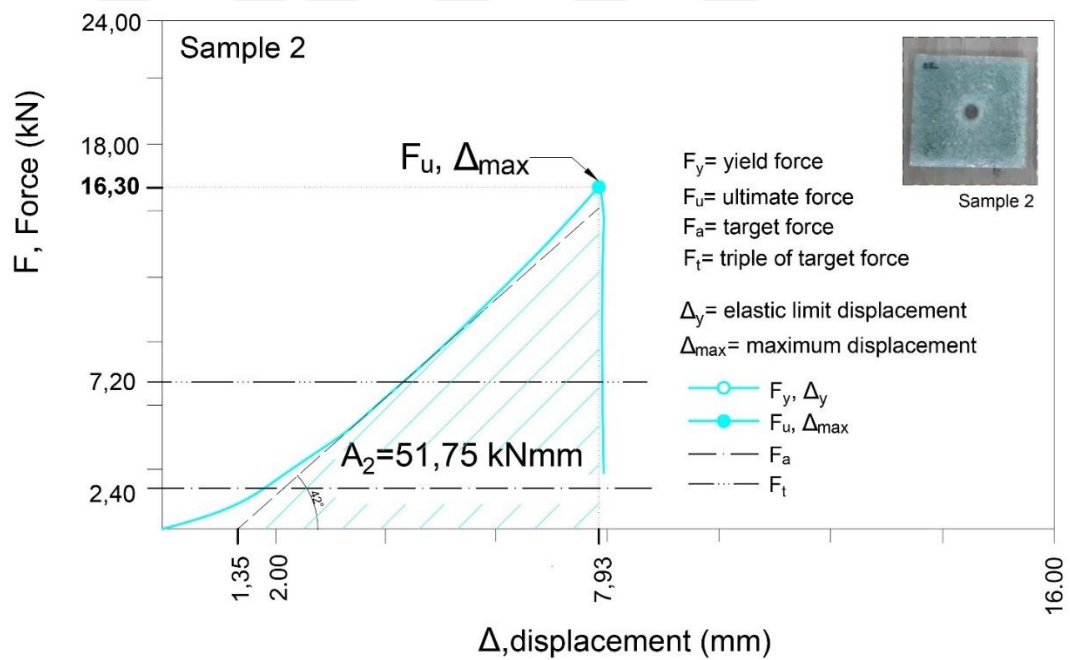


Figure A.75 : Sample 2 Force-Displacement Diagram.

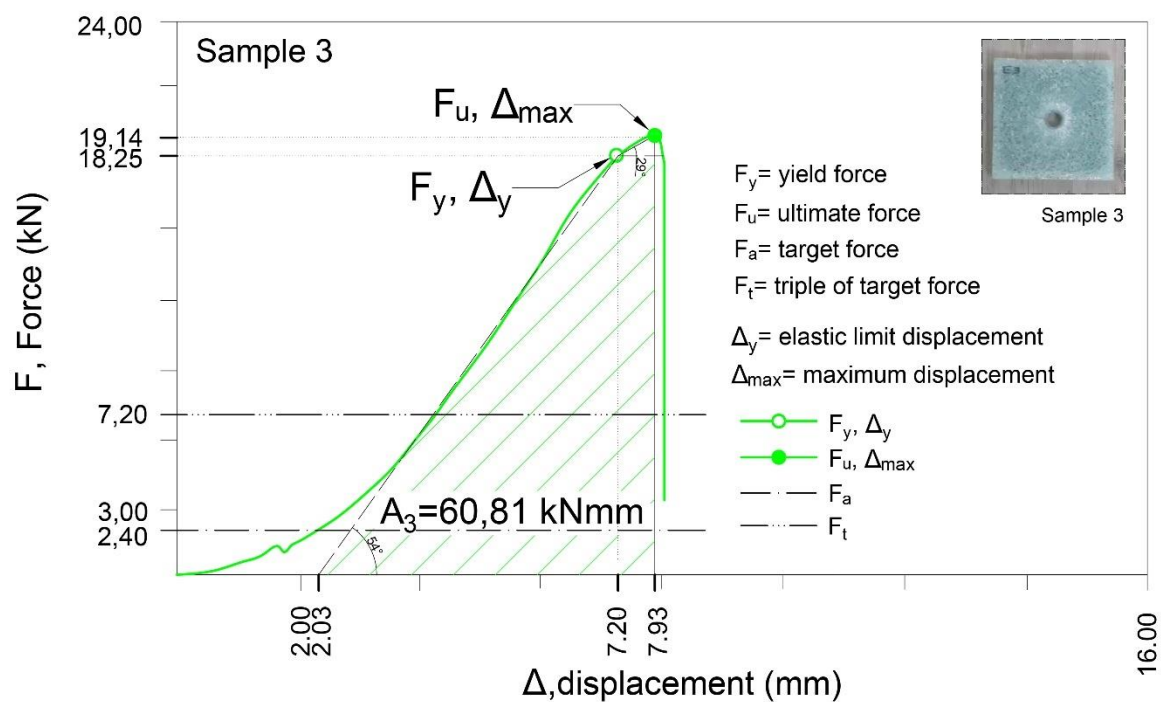


Figure A.76 : Sample 3 Force-Displacement Diagram.

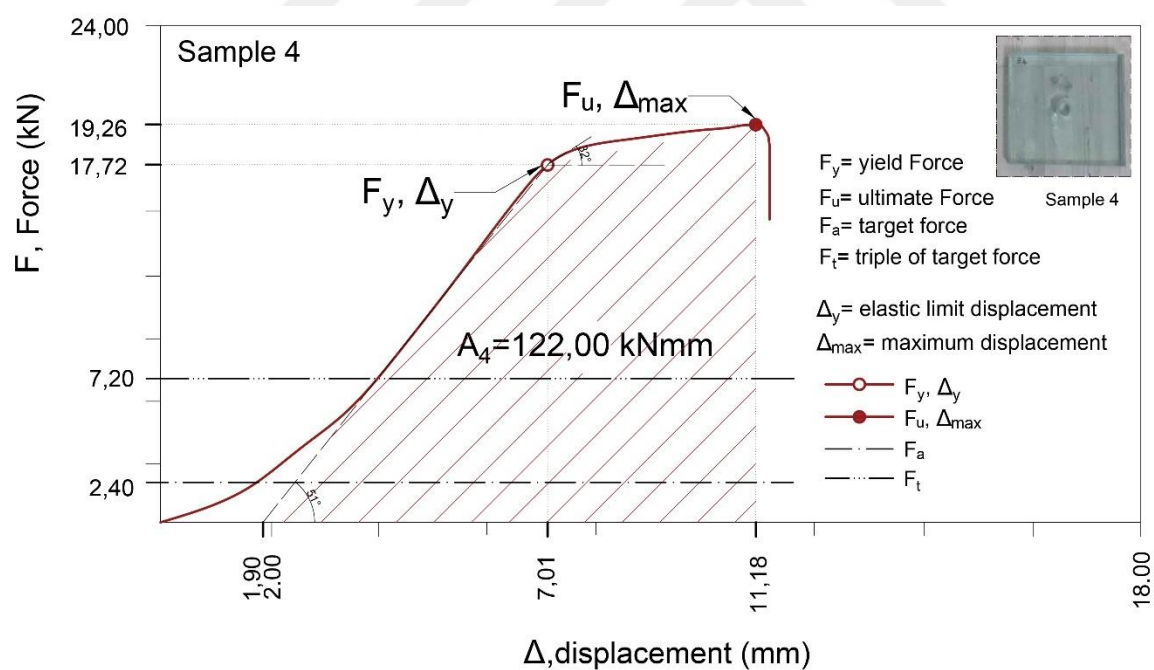


Figure A.77 : Sample 4 Force-Displacement Diagram.

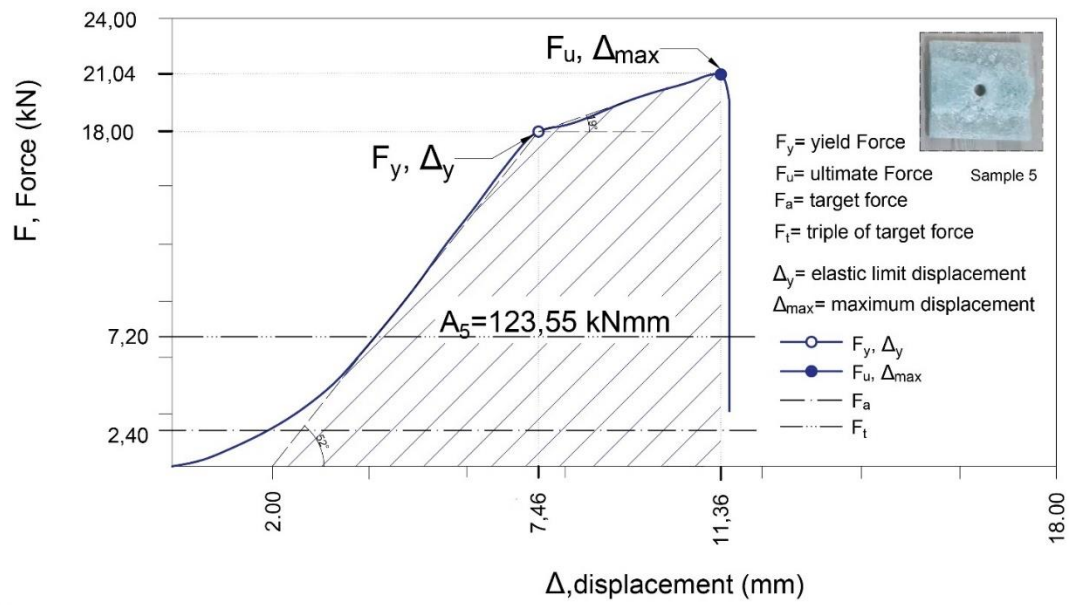
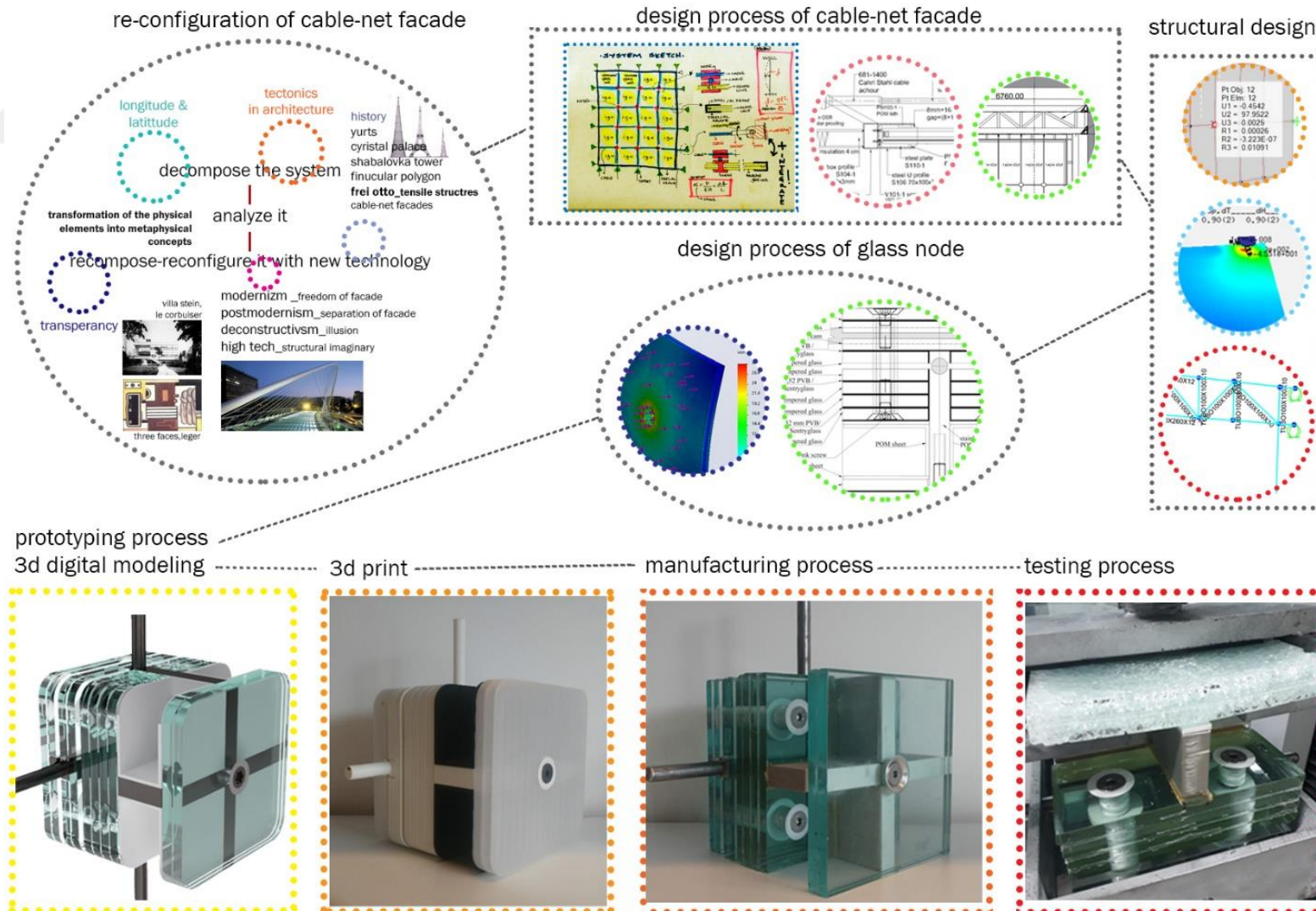


Figure A.78 : Sample 5 Force-Displacement Diagram



APPENDIX K

Figure A.79 : Diagrammatic representation of thesis study



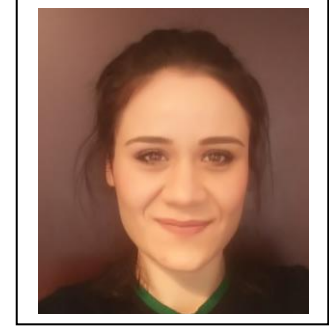


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- 2015-2016 Research Assistant at Istanbul Arel University
- 2016-2018 Volunteer Research Assistant at Trakya University
- 2017 International RMB Workshop Marl, Germany, attendant.
- 2017 ICBEST International Facade Conference, Istanbul Turkey, attendant.
- 2017-2018 Freelance Architect, Ç House.
- 2018 Parametric Design Workshop Instructor at Trakya University.
- 2018 Acousmatic Spaces Workshop Instructor at Istanbul Bilgi University.
- 2018-continued Research Assistant at Istanbul Bilgi University.
- 2018 Candidate of TUBITAK 1512: Techno-Initiative Capital Support Program with Structural Glass Node Project (SGN).
- 2018 Interior Design of Technology Transfer Office of Istanbul Bilgi University with Burcu Kütükçüoğlu and Eda Özgener.
-

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Celiker E.Y.** 2016: Urbanism Strategies Analysis and Suggestion Notes on the Concept of Migration in Turkey, Bursa Urban Culture and Urbanism Consciousness Symposium, Poster Presentation, 26-27 May 2016, Bursa, Turkey.
- **Satoğlu, S., Şuta, O., Çeliker E.Y.** 2017. An Example of Re-Functionalizing of Historical Buildings in Edirne: Sultan II. Bayezid Complex, 28 September-1 October 2017, Antalya, Turkey.