ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

AN EXPERIMENTAL STUDY ON SMALL-SIZED SPECIMENS MADE OF LOAD BEARING TIMBER-GLASS COMPOSITES

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

AHŞAP-CAM KOMPOZİT YAPI ELEMANLARININ KÜÇÜK ÖLÇEKLİ NUMUNELER DÜZEYİNDE DENEYSEL BİR İNCELEME

YÜKSEK LİSANS TEZİ

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To my father and mother

FOREWORD

This master thesis was carried out during the spring of 2015. The work has been conducted at Istanbul Technical University, Department of Architecture.
First I would like to thank my advisor Dr. Halet Almıla Büyüktaşkın for giving me the opportunity to carry out my master thesis work within this research area. I am also very grateful to Dr. Gülseren Erol at Istanbul Technical University for her expertise and advice which she has shared with me through our discussions.
Finally I want to thank my family for their great support throughout my education.

May 2015

Morvarid DİLMAGHANİ
(Architect)

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ABBREVIATIONS

LBTGC **:** Load Bearing Timber Glass Composite

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AN EXPERIMENTAL STUDY ON SMALL-SIZED SPECIMENS MADE OF LOAD BEARING TIMBER-GLASS COMPOSITES

SUMMARY

Building has a major and long-term impact on the cultural, social and economic aspects of our society, as well as the appearance of our urban and rural environments. But now besides the architecture, the building forms, the engineering criteria of materials and structures, building must also consider the ecological characteristics with a growing environmental awareness. In the light of this, building and the future role of timber in our buildings must be re-examined. On the other side, it is well known that the presence of natural sunlight improves the health of the persons living or working in buildings, why the possibility to increase the glass surface in buildings. By the use of load bearing timber-glass composite elements, it is possible to use timber as a natural, ecological material and glass as a transparent material together. Also, it is necessary to develop design and bonding joints. The unique combination of timber products with glass components will also request deeper investigations regarding the interfaces and the compatibility. The main issue is optimising a composite system by using the best characteristics of each material in order to develop and advance a high competitive composite building system. This research intends to develop the timber-glass load bearing elements, taking into consideration experimental studies on small-sized specimens and long term behavior of medium-sized specimens. Small-sized experiments include durability and mechanical strength tests. The aim of these tests is to investigate the behavior of adhesion and the properties of timber-structural silicone joints in order to understand the failure modes and strength of this bonding. For this purpose, adhesion and shear strength tests on the timber-glass small-sized specimens were carried out in order to investigate the adhesion strength. Durability tests that were done in order to investigate the behavior of the material under the effect of accelerated aging. The aim of these tests is to determine the effects of environmental conditions on the mechanical properties and volume stability of the timber-glass composites. Durability tests include: Wetting-drying, freezing-thawing, UV-light, resistance to high temperature, resistance to acids tests. Influence of the durability tests on strengths was measured afterwards. In most of these tests, it has been concluded that, water settles in the upper level of the timber, deforming the inner structure of it by swelling and shrinking.

As is known, transparency is one of the significant features of modern architecture. This thesis specifies the possibility of employing glass as a load-bearing element. In order to be able to use this material as part of the building structure it is essential to know its long-term behaviour under various conditions like different temperatures, environmental impacts or the load duration. This purpose is achieved by the medium-sized experiment. With the purpose of evaluating the behavior of the bonding between timber and glass materials, this experimental test has been carried out at the campus of Istanbul Technical University, Faculty of Architecture. The aim of medium size test is to determine the creep behavior of timber-glass composite elements under long-term loading at outdoor conditions. For the specimens, birch

plywood, tempered soda-lime glass and two-component silicone adhesive were used. L-sectioned timber elements were bonded to the both sides of the glass by silicone adhesive. Eight medium size specimens were exposed to long-term loading at exterior conditions. The experimental setup for long-term loading was prepared in the form of wooden boxes. Loading of the specimens were performed by filling the wooden container with sand. Timber-glass composite specimens were attached to the loading boxes. The specimens were loaded under two different long term load levels. During the test, vertical displacement of the glass was recorded once a day. The results show displacement of glass in the specimens with higher load is more than specimens with lower load. Also, the little displacements of the medium-size specimens, is an appropriate result for using the elements in the structures of buildings.

Furthermore, possible architectural design applications of timber and glass as composite structural materials are provided in this thesis. The pilot projects which have been designed are kiosk, resting place, tourist information center and canopy. Initiation of pilot projects will provide the possibility to experience the practicality and applicability of developed composite systems, and create different design and application solutions. The research also includes the questionnaire method to explore Turkish market for this product. In order to the new product take a place between other structural systems timber and glass questionnaires were performed. The intention of this study is to contribute to the knowledge required for the industry to be willing to produce timber-glass components for the market. As a result, many timber and glass industries have stated that timber-glass composite structural elements can have high load-bearing capacity. Also, according to the timber componies reviews, if the operation of timber can be controlled and disadvantageous properties of glass can be prevented, timber-glass composite can be a structural element with high strength. The research of thesis is began with the study on the properties of timber, glass materials and the adhesives which hold materials together to form timber-glass composite elements. The experiments, pilot projects and questionnaires are explained afterwards.

AHŞAP-CAM KOMPOZİT YAPI ELEMANLARININ KÜÇÜK ÖLÇEKLİ NUMUNELER DÜZEYİNDE DENEYSEL BİR İNCELEME

ÖZET

Binalar, toplumumuzun kültür, sosyal ve ekonomik boyutlarının yanı sıra kentsel ve kırsal çevrelerin görünümünü üzerinde de büyük ve uzun vadeli bir etkiye sahiptir. Mimarinin, bina formlarının, malzeme ve yapıların mühendislik kriterlerinin yanı sıra, binalarda çevre bilinci ile büyüyen ekolojik özellikler de dikkate alınmalıdır. Bu durum düşünülerek, bina ve yapılardaki ahşabın gelecekteki rolü yeniden incelenmelidir. Ahşap ilk zamanlardan beri inşaatta kullanılan doğal bir inşaat malzemesidir. Ahşabın dayanımının ağırlığına oranı, çelik ve betonarme gibi yapı malzemeleri ile kıyasla daha yüksektir. Aynı zamanda, ahşap doğa koşullarına diğer yapı malzemelerine oranla daha dayanıklıdır. Ahşap ısı geçirgenliği düşük olduğundan, değişik iklim koşullarında çok iyi ısı izolasyonu özelliğine sahiptir. Yangına karşı direnci yüksektir. Kolaylıkla yanmasına rağmen, yanan kısmında oluşan kömür tabakası ısıyı az naklettiğinden içeriye doğru yanma hızı azalır. Bu davranış tipi, genellikle büyük kesitli ahşap elemanlarda (kolon, kiriş) görülür. Yanısıra, ahşap organik bir malzeme olduğu için çeşitli bitkisel, mantar ve hayvansal (böcek, kurt) parazitlerden zarar görür. Bu durumu önlemek için ahşap elemanları rutubetten korumak ve etrafından hava geçecek şekilde tasarlamak lazımdır. Ayrıca bazı zehirli sıvılarla ahşabı emprenye etmek yoluyla da mantarların ve parazitlerin etkisi önlenebilir. Dış etkenlerden doğru bir şekilde korunan ahşap elemanların kullanım ömürleri oldukça uzun olmaktadır. Ahşabın diğer dezavantajı ndan biri rutubet alıp vererek çalışmasıdır. Çalışma şekil değiştirme ve hacim değişikliğine sebep olduğundan konstrüksiyon için olumsuz etki yapar.

Saydamlık günümüz mimarisinde önemli rol oynamakta ve tasarımlara yön vermektedir. Bunun dışında, doğal güneş ışığının varlığı, binalarda yaşayan ya da çalışan kişilerin sağlığını olumlu etkilediği bilinmektedir ve bu nedenle binalarda cam yüzeyler artırılmaktadır. Bu gelişime paralel olarak, özellikle gelişen çevre bilinci ile ekolojik ve sürdürülebilir yapı teknolojileri, yapı sektöründe önem kazanmaktadır. Cam yapılarda ışık geçirme, ısı yalıtımı, görüntü gösterme, güvenlik sağlama, istenilen ışıkları geçirme ve benzeri daha birçok basit ve birden fazla işlevin aynı zamanda karşılanması gibi karmaşık işlevlerin çözülmesinde kullanılan nadir malzemelerden biridir. Cam, ahşap yapılarda cephe elemanı olarak sıkça kullanılmasına rağmen, cam ve ahşabın taşıyıcı kompozit sistem elemanı olarak yeralması geleneksel yapı yöntemleri arasında çok sık rastlanmamaktadır. Ahşap-cam kompozit taşıyıcı elemanlar olarak, doğal ve ekolojik bir malzeme olan ahşabı ve şeffaf bir malzeme olan camı bir arada kullanmak mümkündür. Ayrıca, tasarım ve yapıştırma bağlantılarının geliştirilmesi gerekmektedir. Bunun yanı sıra, ahşap ürünlerinin cam bileşenleri ile eşsiz kombinasyonu, arabirimleri ve uyumluluğu konusunda daha derin araştırmalara da ihtiyaç bulunmaktadır. Araştırmanın ana konusu, ahşap-cam kompozit yapı elemanının optimizasyonu ve geliştirilmesi amacıyla, her malzemenin en iyi özelliklerinin kullanılmasıdır. Yapıştırıcılarla yapıştırılan cam ve ahşap malzemenin ısı genleşme katsayılarının birbirine yakın

olması birleşim kuvvetini arttırmakta, ömrünü uzatmakta ve malzemeler arasındaki yük aktarımını mümkün kılmaktadır. Ahşap ve cam kompozit elemanının üretimi için ağır sanayiye ihtiyaç olmaması da önemli bir özelliktir. Tam aksine bu kompozit elemanlar hızlı ve düşük enerji sarfiyatı teknikleri ile imal edilmektedirler. Kullanılan malzemelerin ekolojik yapı tarzına daha uygun olması ahşap-cam kompozit elemanların değerini daha da arttırmaktadır. Bu araştırma kapsamında, yenilenebilir kaynaklara dayalı, çevreye duyarlı taşıyıcı sistem modüllerinin yaratılması, düşük enerji ile üretilen malzemelerin kullanılması, geri dönüşümlü ve bina içerisinde değiştirilebilir yapı elemanlarının kullanımının geliştirilmesi hedeflenmiştir. Cam ve ahşap malzemenin kullanıldığı yapılarda, doğru tasarım iyi uygulama ile buluştuğunda dış enerji kaynaklarından bağımsız, kendi enerjisini üretebilen akıllı yapılar inşa edilebilmektedir. Ancak bu olumlu gelişmelerin tersine, malzemenin yanlış kullanılması durumunda, ortaya olumsuz sonuçların çıkması kaçınılmazdır. Sunulan bu tezde, uluslararası projenin kapsamında, ahşap-cam kompozit yapı malzemesinin özelliklerinin daha iyi kavrayabilmek ve davranışlarını özümseyebilmek amacı ile, öncelikle ahşap ve cam ayrı ayrı, sonrasında ise iki malzemenin beraber ve onları birarada tutan yapıştırıcı incelenmiştir. Ayrıca bu malzemelerin gerek tek tek, gerekse kompozit olarak uygulanmasının, Türkiyedeki kullanılma durumları araştırılmıştır.

Bu araştırmada, küçük ölçekli ve orta ölçekli numunelerin üzerine yapılan deneysel çalışmalar dikkate alınarak, ahşap-cam taşıyıcı elemanların geliştirilmesi planlamaktadır. Küçük ölçekli ve orta ölçekli deneylerde huş ağacından üretilmiş kontrplak, soda-kireç malzeme temperli cam ve Otto-Chemie markalı Ottocoll S-660 ahşap-cam yapıştırıcısı kullanılmıştır. Sunulan tez, camın taşıyıcı bir eleman olarak kullanılma olasılığını belirtmektedir. Bina yapısının bir parçası olarak kullanılan bu malzemenin, farklı sıcaklıklarda, çevresel etkiler veya yük süresi gibi çeşitli koşullarda uzun vadeli davranışını bilmek önemlidir. Bu amaç orta ölçekli deneyler ile elde edilmektedir. Ayrıca, küçük ölçekli deneyler durabilite ve mekanik dayanım testlerini içermektedir. Durabilite testleri, hızlandırılmış yaşlanma etkisi altında, malzemenin davranışını araştırmak amacıyla yapılmıştır. Ahşap-cam kompozit numunelerin mekanik mukavemeti, çekme-yapışma ve kayma deneyleri ile ölçülmüştür. Ahşap-cam kompozit küçük ölçekli numuneler üzerinde yapılan eskitme deneyleri kapsamında, donma-çözülme, ıslanma-kuruma, yüksek sıcaklığa dayanım, asitlere ve UV ışınlarına dayanım bulunmaktadır. Ayrıca, eskitme deneylerinden çıkan numuneler üzerinde tekrar mekanik deneyler uygulanarak, çevresel koşulların eskitici etkisinin numunelerin mevcut dayanımı üzerindeki etkisi de incelenmiştir. Durabilite deneylerinin yapılmasının amacı çevresel koşulların ahşap-cam kompozitlerin mekanik özelliklerine ve hacim sabitliğine etkisinin incelenmesidir. Türkiye'nin sert iklim koşulları binaların performansını etkilemektedir. Özellikle çevresel koşullar ahşap yapıları daha fazla etkilemektedir. Ahşap-cam kompozitleri açık havada kullanımı sonucu, çevresel koşullar ahşap kısımlarda deformasyon ve çürümelere sebep olmaktadırlar. Bundan dolayı, durabilite deneyleri ile ahşap-cam kompozitlerin performansı ölçülmüştür. Küçük ölçekli deneylerde suyun özellikle ahşabın üst yüzeyinde kalarak iç kısımlarda şişme-büzülme ile hasar oluşturması fark edilmiştir.
Orta ölçekli deneylerde, sekiz adet orta ölçekli numune, deney düzeneğine monte edilmiş dış ortamda uzun süreli yükleme deneylerine maruz kalmıştır. Numunelerin üzeri bir sundurma ile örtülerek dış etkilerden kısmen korunması sağlanmıştır. Numunenin L-kesit kontrplak elemanlar ile üretilmiştir. Kontrplak kesitler camların

düşey doğrultuda iki yanına yapıştırıcı ile yapıştırılmıştır. Numunelerin uzun süreli yüklemeleri için ahşaptan kutu şeklinde deney düzenekleri hazırlanmıştır. Yükleme, düzeneğin içerisinde bulunan ahşap hazneye, hedeflenen yüklemeye uygun miktarda kum doldurularak yapılmıştır. Numunelere yükleme iki farklı yük seviyesiyle yapılmıştır. Buna göre, camın iki yanında bulunan yapıştırıcı şeritleri, iki farklı gerilmeye maruz kalmış şekilde yüklenmiştir. Deney süresinde, günde bir kere camın rölatif düşey hareketi okunup ve kaydedilmiştir. Bu ölçüm, numunenin üzerinde orta seviyeye yerleştirilmiş olan mekanik yerdeğiştirme ölçerler (komparametreler) ile yapılmıştır. Bunun yanısıra her gün, havanın bağıl nemi ve ısısı otomatik ölçüm aleti ile ölçülüp kaydedilmiştir. orta ölçekli deneylerin sonucunda camın rölatif düşey hareketinin değeri küçük cıkmıştır ve bu iyi bir sonuçtur.

Ürünün çok yönlü özellikleri ve mükemmel uyumuna, deneyler sonrası olumlu sonuçlara rağmen ilk hemen piyasada kabul gören ve eline geçiren bir ürün olması beklemek iyimser bir yaklaşım olabilir. Ancak projenin ana hedeflerinden biri, Türkiye'de yavaşta olsa örnekleri görülen ekolojik az enerji tüketen yapılar için olumlu bir yapı sistemi olması beklenmektedir. Ekolojik yapıların vazgeçilmez malzemesi olan ahşabın kullanım alanlarının arttırılması ve cam kullanımının, beton ve çelik ile beraber kullanılmasının dışında özendirilmesi beklenen sonuçlardan biridir. Böylece, Türkiye'de çok tanınmayan ahşap ve cam kompozit taşıyıcı elemanların daha yaygın olarak ve güvenle kullanılabilmesi için deneysel ve teorik çalışmalar yaparak, gerek ahşap-cam üzerinde daha fazla veri elde edilebilir.

Ayrıca, tez, tasarım kavramlarını ve genel performansı artırmak amacıyla yapılan bileşenlerin performans değerlendirmelerini içermektedir. Ahşap-cam kompozit perde elemanları kullanılarak pilot projeler tasarlanmıştır. Bu projeler; dinlenme alanı, kiosk, turist bilgilendirme ofisi ve gölgeliktir. Doğal bir malzeme olan ahşabın yapıya kattığı sıcaklık ile camın şeffaflığı bu pilot projelerde bütünlük sağlamıştır. Sürdürülebilir ve ekolojik bir malzeme olan ahşabın yapısal eleman olarak tek başına kullanılması halinde diğer yapı malzemeleri ile beraber de kullanılmaktadır. Ahşap, diğer yapı malzemesi olarak cam ile beraber kullanılabilmesi için ahşap-cam kompozit yapı elemanın piyasaya tanıtılması ve diğer yapı sistemleri arasında yer alması için ahşap ve cam endüstrisiyle birlikte çalışılması yapılmıştır. Bu amaca yardımcı olmak ve genel eğilimi belirlemek için ahşap ve cam endüstrileriyle anket yoluyla iletişime geçilmiştir. Bu anketler, grafiksel olarak sonuçlandırılmıştır. Ahşap ve cam endüstrileri büyük oranda ahşap-cam kompozit yapı elemanının taşıyıcı özelliğinin iyi olabileceğini düşünmüştür. Ahşabın çalışması kontrol altına alınıp, camın olumsuz yönleri önlenebilirse yüksek mukavemetli bir yapı elemanı olacağı düşünülmektedir. Bu çalışmanın amacı, sanayiye ahşap-cam parçaları üretmek için gerekli bilgi katkısı sağlanmasıdır. Çalışmaya, ahşap, cam malzemeleri ve ahşap-cam kompoziti oluşturmak için malzemeleri bir araya getiren yapıştırıcıların özellikleri üzerine yapılan araştırma ile başlanmıştır. Bu çalışmanın ardından, deneyler, pilot projeler ve anketler anlatılmıştır.

1. INTRODUCTION

Timber construction systems are used as main building systems by many countries in the world. As well as, timber is a traditional constructional material in Central Asia where the seeds of Turkish architecture were sown. The material was used as a structural material extensively at traditional structures in Turkey. After the 1509 Earthquake in Turkey, stone structures were banned in Istanbul, because all the stone structures of byzantine era were badly damaged that was reason for return to the timber structures. During the Ottoman period in Turkey, majority of houses in Anatolia were made by timber. Since 1999 Marmara Earthquake, because of timber structures were more resistant against earthquake, the use of timber was increased, but the usage of the material has been decreased significantly in recent times. The developments in other building materials are main reasons to reduce the use of timber structures.

1.1 Objective

Since timber is a natural, durable and sustainable material, it is important to find an appropriate method to increase the usage of timber structures. According to the research for this thesis, the unique combination of timber and glass structural elements may be a good alternative to use more timber structures. To be able to perform this composite element, it is important to get a good knowledge of the materials timber, glass and the adhesive that holds these materials together. This has been achieved by an introductory literature review. Timber with its aesthetically expression and glass with transparency property give architects and engineers new opportunities to use them as load bearing systems for constructions. Also, it is significant to introduce these materials to the contemporary construction industry.

The thesis includes experimental tests which were performed at Istanbul Technical University, Faculty of Architecture. Tests provide more details and informations about the behaviour of timber-glass composite system. The research was carried out as a part of European Project, EUWOODWISDOM-NET research program with participant from Austria, Brazil, Chile, Germany, Sweden, Turkey and Slovenia. The

WoodWisdom-Net International Research Programme is on timber material science and engineering in forest-based value chains. Scientific and the Research Council of Turkey (Tubitak) is the national funding organisation of Turkey. The part of mentioned research project which carried out by the Turkish team was supported by TÜBITAK. The Tubitak project no is 110O950. Project title is Urban Wood, timber based construction for multi-storey buildings concerning the potential of adhesives bounded timber-glass composites as load bearing beams, columns, stiffening panels, with the project acronym "Load Bearing Timber-Glass Composite Structures (LBTGC)". Duration of the Project was 3 years, starting from January 2012 and ending in December 2014. The project comprises investigations relating to the mechanical behaviour as well as architectural aspects on timber-glass composites in load-bearing structures. Also, the research includes feasibility studies and performance assessments of the components in order to improve the overall performance. The main idea in the project is that combining timber and glass by using adhesive joints.

1.2 Scope

Timber and glass are materials with applicable properties. If the materials can be combined appropriately, benefits can overcome the drawbacks and timber-glass elements can be use as a part of the load-bearing structure of buildings. The main aim of the research for this thesis is using timber and glass as load-bearing elements and the elements can be used like concrete or steel structures in buildings. This has been done in terms of a research on both materials and the adhesive for timber-glass applications. The other scope is to further analyse the durability of the timber-glass materials as small-sized specimens. This purpose has been done with evaluate results from laboratory tests. In order to be able to use the system as part of the building structure, its long-term behaviour under climatic conditions are evaluated. This purpose is achieved by the medium-sized experiment. Other main scope of the master thesis, as a part of international research project, is develop a marketable building system composed of timber and glass sections and show an overview of possible architectural design applications with using of the structural composite. Also, another aim is research for industry to produce timber-glass components for the Turkish market to develop sustainable systems with using renewable and recyclable components. The intention is raising knowledge about how much is possible to produce this new product and how much customers will tend to use it. This purpose has been done by questionnaire study method.

1.3 Outline of the Thesis

In the first part of the thesis, a summary about the materials timber and glass is given in Chapter 2. Also, the research on timber-glass composite and the adhesives that hold two materials together are presented in this chapter. Examples of timber and glass structures of Turkey are also shown in this part. In Chapter 3 the overview of performed experiments are provided. This includes method, scope and results of the experiments. In Chapter 4 the pilot projects that were designed with timber-glass composite elements are described. In Chapter 5 a market research which has been done on the both materials are presented. The Chapter 6 comprises conclusion of research and suggestions. References are presented afterwards.

2. LITERATURE REVIEW

The intention of this chapter is to give an overview of timber, glass, the adhesive that holds these materials together and timber-glass structural composite. The first part of chapter includes the description of timber material properties, structural timber products and structural applications of timber. Also, the relevant examples of timber structures in Tureky are described. The second part includes material properties and types of glass. The study of glass as a load-bearing building material is also given in this part. In addition, several examples of glass structures in Turkey are presented. The third part of literature review is a study on structural adhesives for timber-glass applications. The idea of research is combining timber and glass with adhesives to produce structural composite elements. The last part of this chapter is a research on timber-glass composite elements with several examples.

2.1 Timber

Today, forests account for about 3.9 billion ha worldwide, i.e. about 30% of land is covered with trees. Some 57% of these forests are located in developing and newly industrialised countries and about 43% in the industrialised world. From prehistoric times to the start of the industrial age, timber always played an important role in our relationship with the environment. At first it was used in simple housing, but later came to be used for more complex projects. Timber is as a building material in Europe and Asia from prehistoric times to the 19th century. In order to use timber as building material it is important to understand timber's anatomical structure. [1] In this section, the knowledges that should be known about the timber material are given briefly.

When using timber, it is important to be aware that a piece of timber, a beam or plank is part of a vegetable organism, a tree, and that its growth and quality are influenced by its surroundings. No one piece of timber is identical to another. Its properties depend in the first place on the kind of tree, and in the second on its position within the trunk. The trunk consists of longitudinal tubiform cells, which are responsible for transporting nutrients as the tree grows. The structure of the cell walls and the cell framework determine the strength of the timber. Unlike building materials such as non-reinforced concrete or masonry blocks, timber has a directional structure, correspondig to the path taken by nutrients from the truk to the branches. Cell growth takes palace around the center of the trunk, called the pith cavity, the oldest part of the trunk. It takes palace in the form of annual growth phases, generally lasting from April to September in temperate zones, and creates annual rings. Within these rings, the softer early timber is formed in the spring from large-pored cells, and the more solid late timber with thick-walled cells follows in the autumn. The proportion of late timber essentially determines the strength of the timber (Figure 2.1). [2]

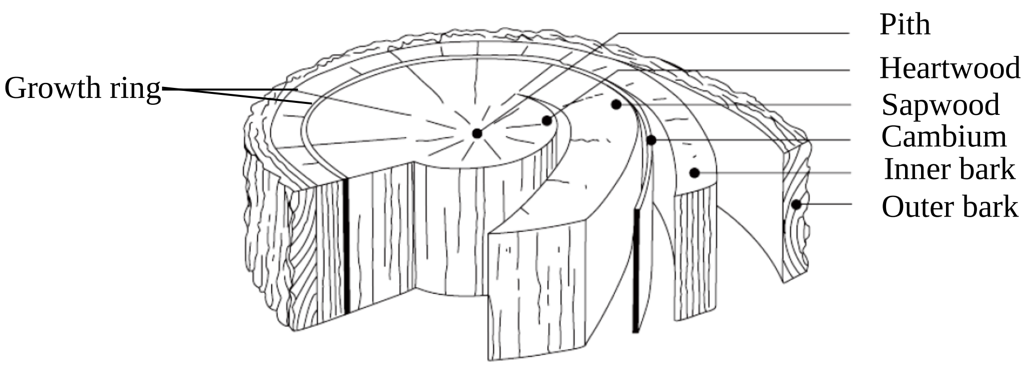


Figure 2.1: Cross-section of timber trunk [58]

Photosynthesis converts solar energy into timber. About 50% of its mass is carbon, which is fixed through absorption of the greenhouse gas carbon dioxide. Because of this, solar energy is stored in timber. Also, forests and timber products make an effective contribution to protecting the climate. The use of timber reduces the consumption of non-renewable fuels and products made from non-renewable resources. As mentioned, timber consists of cells whose cavities provide thermal insulation and whose cell walls absorb and release moisture. One of the benefits of that is to ensure a healthy interior climate. This property makes timber as a building material. A large number of species of trees can be used to produce structural lumber. As a biological material, timber represents a unique structural material because its supply can be renewed by growing new trees in forests which have been harvasted. [1,3]

2.1.1 Properties of Timber

Timber properties are divided into two parts: physical and mechanical properties. The properties are described as following.

2.1.1.1 Physical Properties

The physical properties of timber vary by species and include density, moisture, thermal, electrical and acoustical properties, combustibility, resistance to chemicals, durability, strength, grain and colour. The strength and stiffness of timber are affected largely by changes in timber density and moisture content.

- **Density**

Density can be measured visually by the annual rings. The density of timber is determined principally by two factors, the amount of timber substance per unit volume and the moisture content. Many characteristics of timber are affected by density. Timber of high density is stronger and stiffer than timber of low density, other factors such as moisture content being equal. Timbers of high density typically shrink and swell more with changes in moisture content than do timbers of low density. Also, timber has a low gross density, so its thermal storage capacity is less than for solid building materials such as masonry or concrete. The thermal storage coefficient of timber is 350 Wh/m^3K, whereas that of standard concrete is 660 Wh/m^3K. This is particularly problemetic for summer thermal protection. The thermal compensation between cool night and daytime warming is less in timber than for solid structures. [2,5]

- **Moisture**

Timber in the living tree is associated with moisture. In the green timber the moisture content varies from as little as 30 percent to about 200 percent. Most uses of timber require that the moisture content be fairly low. The timber should be dried to a moisture content as close as possible. Removing it by drying renders it usable as building material. [5]

- **Thermal Properties**

Timber, as is common with other materials, expands when heated, but not generally to the same degree as do materials such as metals. The thermal coefficient of expansion for timber parallel to grain may, for example, be as little as one three-hundreds that for steel. Timber is a good insulator, that is, it has a high resistance to heat flow. The thermal conductivity of timber is much less than that of many other structural materials. The thermal conductivity of timber is only about one-sixteenth that of sand and concrete and only about one four-hundredth that of steel. So timber has considerably better thermal insulation properties than many other building materials. This characteristic that presents timber suitable for use as internal paneling, the sheating of timber-framed buildings. [4,5]

- **Electrical Properties**

The most important electrical property of timber as it relates to structural use is its resistance to the passage of electric current. At low moisture content, timber is classified as an electric insulator rather than a conductor. The electric resistance varies greatly with the moisture content. It decreases as the moisture content increases. [5]

- **Acoustical Properties**

As mentioned previously, timber has lower gross density. This means that timber has good acoustic absorption properties, for which reason it is used with good results in construction. It is however a poor acoustic insulator. The lightness of timber construction elements means that by weight alone it provides insufficient insulation. Nonetheless, by employing multiple layers of different thickness and properties it is possible to achieve a genuinely high specification. As well, timber has a much greater damping capacity than do most other materials. Timber frame walls have been found to provide good sound barriers in buildings. [5,7]

- **Combustibility**

Timber is combustible. It is also a good insulator, as is the char formed during combustion. The exposure of timber to elevated temperatures results in a loss of unit strength. With short-time exposure there may be no lasting effect, but long-time exposure causes a permanent loss in unit strength, the degree of loss being dependent on both the temperature and the duration of exposure. In fires of short duration, the loss of load-bearing capacity may be only the loss that results from a reduced effective cross section. Different timbers char at varying rates, largely as function of their density with the higher density timbers charring more slowly. Certain of the denser hardwoods (>650 kg/m^3) used for structural purposes merit rates of 15 mm in 30 minutes, e.g. keruing, teak, greenheart, jarrah. Timbers of lower density will char more quickly, e.g. western red cedar is quoted as 25 mm in 30 minutes. The rate of charring is little affected by the severity of the fire, so for an hour's exposure, the depletions are 40 mm for most structural timbers and 30 mm for the denser hardwoods. [4,5]

- **Resistance to Chemicals**

Timber is naturally resistant to many chemicals. As a consequence, it is the preferred material for numerous applications in industries where chemicals are used in processes. It is also commonly used in the construction of buildings for bulk chemical storage where the timber will be in direct contact with the chemicals. [5]

- **Durability**

As will be mentioned in the protection of timber’s part, timber, like other materials, is subjected to attack by various destructive agents. The ability of timber to resist organisms that cause decay is referred to as natural durability. The durability of buildings can be enhanced by use of naturally durable timber species, by preservative treatment of less durable species and by good practice in design and construction to protect the timber from degrading influences. When kept at a moisture content below 22% timber will exceed the 60-year life expectancy required for buildings. However, if timber is subjected to an environment where its moisture content may rise above

22%, e.g. as a result of poor workmanship, the failure of a cladding system or poor detailing around openings, then it may suffer from fungal decay. [4]

Some of the more important growth characteristics that affect the structural properties of timber are density, moisture content, knots, checks, shakes, splits, slope of grain, reaction timber, and decay. Density and moisture content have been described previously. Knots constitute that portion of a branch or limb that has been incorporated into the main body of the tree (Figure 2.2). Knots decrease the mechanical properties of the timber because the knot displaces clear timber and because the slope of the grain is forced to deviate around the knot. In addition, stress concentrations occur because the knot interrupts timber fibers. Knots have an effect on both tension and compression capacity, but the effect in the tension zone is greater. [3]

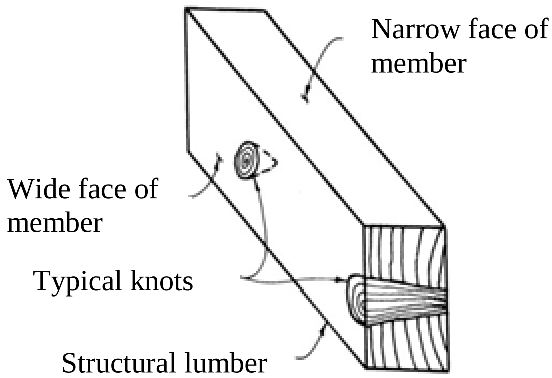


Figure 2.2: Examples of knots [3]

Checks, shakes, and splits all constitute separations of timber fibers (Figure 2.3). Checks are radial cracks caused by non-uniform volume changes as the moisture content of timber decreases. Checks therefore are seasoning defects. Shakes, on the other hand, are cracks which are usually parallel to the annual ring and develop in the standing tree. Splits represent complete separations of the timber fibers through the thickness of a member. A split may result from a shake or seasoning or both. [3]

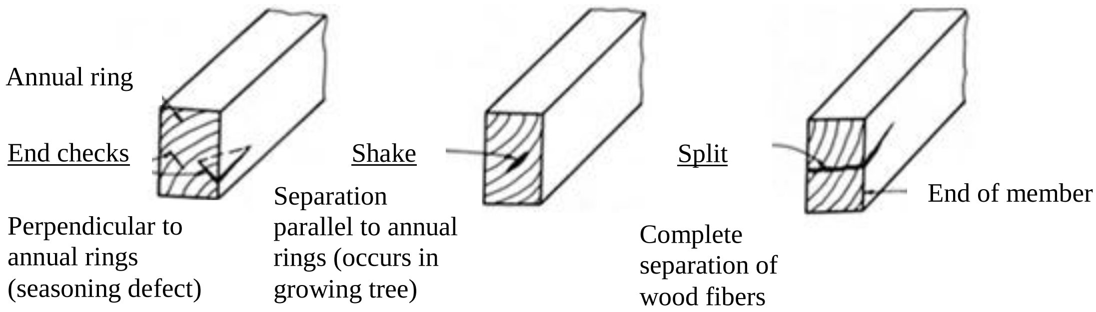


Figure 2.3: Checks, shakes, and splits [3]

The term slope of grain is used to describe the deviation of the timber fibers from a line that is parallel to the edge of a piece of lumber (Figure 2.4). Slope of grain has a marked effect on the structural capacity of a timber member. [3]

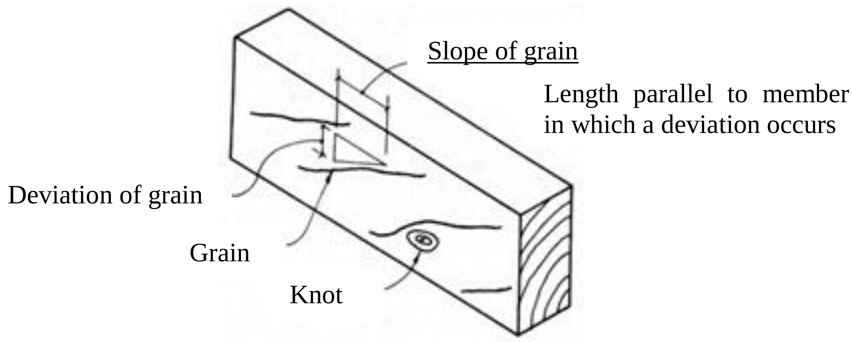


Figure 2.4: Slope of grain [3]

Decay is a degradation of the timber caused by the action of fungi. A more complete overview of several effects that led to destroy timber are described in the following part. The major ones are; decay, moisture, insects and fire. Extra care should be devoted to protect the timber. The most important issues to be considered in order to increase the service life of timber structures and decrease the maintenance costs are explained as following.

2.1.1.2 Defects and Deterioration of Timber and Protective Treatments

Unlike the mineral materials masonry and concrete, timber, as an organic material is subject to damage from fungi and insect. Decay is caused by fungi which feed on the cellulose or lignin of the timber. Fungi that destroy or discolour timber can grow when free moisture is available in the cell cavities from condensation or precipitation. Accordingly, protecting the timber against fungi in the first place relies on limiting the moisture content through the type of construction. In addition, Michael Volz [1] has expressed that “problematic changes in moisture content lead to damaging deformations through swelling and shrinkage, or create the right conditions for fungi that destroy timber.“ Where it is not possible to limit the moisture content, e.g. roof covering of timber shingles, outdoor floor coverings, resistant species of timber can ensure a durable construction. Insects can attack and destroy timber too. Insect attack is much less dependent on timber moisture content. However, it is most likely to occur when timber is unseasoned or wet. The best ways of dealing with this are to leave the timber exposed so that it is easily inspected, e.g. exposed columns and beams in timber-frame construction, or to enclose the timber so that it is inaccessible to insects, e.g. behind walls and in floors. Good ventilation of crawl spaces and proper drainage also aid in preventing insect attack. As previously mentioned in behaviror of timber in fire’s part, timber is a flammable material. Its behaviour in fire is not as problemetic as would seem at a first glance. Timber with a large gross section burns relatively slowly and evenly from outside to inside because of the accumulating charcoal layer, so that it takes time to lose its loadbearing capacity. Beside, if timber is attacked, the outward form of the timber can be affected, but also its loadbearing capacity, to the extent of completely destroying the building. It is important to get these several ways to protection of timber, when planning timber buildings. Timber moisture content of at least 20% should be considered for construction. Also, the design of planners and particularly the details of structural buildings, should be laid out to avoid permanent moisture penetration of timber building sections. Chemical timber protection should be used only when all other timber protection methods are exhausted. Possible chemical timber preservatives include water-soluble, solvent-based or oily coatings or impregnation materials. Also, “chemicals can be impregnated into the lumber and other timber products by a pressure-treating process. The chemical preservatives prevent or effectively retard the destruction of timber. Pressure treating usually takes place in a large steel cylinder. The timber to be treated is transported into the cylinder on a tram, and the cylinder is closed and filled with a preservative. The cylinder is then subjected to pressure which forces the chemical into the timber.” [3] For loadbearing timber structures, preventive treatment is necessary. Timber components which are near or in contact with the ground are subject to the highest risk. Contact with the soil and thus permanent exposure of the timber to moisture should be avoided in any structure. A base zone of about 30 cm separating the timber from the ground is typical of timber structures. [2] As well according to Julius Natterer [1], protection against splashing water-the bases of columns should be raised $\geq$ 150 mm above the ground. He also has expressed that horizontal surfaces exposed to the weather should be avoided as far as possible and galvanised steel, stainless steel or brass parts should be used outdoors. The regulations prescribe protection for loadbearing timber components and recommend it for non-loadbearing timber components. Accordingly, the aim of building with timber must be to achieve the lowest possible risk class by means of constructional measures. As a conclusion, if timber is protected (i.e., not exposed to the weather or not in contact with the ground) and is used at a relatively low moisture content (as in most covered structures), timber performs satisfactorily without chemical treatment.

2.1.1.3 Mechanical Properties

Mechanical properties of timber include resistance to compressive and tensile loads, resistance to bending loads, resistance to deformation and resistance to rapidly applied or long-continued loads.

- **Resistance to Compressive and Tensile Loads**

The crushing strength of timber is an important characteristic in posts, columns, piles, and truss chords and in those web members of trusses that are subjected to compressive stress. When timber is compressed under high loads perpendicular to grain, the cell cavities are eliminated and cell wall bears on cell wall. Eventually the timber becomes greatly densified and its compressive strength across the grain becomes very high. However, the crushing which takes place with increasing loads may produce deformation, which is unacceptable. The tensile strength parallel to grain is the highest strength property of timber. The tensile strength perpendicular to grain, on the other hand, is one of the lowest strength properties of timber. Besides its weakness when loaded in this direction, this property is sensitive to stress concentrations. [5]

- **Resistance to Bending Loads**

Timber develops high strengths in the extreme fiber in bending and has a high strength-to-weight ratio in comparison with other materials. The bending strength increases markedly with drying, but this increase is offset by the development of drying defects. [5]

- **Resistance to Deformation**

Timber under long-continued load will continue to deform, a deformation which is generally non-recoverable. Creep, or sag, will generally be greater if the timber is wet when the load is applied and then dries during the time the load is on the member. Typically, creep deformation may be expected to be about equal to the intial deformation if environmental conditions do not change. [5]

- **Resistance to Rapidly Applied or Long-Continued Loads**

The load that will cause failure in a member that must carry loads continuously for a long period is much less than the load that would cause failure in a few minutes. For example, a timber member under the continuous action of bending stress for 10 years will carry only about 60 percent of the load under which the same member would fail in a few minutes. Conversely, if the duration of stress is very short, the load-bearing capacity will be much higher than normally published strength properties. The load that will produce failure in 1 second is approximately 25 percent higher than that causing failure in a few minutes. [5]

2.1.2 Structural Timber Products

Timber products are explained in this section. Recent improvments in technology have expanded the types of panel products which can be labeled as structural. This term is used to mean that one of the intended functions of the panel product is to successfully resist the actions of externally applied forces on the panel for a specific applications. This indicates that it is possible to influence the load-bearing capacity in a certain direction through the deliberate arrangement of the individual particles. Swelling and shrinkage of timber-based products is generally less than that of solid timber. Another advantage of slab-like timber-based products is the possibility of producing boards or beams in unlimited sizes. [5,6]

2.1.2.1 Types of Structural Panels

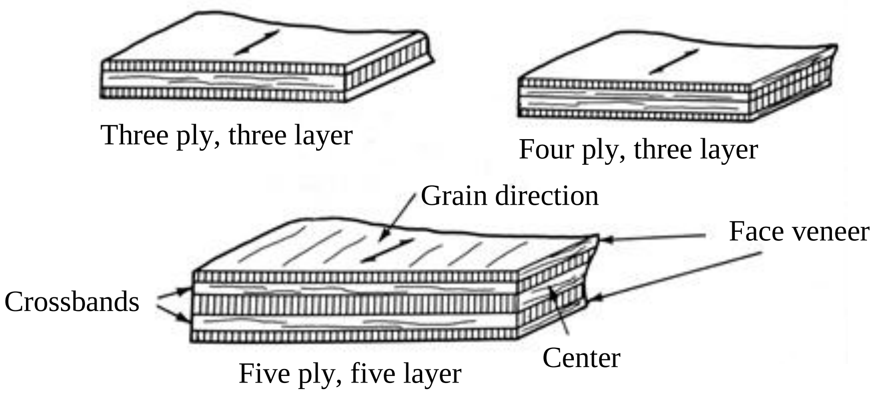
All timber-based structural panels are composite materials. That is, they are a composite of timber elements such as veneer, particles, flakes, or fibers and some form of adhesive. Plywood is the most commonly known structural product and is a glued assembly of thin sheets of timber called veneer. Particleboard is a combination of wood particles and adhesive and has found wide acceptance structurally as floor underlayment. Waferboard is a variant of particleboard with flakes as the basic timber element and is designed to compete directly with the softwood plywood in the structural sheathing market. Other forms of this product have timber strand or flakes in layers oriented in diffirent directions through the thickness of the panel. These oriented strand boards (OSB) compete strongly with plywood in the light-frame residential and commercial marketplace. [5]

2.1.2.2 Typical Applications

Structural timber panels are typically used as sheathing to provide a strong, stiff covering over some relatively flexible and weak framework. In new residential and commercial construction, timber panels are most often used as roof sheathing and decking, floor decking and underlayment, wall sheathing, and exterior siding. Additionally plywood is used in the manufacture of structural subsystems such as stressed-skin panels, built-up beams or columns, and other modular assemblies. Because plywood has long been popular in the building industry as structural panel material, its performance has become the standard by which other panel products are judged. [5] For this and due to it was used as a material of experimental specimens which will be explained in Chapter 3, plywood is described firstly and thoroughly.

- **Plywood**

Plywood is a panel or sheet product composed of an odd number of layers of thin sheets of timber called veneers. These layers are then glued together with the grain of the adjacent layers at right angles (Figure 2.5). Each layer may contain one or more veneers according to the thickness of the board (8-33 mm). The face veneers are oriented with the grain parallel to the long dimension of the panel, and the crossbands are parallel with the short sides. Plywood is manufactured in sheets or panels with 4 by 8 ft (1.22 by 2.44 m) as a generally standard size. Other sizes maybe available for specific types of plywood. [5]



Figur 2.5: Layer nature of plywood [5]

Many variables in the composition of plywood affect its properties and performance as a structural panel. These include: [5]

1. Number and thickness of the layers and plies
2. Species of veneer (may not all be the same)
3. Grain orientation of the plies
4. Quality or grade of veneer
5. Type of adhesive

Combinations of these variables enable the manufacturer to tailor the product for specific uses. Hence, many different types of plywood are available. Thus, designers must understand something of the composition of plywood to select the appropriate panel for a specific application. [5]

Plywood also has many of the advantages and properties of solid timber such as light weight, ease of working, high strength-to-weight ratio, and ease in fastening. Additionally, plywood is split-resistant and has excellent shock absorbancy characteristics. Like timber, plywood is an insulator and has low thermal conductivity when dry. It is also an electrical insulator when dry and has excellent chemical resistance. (all these properties vary by species and mositure content.) One of the major advantages of plywood is its fastening characteristics. Because of the crossbands, nails may be placed near the edge of the panel without danger of panel splitting. This is one of the keys to its success as a sheathing material. Another advantage is its use as a slab element with a high shear strength where a stiffening function is necessary, e.g. in roof plates, in conjunction with ribs as ribbed slabs. Plywood in conjunction with squared sections can also be made into panels for use in house building. The consumption of material is low in I-beams, T-beams and box beams, but labour costs are high. [1,5] Moreover, the transverse arrangement layers of plywood, prevents the timber from moving and gives the panel the necessary strength and stability in every direction. Plywood is thus particularly suitable for reinforcing timber structures and loadbearing walls. They can also be used for exterior work, provided the correct adhesive is used, also edges are particularly susceptible to damp, and should be covered or sealed if installed as façade panels. [2]

About common types of plywood, it is manufactured in two types, classified on the basis of moisture resistance. Exterior plywood has a 100 percent waterproof glueline. Exterior-type panels should be used when they will be exposed to weather or when their moisture content exceeds 18 percent. Interior plywood may be manufactured with several different (including waterproof) adhesives and veneer combinations. It may be used if not exposed permanently to the weather or if the equilibrium moisture content in service does not continuously or repeatedly exceed 18 percent. [5]

If it is decribed other types of plywood, veneer plywood, with at least five layers and more than 12 mm thick, is also called multiplex board. In comparison with other timber-based products, this material is suitable for loadbearing constructions because its very high modulus of elasticity and high strength make it suitable for situations with high stresses and aslo can be used for external cladding. [2,6] Strip board and blockboard, also known as coreboard, is plywood, that consists of at least three layers with a middle layer of strips lying crossways to the covering veneers and giving the board particularly good loadbearing properties. The most commonly used plywood and laminated boards include veneer plywood, strip and blockboard, three- and five-ply boards, laminated boards, multiplex boards (Figure 2.6). [2]

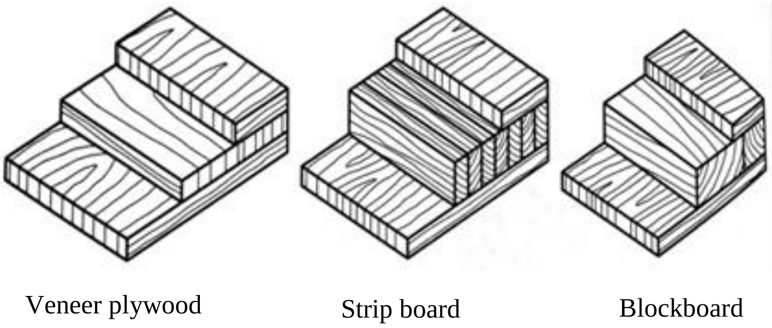


Figure 2.6: Isometric diagram of veneer plywood, strip board, blockboard [2]

In addition to plywood, a brief description of other timber structural panels is given in following paragraphs which includes structural particle board, wafer board and OSB.

- **Structural Particleboard**

Structural particleboard is a nonveneer panel manufactured from small wood particles (as opposed to larger wafers or strands) bonded with resins under heat and pressure (Figure 2.7). It is most widely used as floor underlayment. [3,5]

Figure 2.7: Structural particleboard [47]

- **Waferboard**

Waferboard is a nonveneer panel manufactured from reconstituted wood wafers (Figure 2.8). These wafer-like wood particles of flakes are compressed and bonded with phenolic resin. The wafers may vary in size and thickness. Waferboard is becoming more widely accepted and is used in competition with plywood for roof and wall sheathing and subfloors. [3,5]

Figure 2.8: Waferboard [48]

- **Oriented Strand Board (OSB)**

Oriented strand board (OSB) is a new product and a nonveneer panel manufactured from reconstituted wood strands or wafers (Figure 2.9). Strand-like wood particles that are compressed and bonded with phenolic resin and directionally oriented. Three to five layers of these particles are arranged in a panel at right angels to one another. Oriented strand material is also used as corestock in composite plywood. These particles measure approx. 0.6 x 35 x 75 mm. OSB is primarily employed in the form of loadbearing and bracing sheathing. [5,6]

Figure 2.9: Oriented strand board (OSB) [49]

As a conclusion, plywood, structural particleboard, waferboard and oriented strand board (OSB), collectively referred as timber structural panels, are widely used building materials with a variety of structural and nonstructural applicattions. Some of the major structural uses are: [3]

1. roof, floor, and wall sheating
2. horizontal and vertical (shearwall) diaphragms
3. structural components
    a. lumber-and-plywood beams
    b. stressed-skin panels
    c. curved panels
    d. folded plates
    e. sandwich panels
4. gusset plates
    a. trusses
    b. rigid frame connections
5. preservative-treated timber foundation systems
6. concrete formwork

Other timber-based products are described as following in this part. These include glue-laminated timber (glulam), cross-laminated timber, laminated veneer lumber (LVL), chip board and fibre products.

- **Glue-laminated timber (glulam)**

Glue-laminated timber (glulam) meets very strict requirements in terms of formal stability and loadbearing capacity. It consists of three or more individual boards, or lamination, stacked horizontally and glued together across their width. The thickness of the laminations should generally not exceed 30mm, although in straight components this can be increased to 40mm. The laminated gluing means that there is next to no deformation of the timber cross section. Glue-laminated timber is often used for wide loadbearing structure spans because it can be supplied in cross sections of up to 200 cm, and up to 50 m long. In addition, glued-laminated (glulam) timber finds its major application for flexural members, columns, arches, truss members, and decking. Because a degree of homogenization is achieved when glue laminating structural lumber into larger sections, glulam structural members and products have higher allowable stresses and more reliable stiffness than sawn timber. Also, they are available in curved or rectilinear forms of larger cross sections and longer lengths than sawn timber. [2,5,6]

- **Cross-laminated timber**

Cross-laminated timber consists of several layers 17 or 27 mm thick glued to each other crosswise. The crossing effect makes the elements very stable in terms of form and these boards are useful for roofs and walls constructions. Walls can therefore be built up to four storeys high using this material. [2]

- **Laminated veneer lumber (LVL)**

Laminated veneer lumber (LVL) is fabricated from sheets of veneer similar to that used in plywood and generally makes use of the same species of timber used in the production of structural plywood. The veneer typically ranges in thickness between 1/10 and 1/6 in. Uses of laminated veneer lumber include beams, joists, headers, and scaffold planking. LVL can also be used for the higher-quality tension laminations in glulams. The use of LVL is economical where the added expense of the material is offset by its increased strength and greater reliability. [3]

- **Chipboards**

Chipboards use the waste products of the timber industry. Boards are made by compressing sawdust and plane shavings with adhesives. Unlike plywood, this does not produce continuous layers. They can be used either as reinforcing planking for walls, floors, ceilings and roofs or fitted in above-floor constructions as dry screed. [2]

- **Fibreboards**

Fibreboards consist of a mixture of prepared long timber fibres and fillers that are pressed together with the help of water, pressure and heat without the need for any further binders. The strength of fibreboards varies from low to high depending on the degree of compression. Fibreboards are suitable for interior fitting-out works, roof decking, packaging, fillings and as sound and thermal insulation. [6]

2.1.3 Timber in Structural Applications

Many of buildings constructed with timber are single-family residences, but many larger apartment buildings as well as commercial and industrial buildings also use timber framing. The widespread use of timber in the construction of buildings has both an economic and an aesthetic basis. The beauty and the warmth of exposed timber are important in architectural considerations. [3]

2.1.3.1 Loadbearing Systems

The structural stability of a building depends on various factors. First, the material used must have an adequate loadbearing capacity and appropriate dimensions to absorb the vertical loads from walls, roof and ceiling. The subsoil must also be able to take such loads. Horizontal forces also affect all buildings, mainly from wind loads, earthquake loads (seismic), but also impact loads that affect the structure horizontally. [2]

2.1.3.2 Load-bearing Capacity of Timber

Unlike masonry, which is ideally suited for dealing with load and pressure, timber can absorb compressive and tensile forces to an equal extent. For construction as far as possible, the timber should be installed so that the load is placed on its efficient longitudinal axis, where it can absorb compressive and tensile forces. In general, load bearing capacity depends on the proportion of thick-walled timber cells, and thus on the density of the timber. Hard deciduous timber such as oak is thus particularly suitable for compressive loading, as a sill or threhold timber, for example, while long-fibred coniferous timber is more suitable for dealing with bending loads. [2]

2.1.3.3 Timber Construction Systems

Modern timber frame construction originated in North America. Rapid changes in the constructions of the country demanded a simple, economical building method that could be carried out in a short time. Timber was the material that was available and suited to all the content's different climatic conditions. [2] Types of timber construction systems are described in this section. The two basic types of light-frame construction: platform frame construction and balloon frame construction are explained. Also, timber frame systems, skeleton construction, timber panel construction, open panel platform frame system, closed panel platform frame system, volumetric, post and beam can be described as following.

- **Timber Frame Systems**

Timber frame construction is a prefabricated building system in which plywood, oriented strand board (OSB) or a similar sheet material is nailed to a timber framework of walls, floors and sometimes roof components, forming structural panels (Figure 2.10). These are assembled to form a rigid structure designed to support and transfer all dead, live and wind loads to the building foundations. Timber frame structural elements form the main structural components of the timber frame house and transfer vertical loads to the ground floor concrete slab and foundations. [4] As well, this system is the most delicate form of construction in timber. Vertical columns and horizontal joist floors or plates form the loadbearing structure. The consistency of the materials used for the vertical and horizontal linear members and the form of the joints determine the spans that can be achieved and the architectural appearance of the loadbearing construction. Assembly of the individual pieces takes place on site storey by storey. Frame construction is distinguished from other forms of timber construction by the fact that the loadbearing structure functions completely independently of the enclosing elements such as partitions or façades (glazing is conceivable). This specialisation of the elements is not very economic in terms of material consumption, but does lead to good flexibility in the internal layout and design of the façade, and enables longer spans. [6]

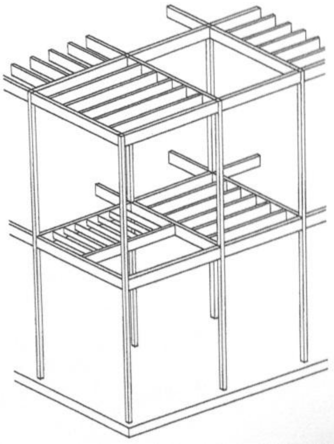


Figure 2.10: Timber frame construction [6]

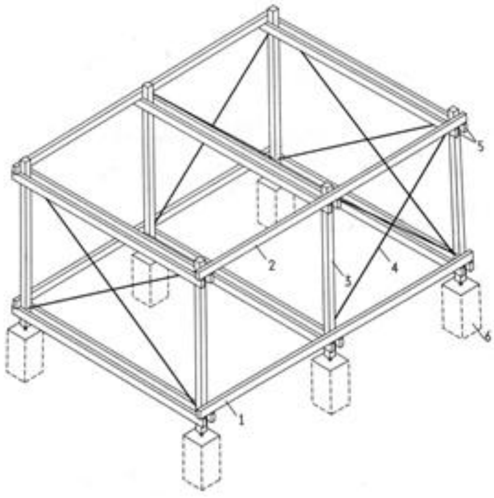
A conventional timber frame external wall consists of 8 layers or materials, each of which has a specific function. This includes protection from moisture penetration, permitting vapour transmission, giving racking resistance, withstanding compression loads, providing thermal insulation, providing vapour transmission, contributing to acoustic and fire performance and providing a decorating surface. [4] Also, as it has been mentioned in description of timber protection, the external timber wall should be 30 cm from the ground for reasons of structural timber protection. It is then connected to the ground with damp-resistant materials. Constructing the base from exposed concrete is a common solution. The concrete provides protection from damp. [2] In relation to this issue, it has been noted that most timber frame buildings, have concrete ground floors, timber intermediate floors and trussed rafter roofs. However, floor and roof panels prefabricated in the factory and known as cassettes are also possible. [4]

Internal walls can be either load-bearing or non-load-bearing. Loadbearing internal walls carry their own load and that of the ceilings and roof. Reinforcing walls are also classed as loadbearing. They are part of the building's loadbearing system as a whole, and like the external wall must be constructed as a rigid wall plate, either by planking or braces. The main function of non-loadbearing walls is to divide rooms. [2]

There are no specific differences in the roof construction of a timber frame building compared to other types of constructions. However, it is important to ensure that additional studs or posts in the timber frame wall panels adequately support any point loads from the roof (from purlins, hips and valleys, etc.). Further, because of timber has a high strength-to-weight ratio, it is particularly suitable for the construction of roofs. In timber frame structures compartment floors act generally as a diaphragm to transmit wind loads to the wall structure. [4] Furthermore, one of the most important rules for timber construction is that timber must always be installed to allow for movement caused by shrinking and swelling, e.g. by leaving sufficiently large gaps between the timber components. [2]

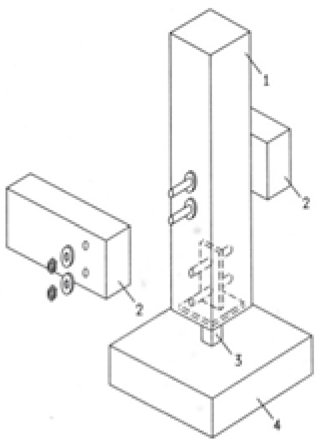
- **Skeleton Construction**

Skeleton construction has been developed from timber structural construction because of a desire for more freedom in dividing up space, and for larger areas of glazing (Figure 2.11). The term skeleton construction is occasionally used for timber construction in general. A building as skeleton construction if it is based on a primary loadbearing structure made up of columns and beams supporting a secondary loadbearing structure of beams and rafters. The system makes it possible to include large areas of façade glazing, as well as allowing greater flexibility in ground plan design. The loadbearing skeleton usually remains visible inside or outside. Glued laminated timber plays an important part in skeleton construction, as beams made of this make the large support spacings possible. In skeleton construction the columns and beams are jointed with metal devices without particularly weakening the timber cross sections (Figure 2.12, 2.13). [2]



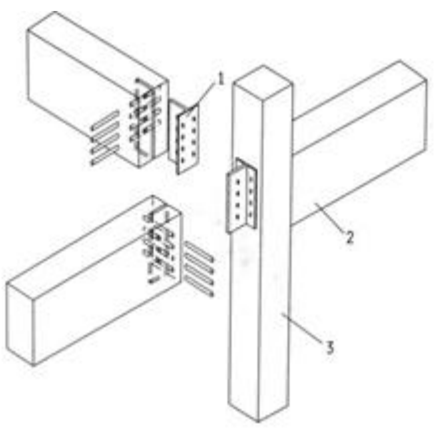
1: beam
2: beam
3: post/column
4: stay
5: horizontal timber
6: individual footing

Figure 2.11: Isometric diagram of an example for a skeleton construction (tie beam joints) [2]



1: column
2: horizontal beam
3: support foot (metal)
4: individual footing

Figure 2.12: Isometric diagram of an example for a support base with dowel joints [2]



1: beam support
2: beam
3: column

Figure 2.13: Isometric diagram of an example for a butted beam-column joint [2]

So that forces can be transmitted more effectively when timber components are jointlaterally, designed connectors which are usually inserted in a ring shape or driven, take the loads from the forces acting on the joint and transfer them to the maximum number of timber fibers. The joints are held together with screwed bolts. [2]

- **Timber Panel Construction**

The particular advantages of timber construction needs relatively short time for assembly which means that the completed structure can be occupied immediately. Efforts to shift the maximum numbers of production phases from the building site to the workshop make the building process independent of weather conditions. The prifabricated panel units, usually a full storey high, are insulated and fitted with all the layers of building components and the external and internal cladding, so that on site they have only to be erected and fixed together (Figure 2.14). One essential detail is the jointing or unit butting. The floor and ceiling panels are also prefabricated and either placed on the wall units or suspended between them. Loadbearing wall units in solid cross-laminated plywood or edge-glued elements rather like oversized timber product panels are produced by the timber industry for panel construction. [2]

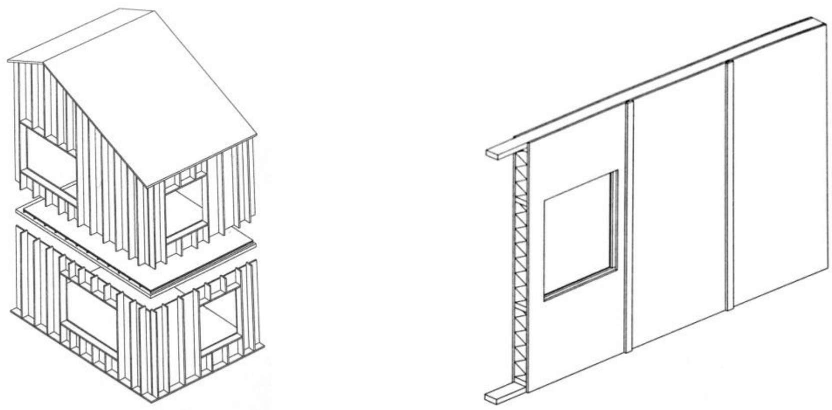


Figure 2.14: Panel construction and timber panel unit [2,6]

- **Open Panel Platform Frame System**

They are produced by the timber frame manufacturer in a factory and delivered to site as open panels, which consist of a sheathed timber frame (studs, plates and lintels), covered with a breather membrane. The figure on left shows openings for windows and doors which are created during the manufacturing process (Figure 2.16). This system is commonly referred to as 'open panel' timber frame kit construction. Internal linings, insulation, a vapour control layer, services and claddings are applied on site. [4]

- **Closed Panel Platform Frame System**

The 'closed panel' system is a method of manufacturing panels that develops on the open panel form of construction by including factory fitted insulation and internal linings. Depending on the precise form of closed panel construction adopted, the vapour control layer, services, windows, doors and even claddings may be added to the timber frame panel in the factory which are shown in the right Figure 2.15. When compared with 'open panel' construction a greater level of design input is required before manufacture and the resulting structure is less flexible to site changes. The manufacture of closed panel systems places a great emphasis on quality control systems in the factory as manufacturing errors are harder to identify on site. Floor and roof cassettes may also be manufactured as closed panels. [4]

Figure 2.15: Open panel timber frame system and closed panel timber frame system [60,61]

- **Platform Frame Construction**

In Platform frame construction the loadbearing elements consist of storey-high pre-assembled frames of squared sections braced by flat cladding panels or diagonal boards. Platform frame construction is based on a small modul. In this system, the previous floor becomes the working platform for the next (Figure 2.16). The advantage of this form of construction is its versatility because it can respond to many design specifications. The system is straightforward and economic because it uses identical timber sections wherever possible, due to their small size are easy and cheap to produce (Figure 2.17). The simple nailed and screwed connections are another advantage of this system. [6]

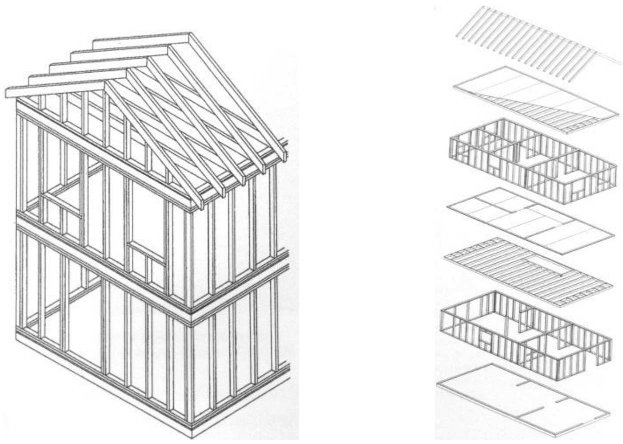


Figure 2.16: Platform frame construction (in platform frame construction the elements are stacked storey by storey) [6]

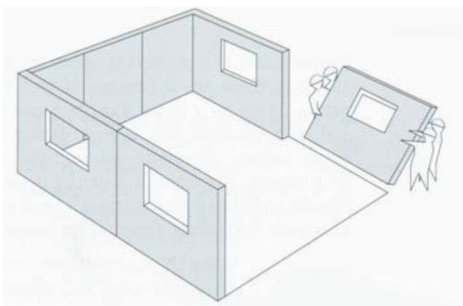


Figure 2.17: Platform frame construction. Utilising small manufactured panels inkit form for assembly on site [4]

- **Balloon Frame Construction**

The balloon frame system widespread in Amercia consists of closely spaced squared sections of standard sizes based on a “2 x 8 inch” module (roughly 5 x 20 cm) (Figure 2.18). This timber stud construction is nailed together on site and usually extends over two or more storeys. Its key feature is the use of vertical wall panels that are the same height as the building. The system is also characterised by a great degree of design freedom regarding plan layout, volume and positioning of openings. Indeed, openings can even be “cut out” subsequently because the construction is oversized and this is a disadvantage compared to newer systems because it leads to high material consumption. [6]

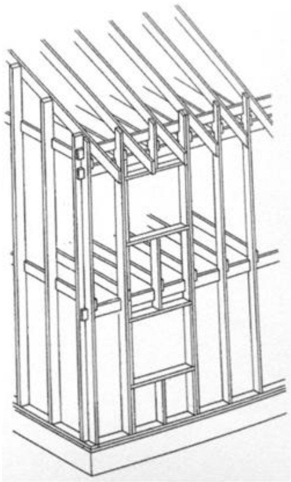


Figure 2.18: Balloon frame construction, timber stud construction [6]

- **Volumetric**

This involves the factory fabrication of timber ‘box’ units or modules, which form one or more rooms (Figure 2.19). They may be supplied as open panel units. However, this negates many of the advantages of factory manufacture and they are normally supplied with at least the insulation, internal linings and service conduits already fitted. Many volumetric buildings are delivered to site with services, windows, doors and claddings already complete. This method is best suited to buildings with repetitive units, such as hostels, hotels or nursing homes and requires the use of a crane during the erection process. [4]

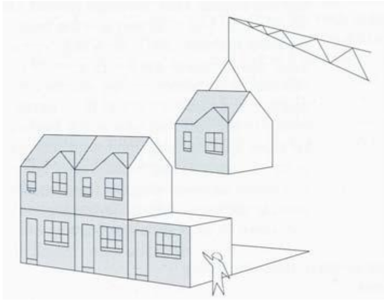


Figure 2.19: Volumetric construction [4]

- **Post and Beam**

Post and beam construction consists of a load-bearing system of posts and beams with lightweight timber or glazed infill panels giving protection from the weather (Figure 2.20). The post and beam structure provides resistance to vertical loads and racing resistance is provided either by the infill panels or diagonal bracing depending on how the infill panels are designed. [4]

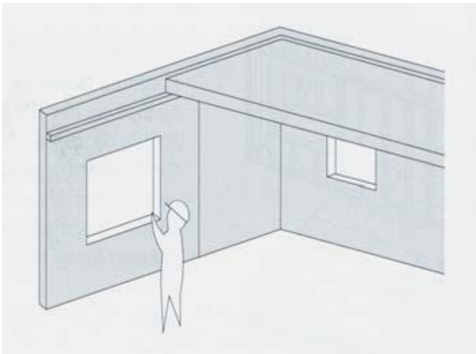


Figure 2.20: Post and beam construction [4]

2.1.4 Examples of Timber Structures in Turkey

Despite that timber was preferred extensively as a structural material for traditional buildings in Turkey for decades, in course of time usage of structural timber decreased significantly and timber has been replaced by modern and innovative materials. Some examples of timber structures in Turkey are provided in this section.

“The Architect's Office" is an example of modern timber buildings which received the best building award of the Turkish Chamber of Architects in 2006 within the biennial National Architecture Exhibition and Awards Program (Figure 2.21). [35]

Figure 2.21: The architect‟ s office, Urla, Izmir, from archive of Serhat Akbay.

An example of residential apartment construction in a village outside of Gölcük is shown in the Figure 2.22. Timber planks are used to form columns, beams, and slabs. The second floor of the apartment building is also presented in the Figure 2.22. Slabs typically span in one-direction and are approximately 100 mm in thickness. Beams span 2 m to 4 m, range in depth up to 500 mm, and are typically 200 mm wide. [43]

Figure 2.22: The apartment building construction (typical gravity framing including beam and column details) [43]

Ahmet afif paşa mansion was built by architect Alexandre Vallaury between the years 1900-1910 in Sarıyer, Istanbul (Figure 2.23). Finely worked timber was the predominant construction material chosen for this mansion, as it was for the large majority of traditional Turkish houses. [44]

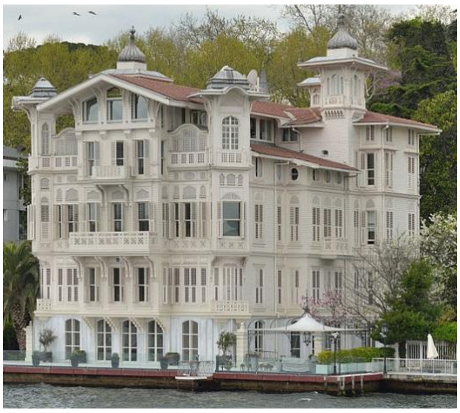


Figure 2.23: Ahmet afif paşa mansion in Istanbul, Turkey [44]

The use of glass panels in timber frame constructions requires the clarification of the glass material properties as well as its load-bearing capacity. These issues are discussed in the following section.

2.2 Glass

Nowadays tendency using transparency in modern architecture, leads to the idea of utilizing glass not only as a window element but also as a structural material able to carry the loads. Glass is the first material that let the light shine through walls in to a building without letting in wind or water and its transparency is the best advantage. It is well known that the presence of natural sunlight improves the health of the persons living or working in buildings. Therefore, modern architecture demands even more transparent building elements, not only in façades but also as interior elements, which can be used as beams or ceilings. Glass as a façade component provides significant solar heat extraction by its selective transparency. Modern and passive houses use this advantage and require solar energy by means of large glass areas and without conventional heating system. In respect of climate change great quantities of CO_2 are saved. [8-11]

In the scientific sense, the term “glass” refers to a frozen, supercooled liquid that has solidified without crystallisation. It is an amorphous substance produced by melting and rapid cooling, and hence does not have an underlying crystal lattic. Generally, glass means the group of silicate glasses, which acount for about 95% of total glass production. These mass-produced glasses consist of about 70% silicone dioxide, i.e. quartz sand, which determines the basic structure of glass. The following are among the most common silicate glasses; soda-lime glasses, lead glasses and borosilicate glasses. The glasses used in the building industry are in the main of the soda-lime variety. The type of lead glass has no significance for the building industry. Borosilicate glass frequently used in the building industry, e.g. for fire-resistant glazing. [12]

2.2.1 Material Properties of Glass

Two properties of glass are especially prominent: its transparency and its fragility. The transparency is due to the atomic structure, i.e. its non-crystalline nature. The lack of boundary surfaces in the material prevent the reflection of light in the range of visible and long wave UV-A light; the atomic structure cannot absorb this light, which means that light can pass through unhindered. Its fragility and its sudden failure characterise glass as a typical brittle material. Up until failure point the glass behaves in an ideal elastic fashion when subjected to mechanical actions. Plastic material behaviour does not occur, which is why it is impossible to predict failure (Figure 2.24). [12]

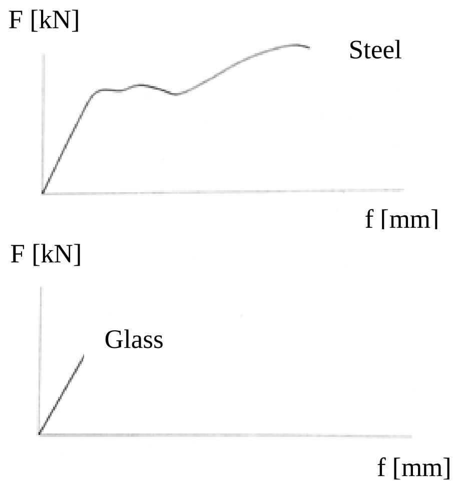


Figure 2.24: Comparison of the mechanical behaviour of steel and glass subjected to tension (F): whereas steel exhibits plasticity after exceeding the elastic limit and is hence highly ductile (f) up until the point of failure, glass exhibits a linear elastic behaviour up to the point of failure, without any plastic material behaviour [12]

Silicate glasses have good surface hardness, also exhibit excellent properties with respect to their resistance to chemicals and are therefore ideal where long-term durability is a requirement. Glass is also highly resistant to water, but pounding on glass surfaces can lead to leaching in the long-term and hence to corrosion of the glass surface. Glass can be damaged by industrial fumes containing ammonia and through contact with plasters/renders, wet concrete or extremely alkaline cleaning agents. It is primarily the easy mouldability of glass that makes it suitable for use as a building material. Glass has no defined melting point at which sudden liquefying or the onset of melting occurs, as is the case with crystals. Glass is characterised by a continual softening as the temprature rises, which means that upon being heated it is observed a constant transition from the brittle material via the viscoelastic range to a viscous melt. The transition range in which glass changes from a brittle to a plastic-viscous material lies between 520 and 550º C for the common, mass-produced silicate glasses. [12] About thermal and acoustic properties of glass, it has a relatively high thermal conductivity. Glass is non-combustible and does not contribute to the building’s fire load. Sound waves in the high frequency range are reflected from hard, smooth glass surfaces, an effect which may be to detriment of local acoustics. Direct reflection can be reduced by texturing the glass surface. Sound absorption depends pricipally on the sound reduction index and can be increased by using thicker glass with higher mass and multiple laminated build-ups. [13] Moreover, the most important physical properties of glass are summarized in Table 2.1. [14]

Table 2.1: Physical properties of glass

Density	25 kN/m^3
Young’s modulus	70000 MPa
Shear modulus	28000 MPa
Poisson’s ratio	0.23
Hardness (Mohs scale)	6
Coefficient of thermal expansion	9.10^{-6} K^{-1}
Tensile strength	45 MPa
Compressive strength	800 MPa

Also, the main physical properties of glass are summarised and compared with other materials in Table 2.2. The coefficient of thermal expansion expresses the relative longitudinal expansion of a component per degree of temperature rise. The value for the most commonly used glass in buildings, soda-lime glass, is 9×10^{-6} 1/K, i.e. about three-quarters that of structural steelwork. [13]

Table 2.2: Various mechanical and thermal properties of soda-lime glass compared with those of another brittle material (concrete) and two tough materials (wood and steel). [13]

	Steel S 235	**Softwood S 10**	**Concrete C20/25**	**Glass Soda-lime glass**
Refractive index η	-	-	-	1.5
Density p [kN/m³]	78.5	6	22	25
Modulus of elasticity E [kN/cm²]	21000	1100	2900	7000 (like aluminium)
Tensile strength f_{tk} [kN/cm²]	24 (yield strength)	1.4	0.22	4.5
Elongation at break Ɛ in %	25	0.7	-	0.006-0.17
Compressive strength $f_{c\,k}$ [kN/cm²]	23.5	ll 1.7-2.6 l 0.4-0.6	2	approx. 50
Limiting tensile stress σ_{Rd}	21.8	0.9	(~0.1)	1.2/1.8
Safety factory	y_m=1.1	y_m=1.3	1.8	2.5
Breaking length σ/p [m]	2800	1500	(45)	480/720
Thermal conductivity [W/m x K]	75	ll 0.5 l 0.2	1.6	1
Thermal shock resistance ΔT [1/K]	-	-	-	40
Coefficient of thermal expansion α_T [1/K]	12×10^{-6}	ll 5×10^{-6} l 35×10^{-6}	10×10^{-6}	9×10^{-6} 60 K = 0.5 mm/m

About the tensile or bending strength properties of glass therefore reflects the surface quality and is not a constant value (Figure 2.25). It relates directly to the size and age of the pane: the larger and older the pane, the greater the probability of a critical defect. The strength of glass also depends on the duration of loading and the surrounding medium; humidity promotes subcritical crack propagation (Figure 2.26). As a result of glass's brittle behaviour, the compressive strength of glass is about ten times higher than its tensile strength in bending. As the notch sites are surcharged in compression in the plane of the pane, the defects in the glass surface do not reduce its strength. [13]

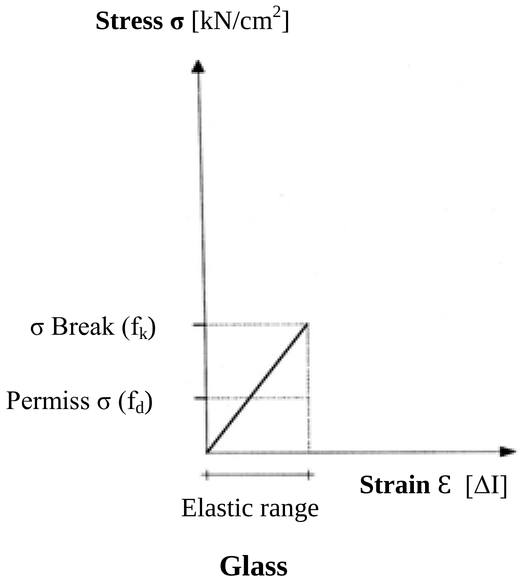


Figure 2.25: Linear-elastic deformation behaviour of glass: Glass breaks without warning after its fracture stress is exceeded [13]

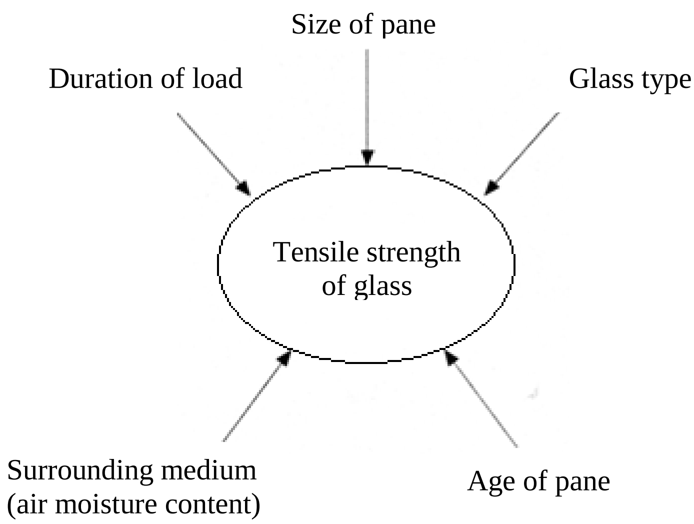


Figure 2.26: Factors influencing the tensile (bending) strength of glass: The strength of glass is not a constant value [13]

Glass with very high compressive strength and modulus of elasticity, which is around a third of that of steel but five time greater than hardwood and comparable to reinforced concrete presents modulus of elasticity almost equal to that of aluminium. Glass shows isotropic and almost perfectly elastic behaviour. [15,16]

2.2.2 Types of Glass

An aspect to consider when planning to use glass in load-bearing structures is what type of glass to use. This is cause to explain types of glass briefly in this section. Basic glass types have different production sizes and properties depending on their recipe and manufacturing process. This section presents a summary of the most important of them. Flat glass is manufactured by the float glass, rolled glass or drawn glass process. Float glass makes up over 90 percent of flat glass production and is the most important basic glass. [13] The sheet glass basic products are described as following:

- **Float Glass**

Today about 35% of all glass products are manufactured by the float glass method. In the float process the glass is transferred at a temperature of about 1050 ºC from the melting tank to the so-called float bath. In the float bath the glass cools down to about 600 ºC. The glass thicknesses possible with this method lie in the range 0.5-25 mm, but for practical building purposes thicknesses between 2 and 19 mm are typical. Float glass to DIN EN 572-2 must exhibit a characteristic tensile bending strength of 45 N/mm^2. The permissible tensile bending strengths used in design depend on the type of application. [12]

- **Rolled Glass**

This is sometimes called cast glass. The modern production of rolled glass involves passing a continuous ribbon of glass, which leaves the melting tank as a viscous glass mass at a temperature of about 1200 ºC, between two water-cooled, contra-rotating rollers. The thickness can lie between 3 and 15 mm. Rolled glass is used for various products. Profiled glass is also produced from rolled glass. The edges of narrow rolled ribbons of glass are turned up through 90º by vertical rollers to create a U-shaped section. As these products can carry high loads because of their cross-sectional form, they are ideal for use without glazing bars, or as single- or double-leaf constructions when inserted into peripheral lightweight metal frames. [12]

- **Drawn Glass**

This type of glass plays a only a subsidiary role in the building industry. Drawn glass is often used for restoration projects on old buildings. Depending on the type of sheet glass, length between 1.20 and 2.16 m and widths between 1.45 and 2.88 m are available. Thicknesses range from 2 to 12 mm. [12]

- **Colourless, Tinted and Opal Glass**

All sheet glass basic products can also be tinted. This is achieved by mixing various metal oxides into the melting tank or through a subsequent colouring process. Opal glass is produced by adding fluorine compounds, phosphates or tin oxide. The glass obtained as light-permeable, but no longer transparent. Adding colour can also have an effect on physical properties of the glass such as light transmission. Today coloured glass is produced in more than thirty different basic colours, clear glass, thin (up to 1.8 mm) and thick (more than 19 mm) using the drawn glass process. [12,13]

- **Thermally Toughened Glass**

The disadvantages of glass are its low tensile strength, dependent on the surface properties, and its brittle fracture behaviour, with the associated high risk of injuries. The thermal toughening process plays an important role in compensating for these weaknesses. The glass to be toughened is first heated up to a temperature of 620-650°C. The heating is followed by an abrupt cooling process, jets of air applied to both sides of the glass to restore it to room temperature. During this cooling process the surface of the glass cool and solidify first, before the inner core hardnes. Thermally toughened glass exhibits thermal fatigue and impact resistances that are far higher than those of float glass. All sheet glass products can be used as the basic material for producing thermally toughened glass. All mechanical operations, cutting, drilling and edge working, must be completed before carrying out the heat treatment because otherwise the inherent stresses in the glass would cause the glass to fracture during such processes. Two types of thermally enhanced glass are toughened safety glass and heat-strengthened glass. Due to the toughening process, toughened safety glass exhibits compressive stresses in the surface in the order of magnitude of about 100-150 N/mm^2. It is produced in thicknesses from 3 to 25 mm. Heat-strengthened glass undergoes the same manufacturing process as toughened safety glass except that the cooling process is slower. This results in a lower inherent compressive stress in the surfaces than is the case with toughened safety glass. The thermal fatigue resistance is also lower than that of toughened safety glass. One great difference between toughened safety and heat-strengthened glass is the fracture pattern of the latter, the coarse structure of which is similar to that of float glass (Figure 2.27). Heat-strengthened glass is generally only produced in thicknesses up to 12 mm. [12]

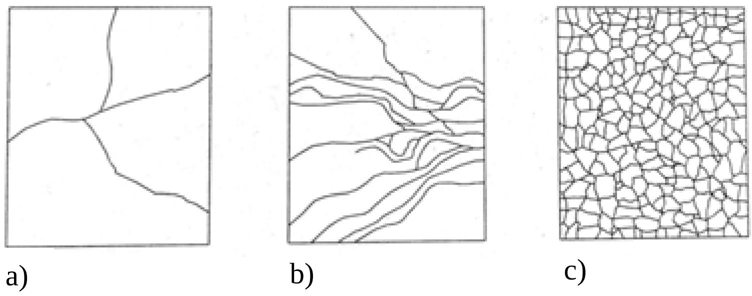


Figure 2.27: Schematic presentations of the fracture patterns of untreated and thermally toughened glasses: a) Float glass b) Heat-strengthened glass c) Toughened safety glass [12]

- **Chemically Toughened Glass**

Glass that has been chemically toughened plays only a subsidiary role in the building industry and is primarily used for very thin panes and complicated three dimensional geometries. The fracture pattern is similar to that of float glass. Chemically toughened glass is primarily used for optical applictions and in the automotive industry. [12]

- **Laminated Glass and Laminated Safety Glass**

The possibility of failure without any loadbearing reserves prohibits the use of single panes as loadbearing elements in structural applications in building. This problem can be overcome by bonding two or more sheets of glass by means of viscoelastic. Laminated safety glass therefore has a decisive advantage which collapse completely once broken: the space-enclosing function of the former remains essentially inact and it still provides adequate protection even though severaly damaged. In addition, it has good light-fastness and out-standing optical properties, which ensure undistorted transparency. A pane of laminated safety glass consists of at least two panes of glass bonded together with a PVB film just 0.38 mm thick. [12]

Moreover, this thesis investigates tempered glass due to that was used in the tests of this research. New applications of tempered glass in structural parts of buildings (posts, beams, and shear walls) necessitate a good knowledge of the load-bearing capacity and the lifetime of this structural glass component.

- **Tempered Glass**

The industry differentiates between fully tempered (toughened) safety glass and partially tempered heat-strengthened glass. Tempered glass has higher internal stresses than heat-strengthened glass. The glass must be at least 4 millimetres thick for the stress profile to be able to develop in the cross section. Tempered safety glass is produced in thickness up to 19 millimetres (occasionally 25 mm), heat-strengthened glass only up to 12 millimetres. Generally sheets of approximately 2.50 m x 4 m can be tempered. Tempered borosilicate glass is available up to 15 millimetres thick and up to 1.60 m x 3 m in plan. The fire-rating can be considerably increased by the use of tempered borosilicate glass, which has a lower coefficient of thermal expansion. The mechanical and thermal properties of tempered glass are summarised in Table 2.3. [13]

Table 2.3: Mechanical and thermal properties of heat treated and annealed flat glass [13]

	Stock sizes	**Surface compressive stress [kN/cm^2]**	**Fracture strength [kN/cm^2]**	**Thermal shock resistance [K]**	**Risk of spontaneous fracture(NiS inclusions)**	**Can be cut**
Soda-lime glass: Float glass	2 mm-21 mm 3.21 m x 6.0 m	-	4.5	40	no	yes
Heat strengthened float glass	4 mm-12 mm 2.5 m x 5.0 m to 3 m x 6.0 m	3.5-5.5	7	100	no	no
Tempered float glass	4 mm-19 mm	10-15	12	150	yes	no
Rolled glass	4 mm-19 mm 2.5 m x 5.0 m	-	2.5	30	no	yes
Tempered cast glass	4 mm-19 mm 2.5 m x 5.0 m	10-15	9	150	yes	no
Borosilicate glass: Float glass	Up to 21 mm 2.3 m x 3.0 m	-	2.5	90	no	yes
Heat strengthened float glass	4 mm-12 mm 1.6 m x 3.0 m	3.5-5.5	7	200	no	no
Tempered float glass	4 mm-15 mm 1.6 m x 3.0 m	10-15	12	300	no	no
Chemically strengthened glass	Up to 19 mm ca. 1.0 m x 2.0 m	(15) Depends on depth of penetration and surface damage		250	no	yes-within limits

Since the surface tensile stress due to actions is smaller than the residual compressive stress in tempered glass, no crack will develop. Annealed float glass breaks into large fragments whereas fully tempered glass presents high fragmentation and breaks into small pieces which does not affect post-breakage strength. Tempered glass, though more resistant to superficial stresses than laminated glass, presents two considerable and decisive disadvantages, such are brittle behaviour and an irregular surface. In addition, the heat treatment influence fracture behaviour. The large amount of energy stored in the glass causes a tempered pane to break into many small glass dice which is shown in the left Figure 2.28. As the fractured pieces are blunt, tempered glass is also called “safety glass”, although the fractured pieces may remain together in larger shards and if they fall out could lead to injury. In contrast, high-strengthened glass breaks from the fracture centre outwards in larger shards and islands in a similar pattern to non-tempered glass (Figure 2.28). [13,15,17]

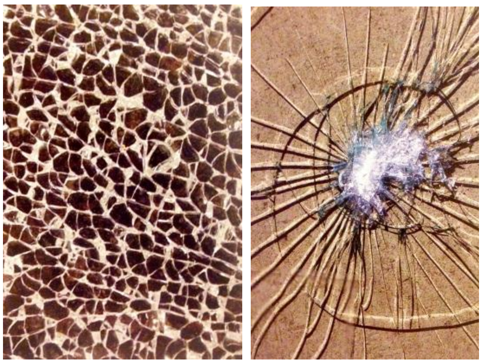


Figure 2.28: Fracture pattern of tempered glass and fracture pattern of heat-strengthened glass [13]

As well, tempered glass and heat-strengthened glass differ in the amount of induced stress. The lower surface precompression of heat-strengthened glass means that its characteristic minimum strength is only half that of tempered glass but twice that of annealed glass. [13]

2.2.3 Glass as Load-bearing Material

Glass as a material, is not ductile and it is brittle. For this reason in the case when glass is used for the main bearing elements, a special detailing and design of the joints between all the elements of the structural system should be carried out. Therefore the load-bearing capacity of glass is investigated in this part.

The use of glass as a construction material differs fundamentally from the use of many other building materials. Owning to the brittle failure behaviour of glass, exceeding its loadbearing capacity results in the sudden and complete failure of the component. In addition, it reacts very sensitively to local stress peaks and has a very low impact strength. Once a crack has started to form, it can propagate unhindered owning to the molecular structure of glass. Another negative characteristic of glass, in addition to its problematic brittle failure behaviour, is the fact that upon failure it shatters into a multitude of sharp pieces that represent a further potential danger. These properties result in far-reaching consequences for the use of glass in building. Building materials such as steel or reinforced concrete are much less problematic because they exhibit a ductile behaviour at the temperatures relevant to construction, meaning that local stress peaks can be dissipated via plastic deformations. [12] In general, in glass structure engineering and design, shear strength of the glass determines the load bearing capacity of whole element. [17] Load-bearing elements for glass structural system are explained as following. This part includes columns, beams, planar elements and curtain walls. Then the glass façade is described briefly.

A column is a linear loadbearing element that is primarily loaded in compression. Columns therefore normally have an axially or rotationally symmetrical cross-section made up of sheet glass or glass tubes. As columns are traditionally primary loadbearing elements in hierarchical structural systems, they play only a minor role in glass constructions. But if glass columns are required, they must be connected top and bottom via pinned joints to ensure that they remain essentially free from any moments (Figure 2.29). [12]

Figure 2.29: Load-bearing glass column and externally prestressed glass column [12]

A beam is a linear member that is used primarily as a horizontal element loaded in bending. Vertical beams are called posts and fins when they bear bending loads in addition to axial loads due to their self-weight. In glass constructions they are mainly used to resist wind loads and reduce the risk of buckling of panes. Glass beams used in glass floors or roofs subjected to unrestricted foot traffic generally have to carry higher live loads as well as medium- and long term loads. The span of individual beams is limited by the available manufactured sizes of glass to between 6 and 7.50 metres. The bearing capacity of a beam is limited by local and lateral torsional buckling as well as tensile bending stresses. Buckling occurs when the tensile bending stress on the glass surface exceeds the effective tensile strength of the glass. [12,13]

A plate is a planar, flat, rigid component loaded only by forces acting in the plane of the plate. A plate can be in the form of a widened column or a very deep beam, and in the form of a shear diaphragm can provide a stiffening or bracing function. A slab, like a plate, is a planar element, but instead is loaded in bending by external forces caused by loads acting perpendicular to the plane of the system. Those loads include: self-weight, snow and wind loads, temperature differences on the surfaces, displacement of the supports and eccentric prestressing forces. In the case of horizontal glazing or sloping glazing at a shallow angle, glass primarily carries out-of-of-plane loads, i.e. acts as slab. [12]

The glass curtain walls of modern office buildings represent a typical vertical glazing application. Situated at the interface between interior and exterior, they have to satisfy numerous, sometimes conflicting, requirements: on the one hand they have to function as a climate, energy and acoustic barrier, and on the other, provide controlled permeability for light, air and heat. In addition, they may also have to protect against fire, intruders, bullets or explosions, and maybe prevent persons falling from a higher to a lower level. [12]

The glass façade is frequently divided into structurally effective components that are specifically planned for resisting the vertical or horizontal components of the following loads: self-weight, snow loads, wind loads, imposed loads, impact loads and loads due to restraint forces resulting from thermal loads, settlement, explosions, earthquakes, etc. In principle, there are two practical ways in which façades can be designed to carry loads: a “suspended construction” is supported from the floor above each storey so that the self-weight of the façade causes tensile forces within the material. This arrangement overcomes stability problems. However, strength problems can occur at the suspension points due to stress constructions. A “standing construction”, on the other hand, is supported on the floor below and transfers the vertical loads occuring to the primary structure by way of compression. Without suitable bracing measures, such a form of construction may suffer from stability problems. [12]

Also, about the seismic resistances of glass structures, it is varied widely between architectural glass types commonly used in contemporary building design. Annealed and heat-strengthened laminated glass exhibited higher resistance to glass fallout than monolithic glass. From the dual perspectives of (1) protecting life safety and (2) maintaining building envelope integrity and serviceability, annealed or heatstrengthened laminated glass units are wise choices for either new or retrofit building envelope systems. Not only do these laminated glass units help protect building occupants and pedestrians from falling glass during a severe earthquake, but they also help maintain building envelope integrity after earthquake-induced building motions that could cause other glass types to fall from their glazed openings. By helping maintain building envelope integrity, laminated glass units can help keep a building secure and weathertight in the prolonged periods of cleanup and rebuilding following a major earthquake. Furthermore glazing details were also found to have significant effects on the seismic performance of architectural glass. Specifically, architectural glass within a wall system using a structural silicone glaze on two sides exhibited higher seismic resistance than did identical glass specimens dry-glazed on all four sides within a comparable wall framing system and this is an important result in the case of design timber-glass wall elements with structural silicone glaze. [18]

2.2.4 Design Building with Glass

The loadbearing capacity of a glass component is basically very much dependent on its surface quality and edge working. Owning to the brittleness of glass, local stress peaks and unworked, sharp edges should be avoided wherever possible. Moreover, glass accepts compressive loads far better than tensile ones, although, in principle, wide support and force-transfer faces are advantageous (Table 2.4). [12]

Table 2.4: Design principles for building with glass. [12]

No contact between glass and harder materials
Avoidance of restraint stresses due to unintentional loads
Choice of a suitable geometry for the glass elements
Specification of a suitable method of connection
Ensuring a sufficient level of robustness of glass constructions
Guarantee of serviceability
Ensuring durability and weather resistance

The design and detailing must be such that glass does not come into contcat with harder materials or damaging mechanical actions. This applies to non-toughened glasses in particular because of their lower strength. Various materials can be used as intermediate pads between glass and harder materials, which also help to absorb any deformations of the supporting construction. Synthetic materials, casting resins or aluminium alloys are especially suitable because they can compensate for small irregularities and ensure a maximum area for the load transfer. [12]

2.2.5 Deformation Behaviour of Glass Under Loading

As mentioned in properties of glass section, the modulus of elasticity of glass is 7000 kN/cm^2, only about a third of that of steel but five times greater than hardwood. The material deforms linear-elastically under increasing load at right angels to the plane of the pane until it exceeds its load-bearing capacity, when it suddenly fractures without warning on the face under tensile stress. The strain is proportional to stress up to fracture. In this respect glass is considerably different to other ductile and therefore “good-natured” construction materials such as timber or in particular steel, which are able to deform plastically to a certain extent in order to reduce stress peaks. The designer must prevent direct contact between glass and glass or between glass and metal in order to avoid stress concentartions. As glass does not strain plastically, it cannot dissipate imposed stresses, such as arise from temperature shock. [13]

The value of the critical bukcling load does not therefore depend on the compressive strength but rather on the tensile bending strength of the glass. Numerous other factors are involved, such as the geometric slenderness of the component, whether the edge supports are hinged or rigid, the presence of initial imperfections and deformations distributed through out the glass thickness, the eccentricity of the load transfer and, in the case of laminated safety glass, the composite action effect. Point supports may lead to failure due to the local effective tensile bending stress being exceeded near the fittings. Shear and compression stresses in the centre of the panel can lead to buckling of plates that are also restrained along their sides. With increasing load, the ratio of the side lengths becomes steadily more important to buckling. After the theoretical buckling stress has been exceeded or the supercritical load situation is reached, initial fracture occurs on the edge which in turn produces an almost explosive breakage of the glass on the tensile bending side. [13] Aslo, it is mentioned that the rate of deformation and time of stress impact has also a high importance on the strength of glass. Glass has a tendency to fail under static fatigue, and unexpected failure can occur at lower loads than what’s expected. It is stronger when loaded rapidly rather than slow. [19] As well brief peak loads are less of a problem for glass than lower, long-term loads. [12]

Several tests on butt joints between glass panes were conducted at the Central Laboratory of Civil Engineering at the University of Stuttgart. These tests were performed in order to investigate whether existing adhesives are able to resist the shear stress arising on glass shells. The shear tests were showed that the glass edges were rather vulnerable to shear loadings, probably because of the abrasion microfractures. This often led to glass failure at the edges, which in case of high loadings propagated along the pane (Figure 2.30). [20]

Figure 2.30: Shear test: test device [20]

For immprovement of structural properties of glass, the residual loadbearing capacity, redundancy represents the most important safety principle in the use of glass as a structural material. [12]

2.2.6 Residual Loadbearing Capacity

Appropriate measures must be taken to prevent the sudden collapse of an entire construction and total failure of a glass component. Even in the case of damage, a glass component must possess sufficient loadbearing reserves in order to remain securely in position and still withstand other loads, e.g. falling persons or objects, for a sufficient length of time. Furthermore, the splinters and fragments of glass must be bonded together in such a way that there is no danger of pieces of broken glass falling onto persons below, nor a serious risk of injury to persons who may fall onto the broken pans of glass. The margin of safety against complete failure of a partially destroyed system is known as the residual loadbearing capacity. This is one of the most important aims when using glass in construction and, in principle, can only be achieved with the help of other, ductile materials. These materials, such as the polyvinylbutyral (PVB) film that holds together the pieces of broken glass, can be virtually invisible. [12]

2.2.7 Redundancy

In principle, glass structures should be designed with inherent redundancies, i.e. upon failure of one loadbearing element in a system, the loads can be carried by other elements in the loadbearing construction (Figure 2.31). [12]

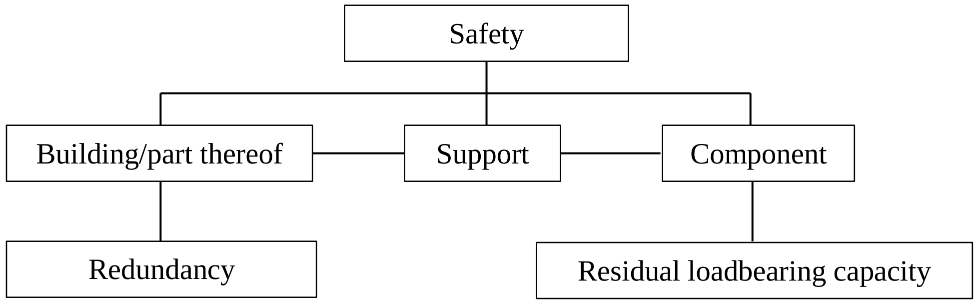


Figure 2.31: Elementary safety concepts in the use of glass as a structural element [12]

The making and forming of the basic glass -normally float glass- is followed by two or more processing stages which optimise the material for specific technical functions such as solar control, structural or safety needs such as the residual strength or purely aesthetic aspects such as colour effect. Tempering or heat-strengthening of glass is done by artificially including stresses into the glass by forced convective cooling of the pane. These stresses improve the load resistance, but also affect the fracture behaviour in specific ways. By laminating glass into composite elements, the load-bearing behaviour, post fracture integrity and robustness can be substantially improved. This method was described briefly in laminated glass part. [13]

2.2.8 Examples of Glass Structures in Turkey

As mentioned in previous sections, glass is one of the most important materials in the building industry. Some examples of glass structures in Turkey are provided in this section.

Modern Turkish city home with glass walls was designed by Architect Bahadır Kul (Figure 2.32). One of the main ideas in design was to capture light, so the architect created glass walls for the ground floor and the private area upstairs. [50]

Figure 2.32: Modern home in Turkey [50]

The House Cafe Kanyon by Autoban Architects is a separate, exclusive dining experience within the Kanyon shopping mall in Istanbul, Turkey. This steel and glass shell is raised above the mall’s stone base with a walnut floor, which combines with the clear glass for an overall warm inner appearance (Figure 2.33). The glass walls of the House Cafe make this restaurant it’s own, free-standing structure within another, creating a sense of separation from the commerce around it. [51]

Figure 2.33: The restaurant’s building inside the Kanyon Mall in Istanbul, Turkey [51]

The Glass Lantern, a feature at the new Apple store in Istanbul, Turkey, has been presented with the Supreme Award for Structural Engineering Excellence**,** as well as the Award for Commercial or Retail Structures (Figure 2.34). The Lantern is made up of only five elements: four 10m x 3m laminated glass walls free of the visible fixings and joins, provide an efficient structural form capable of resisting seismic loads, while providing total transparency and architectural purity. The lightweight ultra-thin roof made of CFRP panels (carbon fibre reinforced plastic) seamlessly joined on site, provides a completely smooth uniform soffit while also improving the seismic performance of the whole glass structure. The five panels being held together by structural silicone. [52]

Figure 2.34: The Glass Lantern in Istanbul, Turkey [52]

The Vakko building in Istanbul comprises two independent structures (both office buildings), one built inside the other. The first structure is a “U-shaped” ring inherited from the hotel’s skeleton. The second structure, at the ring’s center, is a six-floor steel tower. The U-shaped concrete structure is covered by exceptionally thin glass panels which make the building totally transparent and allow views through to the inner building (Figure 2.35). [53]

Figure 2.35: Vakko Headquarters and Power Media Center [53]

The bus terminal has been designed by Bahadir Kul Architect in Kayseri, Turkey. The building is formed around a continuous and monolithic stone-clad wall, which takes a stretched Z-shape through the floor plan. Glass curtain walls enclose two separate foyer areas, with angled red columns elevating the large roof (Figure 2.36). [54]

Figure 2.36: Full height glass curtain walls providing views to the outside [54]

As a result, in response to the question why glass is used in timber-glass composite structures, three reasons can be mentioned; aesthetics, functional and structural. In terms of aesthetics, architectural expressivity, transparency and natural lighting can be mentioned. In terms of functional, thermal efficiency, sustainability can be mentioned. Also, in terms of structural, structural capacity, stiffness and strength can be referred. [21]

2.3 Adhesives for Timber-Glass Applications

For ever object of the timber-glass structural composite system which includes beams, columns, plates or slabs, another aspect which must be taken into consideration is the bonding system. While assuming a role which is as important as, or even more important than the two original elements, the bonding system will be the main responsible for the unity of the set. As far as the present research is concerned, the structural adhesive bonding was chosen as the bonding system. Uniform distribution of forces, reduction of fragilization of materials by avoiding drilling, averting of high peak stresses and aim at the ductility in the unity of the set were the criteria for this decision [22]. Adhesives play a crucial role in the load transfer in timber-glass composites as they are mechanically loaded in tension/compression and shear. Furthermore, they are subject to a variety of other loads such as high and low temperatures, moisture, direct sunlight (UV), etc. [23] Since glass is a brittle material it is important to connect glass and timber in a way that avoids stress concentrations in the glass. Adhesives have the ability to transmit loads from timber to glass in a uniform manner if a flexible adhesive is used instead of more commonly used rigid adhesive. [9] The purpose of this section is to provide information on the use of adhesives in timber-glass applications. Appropriate investigation of adhesives with their properties and criteria to choose proper adhesive are provided in this part of research.

It is also of great importance that the adhesive brings together strength and flexibility. That is the path to its structural utilization, necessarily subject to transmission of heavy loading. The adhesive must also allow bending, expansion and shrinkage of timber, according to loading and humidity variations. Given the basic difference of characteristics between glass (brittle) and timber (ductile), it is believe that this could be the best way of enhancing the performance of the different composing elements in a unitary set. Beside, if the adhesive is not able to minimally absorb the various resulting stresses, it will not efficiently play the role of interface, as it will not prevent from a direct confrontation of different behaviours of materials. [22]

One of the most important reasons for using adhesives is to construct composite systems which economize material usage. Adhesives enable different grades of timber to be assembled in the most efficient manner, minimizing the effect of defects on strength and stiffness. Also, many composite combinations are feasible only with the use of adhesives. Because a properly bonded joint can provide efficient load transfer, a full utilization of material is often possible where it would not be the case with mechanical connection devices. Another advantage of adhesive bonding is that building components can be preassembled. Stressed-skin panels, trusses, and built-up box or I-beams are typical examples. Not only is on-site labor reduced, but the bonding process can be highly controlled in a factory environment. A third advantage is that adhesive bonding increases the rigidity of the joint and enables the full strength of the materials to be utilized. Because of the porous nature of timber, a properly applied adhesive penetrates the timber surface and forms a strong bond. The most effective way to take advantage of load transfer using adhesives is through shear resistance at the bond line. As a consequence, most uses of adhesives in timber construction are related to shear transfer of load. [5] In addition, it is mentioned that for structures that have to be mounted and dismantled, glued joints that can be easily completed at the building site and that can be easily removed without damaging the glued glass elements. This is another advantage of using adhesive. [24]

2.3.1 Selection of the Adhesive

With the wide choice of adhesives available, the selection of the most suitable adhesive can be difficult. Several factors should be considered before making a selection. These factors are durability of adhesive, strength and stiffness of it, methods of application, physical and working properties and cost considerations. The glueline joints must be properly designed. Special consideration must be given to environmental conditions when using adhesives. Of particular concern are temperature and moisture. Some adhesives are sensitive to these parameters. For examples, many epoxies begin to lose strength at 150º F (65.6º C), a temperature that might be found in roof sections on unsually hot days. Also, certain adhesives deteriorate in the presence of moisture. To ensure that the adhesive is compatible with the environment, the adhesive properties must be carefully matched to the expected temperature and moisture conditions. In order to achieve this objective several tests were done on experimental specimens of this research. In the specimens silicone adhesive was used and according to tests, adhesive's behaviour was evaluated. Also, unplanned conditions, such as leaks in roofs, moisture condensation on walls, wet-dry cycles during construction, and high heat during a fire, deserve consideration should be taken in selecting the proper adhesive. For this reason, durability is usually associated with temperature and moisture. Care must be taken to match the adhesive to the environmental application. Lack of control during any phase can lead to poor bonds and possible failure of the structure in service. Also, an effectively glued connection requires certain strength and stiffness characteristics. An evaluation of these requirements may necessitate a structural analysis of the system. A knowledge of the a type of silicone adhesive's strength for various loading conditions may also be needed. In this thesis's research, tests were performed to evaluate the strength of Ottocol-S 660. In addition, selection of an adhesive may well depend on the method of application. Factors to consider are surface conditions, moisture content of timber, temperature at time of application, equipment required, setting time, and final cure time. The amount required on the bondline must also be taken into account. Many manufactureres list a rang of spread date in their technical literature and on labels. Use of these data allows the engineer to predict adhesive cost accurately. [5]

In comparison to force and interlock connections, the designer needs to take into account that the strength of an adhesive connection in service can be influenced by a large number of factors. Its strength depends on the mechanical characteristics of the system and the type and duration of loading, the geometric shape of the adhesive joint, the quality of its installation and the surface quality of the joined parts, as well as environmental influence such as UV light, moisture and temperature. [13] An important aspect to consider in timber-glass components is that the large difference in behaviour in the case of varying moisture. [25] According to several tests were performed due to the stiffening glass panels are used for façades, the adhesives of structural sealant glazing systems with timber were tested under different temperatures. It is characteristic for the adhesives, that the modulus of elasticity decreases during rising temperatures. The dependence of the mechanical behaviour on temperature level has also relevant meaning as the duration stress on the structural material. [26] Also, adhesive bonds which are mainly for gluing materials such as glass and metals or timber must also be able to handle moisture induced deformation in the timber without enforcing too much strain on the glass. [27]

2.3.2 Types of Adhesives

Most often used adhesives can be divided according to their modulus of elasticity and shear modulus into flexible-elastic (i.e. silicones, modified silicones and polyurethanes) and rigid (i.e. epoxy or polyester resin, acrylics). Rigid adhesives have extremely high strength but very low elongation in comparison with elastic adhesives, which show elongation at break even more than 250%. [28] Furthermore, according to the analysis results of several tests, it is possible to identify three group of adhesives in the context of strength and relative displacement. These include: adhesives highly resistant and insufficiently flexible, highly flexible adhesives, yet insufficiently resistant. Adhesives that balance both key factors: strength and ductility are silicones. Since, the silicone was is in our experimental tests, a brief description of it is given in this chapter. [16]

Silicones, MS polymers (modified silicones) and polyurethanes (PUR) are some of the flexible systems. Flexible adhesives normally have a strength in excess of 1 N/mm^2 and an elongation at break of more than 150 percent and are therefore suitable for linear bonded joints. With a jonit thickness of approx. 5 millimetres, an elastic adhesive fills gaps and equalises stresses. The flexible connection is very suitable for accepting dynamic loads, damping sound transmission between the components and functioning as a seal. Compared with hard adhesives, it is more feasible to repair or take apart a connection made with an elastic adhesive. Further, epoxy resins and acrylates are usually considered as hard adhesives and at thicknesses of between 0.1 and 0.5 millimetres they have a very low elongation at break (Figure 2.37). At the optimum thichness they have extremely high strengths but do not accommodate construction tolerances nor do they equalise stresses, therefore they are mainly suitable for connections with point fixings. Hard adhesives fail through brittle fracture without warning. [13]

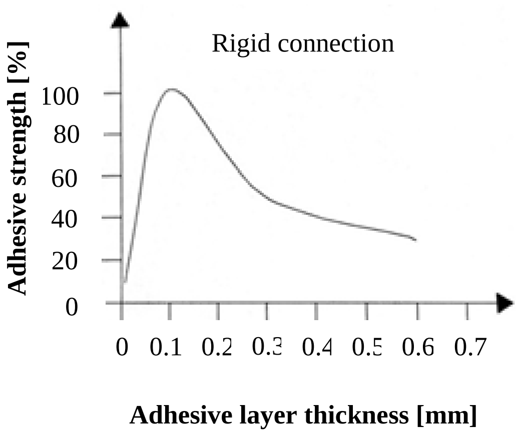


Figure 2.37: Graph of strength against layer thickness for a hard adhesive [13]

Moreover according to the study, each adhesive shows different behaviour under increasing load regarding to the thickness of the joint. According to experiments for common types of adhesives, that by increasing thickness of the joint over the ideal value, possible elongation (or slope) of the adhesive layer increases too, but the connection loses its load bearing capacity. One of the main tasks of the connection design is to find the state of the adhesive thickness, where the glued joint can fulfil the requirements on load bearing capacity and also provides a necessary elongation (or shear slope). [17]

According to several tests were performed at Linnæus University on the timber-glass small specimens with three different types of adhesives, acrylate (SikaFast 5215), polyurethane and silicone. The adhesives were tested in shear and tensile stress with the mean values of strength (stress at failure). Therefore, the following results have been obtained. The adhesive with the largest strength in the tests performed was the acrylate (SikaFast 5215), both in tension and shear. The mean strength for this acrylate adhesive was 3.0 MPa in tension and 4.5 MPa in shear. In tension, the polyurethane has less than 67 % of the strength of the acrylate. In shear, the difference between the strength of acrylate and polyurethane is smaller; the strength of the polyurethane is 85 % of the strength of the acrylate. The silicone is, by far, the weakest adhesive in the tests; it had about 25 % of the strength of acrylate in tension and 20 % in shear. The deformation capacity of the silicone adhesive bond was measured to about 2 mm in tension and 10 mm for shear. The silicone adhesive tends to fail mainly in a mixture of adhesion to timber and cohesion in adhesive, the acrylate adhesive appears to be so strong in cohesion that the failure occurs either in the timber or in adhesion to timber while most of the polyurethane specimens have failure partly, or only, in adhesion to glass. One important factor when gluing glass is the load distribution ability. The flexible silicone adhesive with a large deformation capacity could be preferred from this point of view, but the stiffness and strength are too low to enable any load to be carried without applying the adhesive bond over a very large area. Then the beneficial transparency of glass is lost. A potential problem with acrylate (SikaFast 5215) adhesive is identified in its thermostability. There is no need to design for extreme temperatures in normal buildings, but the low glass transition temperature of 52˚C of the acrylate adhesive could result in a significant reduction in stiffness already for temperatures that can be reached in the interior climate of for example a building with a glass façade and solar radiation. [27]

2.3.2.1 Silicone Adhesive

The black silicones used are made from a polymer base plus chalk, silicic acid and soot fillers and further substances. The fillers stabilise the polymer so that a strength of about 1 N/mm^2 can be guaranteed. They also ensure a workable viscosity. The black colour of the silicone is due to the addition of soot. Production is simple and cost-effective. Transparent silicones are possible in principle, but require more expensive polymers (resins). The properties of silicones are summarized in Table 2.5. [12]

Table 2.5: Properties of silicones in relation to load-bearing adhesives for façades [12]

Requirement	Properties of silicone	Construction
	Creep	Mechanical support
Resistance to chemical media	Good resistance	
	Low strength with respect to tension and combined tension and shear stresses	Sufficiently large adhesive faces
Accommodation of component tolerances		Minimum joint width
Weather resistance	Permanently weather-resistant	
Component deformations	Elastic over the range -40 to +150°C	
	Damaged by permanent moisture	Open joints to allow drying out
Thermal stability	Resistant up to 200°C	
UV resistance	UV-resistant	

Especially due to the utilization of glass in the timber-glass composite system, solar radiation is a decisive aspect when choosing the adhesive, not only for functional and structural reasons (UV resistance), but also for aesthetic reasons (Figure 2.38). Silicone is the product that best responds to this type of necessities. Furthermore, regarding the analysed adhesives, silicone adhesive is the most advisable, as it allows greater indexes of flexibility, thus assuring the needed structural mechanical resistance. [29]

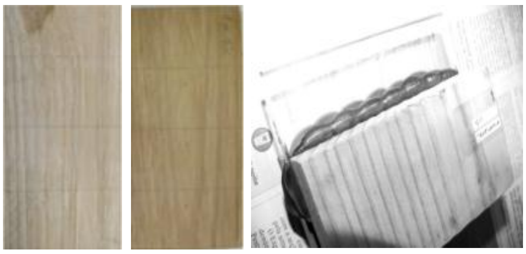


Figure 2.38a, b and c: Effects of solar radiation on timber surface with different colours - picture before (a) and after solar exposure (b) and on initially transparent adhesive (c) [29]

As silicones are elastic even at low temperatures and adhere very well to glass and common frame materials, they are extremely suitable for structural glazing systems. With structural sealing glazing (SSG), the linear bonding of façade and roof panels onto a frame is normally performed with silicone; the adhesive joint does not only provide the seal but also transfers the loads into the supporting structure. Silicones have long-term weather resistance and are temperature-resistant between -50º C and 150º C (some special silicones as high as 300º C) and have good chemical resistance. The joint thickness is between 6 and 8 millimetres, the ratio of joint depth to thickness is usually between 1:1 and 3:1. The best arrangement is a bond on two parallel surfaces. [13] Also, according to the statement of Winter the most suitable adhesives to be used in a façade construction would be the silicone adhesive. Although their strength is lower they have a much more consistent behavior under effect of moisture and temperature, and the creep behavior is lower. [11]

2.3.3 Adhesive Point Fixings

With structurally bonded point fixing, the glass is obviously not weakened by drilled holes, but additional means of carrying self-weight in-plane and ensuring adequate residual load-bearing capacity are often required. The systems are unsuitable for suspended overhead glazing. If the adhesive is an acrylate or 2-component epoxy resin then it should not be exposed to the effects of the weather. The load-bearing behaviour depends on the adhesive thickness and the radius of the fixing plate. [13]

According to the experiments were conducted before, new modified adhesive systems have been developed in the last years. The elastic adhesive bond represents an entirely new technology compared to the rigid adhesive bond in usual timber constructions (Figure 2.39). The elastic adhesive bond especially for timber-glass-composite elements offers the advantage of a smooth, uniform and linear stress initiation, so that glass can be activated as structural element. [11]

Figure 2.39: Elastic adhesives for timber-glass composites [30]

Today primarily silicones, silanes, polyurethanes or acrylates with different properties are used as adhesives. As it has been mentioned previously, silicones have strength characteristics of a relatively low level but they are extremely resistant to environmental influences (temperature, humidity, UV exposure, etc). Acrylates show semi elastic behavior with relatively high strength, but lose partly dramatic strength at temperatures above 50 ° C and / or high humidity. Besides the classic static properties for the adhesive the compatibility with other building materials and the creep behavior are crucial. In order to transfer the dead load, the adhesive bond need to show uncritically creep behavior. The load transfer of permanent loads must be guaranteed both in normal conditions as in special conditions like high temperature (solar radiation), UV light and/or occurring moisture (such as condensation). The very elastic adhesive compounds, such as silicones, can transmit sufficiently high loads, and with semi elastics adhesives (for example acrylates) high loads can be transmitted on the level of timber frame walls. [11] As mentioned in the previous section, silicone adhesives are favorable in façade constructions; not least because the long-term behavior of silicone adhesives by the decades of use in structural glazing façade is well known. Highly stressed building elements like trusses and plates in contrast require stiff adhesives like acrylates. [31] Creep behavior of the silicone adhesive will be described in the experiments part, chapter 3.

In general, glued joint offers a bigger ability to assemble thinner materials or to connect different materials together as well as aesthetic appearance and reduction of self-weight. [28] Adhesive layer itself also provides a protection from direct contact between timber and glass, which always has to be avoided in glass structure engineering. For the purpose of composite structures, in general, adhesively bonded joint should be rigid enough to provide an optimal interaction between both connected elements, but whole connection has to be able to compensate pertinent different temperature deformations of glass and another material (e.g. steel, aluminium, stain-less steel) especially in case of longer composite structures. [17]

As mentioned in the part of glass, glass panes can be used as shear walls. This is the case of glass pavilions and some timber or steel frames or façades. The behaviour of such structural systems mainly depends on the stiffness of the connections. Possible applications of glued joints could be point supports or linear bearings to carry single façade elements or connect them to plates, columns and beams. Circumferentially glued joints are generally classified in three different types as shown in Figure 2.40. Glazing elements in façades are usually designed only to support out-of-plane loads. However glazing elements can also support high in-plane loads and, thus, contributing to minimize the number of steel elements and their cross sections. [32]

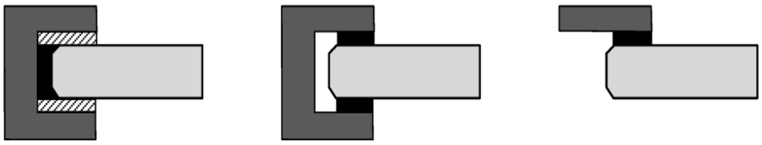


Figure 2.40: Adhesive joint types [32]

The lesser the support system, the more complicated the transference of loads and actions from glass into the substructure will be. If high loads have to be transferred by small dimensions, the corresponding fixing system plays a key role in this field and different strategies have to be balanced in order to avoid unpredictable and brittle failure. [32]

About the influence of layering within the substrate, beside the variation of different timber materials and adhesives, also the influence of the substrate layering has an essential influence on the adhesive behaviour for structural sealant glazing systems. Examinations carried out under standard climatic conditions have shown that an increase in strength of the bonding can be reached by different orientations of the timber layering. The level of ultimate strength, e.g. of polyurethane gluings on end-grain timber have a higher average level of strength than gluings on the side timber. [26]

In conclusion, primary idea is to develop a suitable connection system, to investigate its behaviour and its influence on the structural behaviour of timber-glass panels. In response to the question why a structural adhesive bonding used in timber-glass composite, the following main reasons can be mentioned: [21]

- Ideal balance between strength and ductility, combining different materials;
- Uniform distribution of forces;

- Reduction of materials fragilization by avoiding drilling;
- Prevention of high peak stresses on glass surface.

2.4 Timber-Glass Composites

The objective of the research project " Load Bearing Timber-Glass Composite Structures ” of the Istanbul Techenical University is to develop industrialized products based in timber-glass composite elements which respond to the structural requirements and climate demands. As mentioned in the glass section, in recent years the develomnet of structural glass provided engineers glass with the higher mechanical properties, which can be used as load-bearing elements. This fact gives the opportunity to create new generation of structural composite systems of timber and glass with high aesthetic, economic and load-bearing value. Its position within the building can vary in the same way; it can be integrated into the façade, the roof, in the interior as a partition wall and even as a floor element. [33] Possible applications of this product in architecture of Turkey could include office buildings, prefabricated homes, greenhouses, load-bearing façade elements, structural elements as part of a system that improves an existing building. As mentioned today combination of timber and glass is frequently used for façades or small size structures. They are used as structural composite system less due to a lack of knowledge of their composite behavior. Raising of knowledge about this composite system and the evaluation of load-bearing capacity of it are presented as the main goals of this part of research.

As a complement, the increasing resort to composite solutions diversifies the range of functional, expressive and structural solutions of products, leading to results that any material alone, with its limitations, could not achieve. Therefore, any composite solution will aim at enhancing the intrinsic increased value of its components and the simultaneous minimization of the disadvantages of each material. This is the central idea behind composite systems and also the starting point for the development of the present research. [22] The composite elements allow the best of the characteristics of two different materials to be brought together for a common purpose. In this case, in structural terms, the timber assumes good bending behaviour, being ductile to compression, whilst the glass presents a very positive result in terms of the compression force. [16] Cruz and Pequeno have refered that the main characteristic of this composite system is that timber provides ductility and glass offers resistance and stiffness. The bonding system is also very important, when the glass cracks, the adhesive bond transfers the tensile force. The adhesive has to service under all conditions and for a significant period of time. [21]

Prefabricated elements in timber engineering have many advantages over traditional types of construction. Traditional approaches to construction are expensive to design and implement, slow and complicated. About a quarter of the material consumed in a structure is simply waste. The advantages of using timber-glass composite structures as prefabricated systems about constructive aspects and structural behavior are: [1,35]

- High quality because the work is carried out under good conditions;
- Multi-structurality: Autonomous triaxial structural element;
- Multi-functionality: Thermally dynamic, reducing the energetic waste;
- Sustainability: Integration of passive solar systems and bioclimatic principles;
- Effective shadowing in several orientations;
- Self-restraint: Ribs integrated inside the element;
- Lighting and translucence: Architectural expressiveness
- Rehabilitation: Integration of technical infrastructures;
- Modulation: Metrics, modularity, habitability and urbanity;
- Can be updated as an intelligent system (domotics and water roof collecting);
- Durability: Protection of the timber and the adhesive by means of glass skins;
- Optimisation of costs;
- Less waste because less adaptation and adjusment is necessary;
- The waste generated in the prefabrication plant can be recycled;
- Lower erection costs on site;
- No construction moisture during erection.

One of the possibilities for using a fixed glazing in prefabricated timber-frame panel wall elements is to replace the classical sheathing boards with the glass panes (as schematically presented in Figure 2.41). The glass panes need to be sufficiently over-strengthened (relative to the metal fasteners that connect them to the timber frame) to ensure that a ductile failure mechanism forms in the connection between the glass and the frame. However the other option is to connect the glass panels to the main timber frame without the use of ductile fasteners (using an adhesive instead) and to sufficiently dimension the glass panels to resist the seismic forces in an elastic state. The glass panes have a substantial influence of the buildings behaviour. [36]

Figure 2.41: Timber-glass prefabricated walls; replacing classical sheathing boards with glass panes [36]

Furthermore, two different, basic methods are for the installation of the glass panel: first, a line of binding tape runs along the perimeter of the panel and second, a combination of flexible adhesive and rigid blocks in the corners appears to transfer the load to the glass pane. The last variable requires an adhesive that is sufficiently malleable to transfer the force in an efficient way and sufficiently rigid so as to not cause excessive deformations. In this case, the glass panel is used as a compressive element, leaving a compressed diagonal in the glass plate activated during the load application (Figure 2.42). [37]

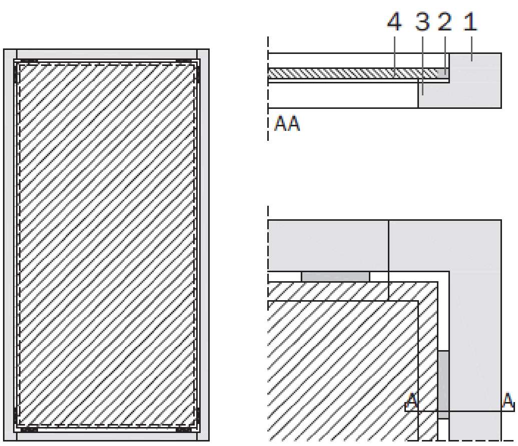


Figure 2.42: 1. Adapter frame 2. Block setting 3. Glue line 4. Glass pane [37]

The Figure 2.42 shows joint system. Only in the frame angles are there joint elements that resist compression and thus allow the respective forces to the glass that can be transmitted in a diagonal direction along the glass pane. The system does not allow the transmission of traction and as such only one side will be structurally activated at a time. By restricting the introduction of forces at the angles, moments and bending forces are not produced on the glass. The silicone transfers the pushing forces from dilatation up to a certain point. [37]

There are numerous parameters, which influence the horizontal resistance and stiffness of the timber-glass composite wall elements, material properties and thickness of glass panes. However, the connection between timber and glass is one of the most important. The following connection parameters have a significant influence on the response of timber-glass walls (if the glass is glued to timber): 1) the position of the glass pane and hence the position of the glue line; 2) the type of the adhesive and 3) the thickness and width of the glue line. Moreover, about the seismic behaviour of timber-glass composite, two typical horizontal load cases on a building are wind and earthquake. Wind forces apply pressure on the outer walls of the building. For a majority of buildings on seismically active areas the more problematic of the two is earthquake. The general principle when designing a building to resist earthquakes is to take into account a certain level of damage allowed to develop on structural elements during an earthquake. Hence the timber-glass building should be either designed strong enough to withstand the seismic forces undamaged or the glass elements should be protected against too high forces by connecting it to the main structure using ductile fasteners. [36]

Another issue related to combining timber and glass materials is their different characteristics. The external timber-glass wall elements will be mostly placed in the south direction. Hence, they will be exposed to high temperature differences. Unfortunately, the coefficients of thermal linear expansion (αt) of timber and glass are quite different. Perpendicular to the grain, the coefficient of thermal expansion for timber is as much as ten times larger than the coefficient parallel to grain. That is almost twenty times lower than for glass. Consequently, temperature differences can cause high shear stresses in the adhesive between the timber frame and the glass panels. [38]

2.4.1 The Results of Experiments Carried-out in Previous Researches

The main conclusion of experiments which were conducted at University of Minho [35,41] on timber-glass composite structural panels, timber panels and then comparison of each other, is glass behaves as a structural reinforcement of the timber sub-structure. Each composite panel was 224 mm thickness, and consisted of two laminated glass bonded on both faces of the timber structure, made of four timber boards. The applied stress types on specimens were bending, compression and shear stress (Figure 2.43). Timber without glass is left excessively exposed to its own natural imperfections. As structural wall system, the glass contribute became even more evident. The carrying capacity of the panel with glass, when compared to that without it, become clear that there is an increase of stiffness and resistance, which makes possible to exceed very high value, still keeping a considerable safety margin, as well as a ductile failure at its post high peak (Figure 2.44).

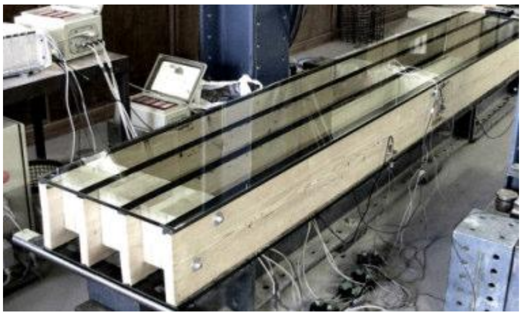


Figure 2.43: Timber-glass composite structural panel, laboratorial bending tests – horizontal position, system as slab [39]

Figure 2.44: Laboratorial bending tests – vertical position, system as wall [39]

This system shall give rise to a product that constitutes an "open system", transmitting high loads both on its plane and perpendicularly to it, being combinable with other structural systems and, by means of the substructure, adaptable to the specific aspects, with the advantage of always using the same standard parts. In terms of safety, the resulting panel prevents the brittle collapse of the system under all circumstances: [39]

- Collapse of timber through tensile stress: prevented by glass and adhesive;
- Buckling of timber boards outwards: prevented by threaded steel rods;
- Buckling of timber boards inwards: prevented by massive timber cubes.

According to mentioned tests, some objectives were ful filled when analysing the use of glass in this system: [34]

- Great mechanical resistance (109,7 kN), increasing in 31% the maximum load obtained with the panel without glass;
- First crack through timber and only then through glass. This confirms the effectiveness of glass in this type of utilization;
- Ductile behaviour and collapsing, prevent brittle behaviour and assure safety;
- Contribution of glass to the effective strengthening of the structure. After its collapse, the loading decreased considerably and never rose again.

Another case in order to tests on shear stress compression, involving different types of adhesives which were carried out at University of Minho on timber-glass composite structural panels, longitudinal deformation of timber is higher than timber-glass relative displacement (Figure 2.45). Each specimen is made up of a glass plate fixed between two timber boards. The results obtained in these tests are to conclusions on various important aspects, such as strength and relative timber-glass displacement; timber deformation and also glass type influence. In first case of experiments timber and glass structural panels were bonded by acrylic adhesive. Three shear stress tests were performed on the specimens. The maximum loads in tests 1, 2 and 3 respectively, were 88 kN, 57 kN and 73 kN (Figure 2.46). In first test, specimen dimension was 400x100 mm; without primers; laminated glass 5+5 mm; contact surface area was 40000 mm^2. In second test, specimen dimension was 400x100 mm; within primers; tempered glass 5 mm; contact surface area was 40000 mm^2. In third test, specimen dimension was 400x100 mm; within primers; laminated glass 5+5 mm; contact surface area was 40000 mm^2. [29]

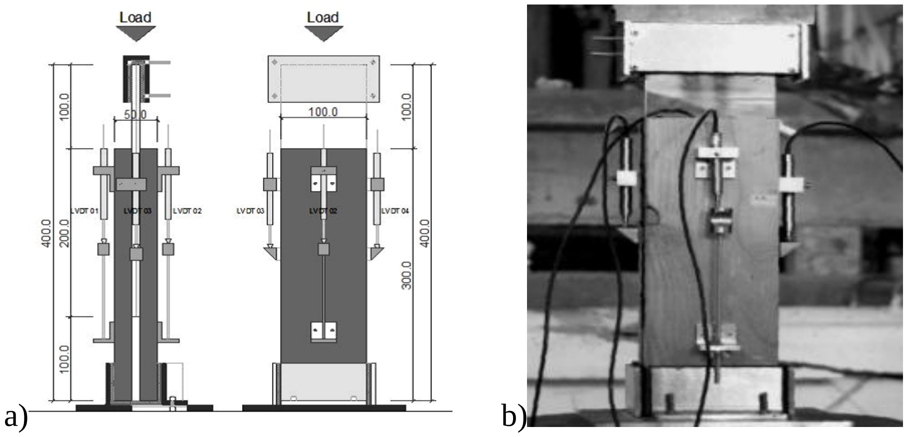


Figure 2.45a, b: Set-up of test, instrumentation and load application (a) and picture of test carried out (b) [29]

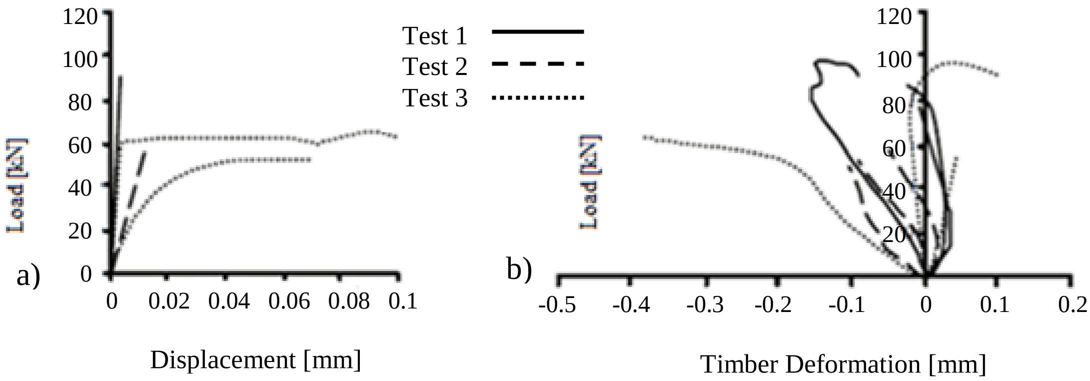


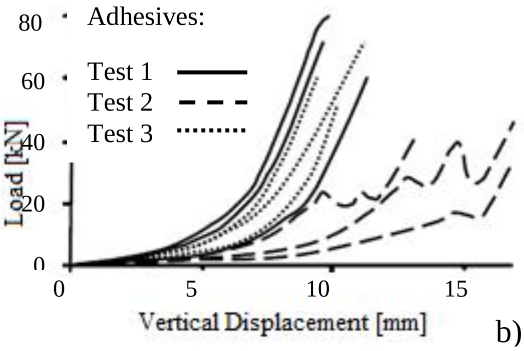
Figure 2.46a and b: Load/ Timber-glass displacement (a) and Load/ Timber deformation (b) [29]

Relative displacement of timber-glass (average [mm]), in first test was 0.1, in second test was 0.0 and in third test was 0.1. In addition, a comparison between Figures 2.46a and 2.46b, both regarding a rigid adhesive (two-component acrylic), shows that longitudinal deformation of timber is higher than timber-glass relative displacement. This fact brings consequences to the specimen behaviour. Longitudinal deformation of timber has repercussions in its tangential expansion. This represents precisely the occurrence that must be minimised, as it is responsible for the application of tensile stress on the glass surface directly in contact with timber, as shown in Figure 2.47.

a)  b) 

Figure 2.47a and b: Consequences of timber tangential expansion on glass [29]

Three other shear stress tests were performed on same specimens with the exception that the maximum loads in tests 1, 2 and 3 respectively, were 72 kN, 50 kN, 62 kN and in these tests, Sika®methacry lat. Adhesive was used. Relative displacement of timber-glass (average [mm]), in first test was 0.1, in second test was 0.1 and in third test was 0.2. The tests also showed that, tempered glass, though more resistant to superficial stresses than laminated glass, presents two considerable and decisive disadvantages, such are brittle behaviour and an irregular surface (Figure 2.48b). Repercussions of these characteristics are shown in (Figure 2.48a). [29]



a)

b) 

Figure 2.48a, b: Load-vertical displacement curves comparing laminated glass with tempered glass (a); Tempered glass irregular surfaces (b) [29]

In other experimental case, in the set of tests in response to a question that the possibility of reinforcing timber through bonding with glass. Parallel reinforcement (Figure 2.49) and transversal reinforcement (Figure 2.50) were tested. Particularly in transversal reinforcement, an increase in the loading capacity of the specimens was observed, especially because collapse is geometrically displaced towards the edge of the reinforcement area, as shown in Figure 2.49c and 2.50b. [29]

a) b) c)

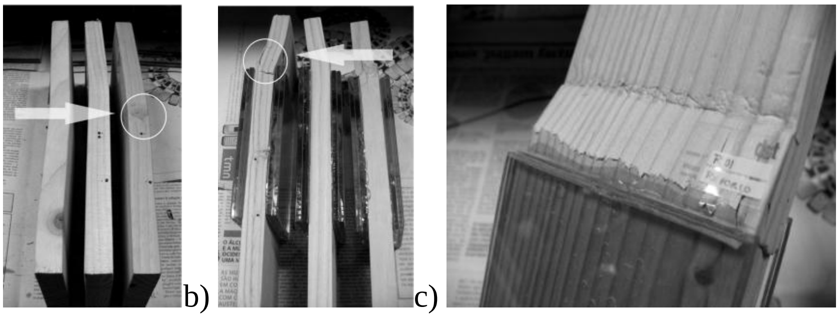


Figure 2.49a, b and c: Timber reinforcement with parallel glass plates [29]

a) b)

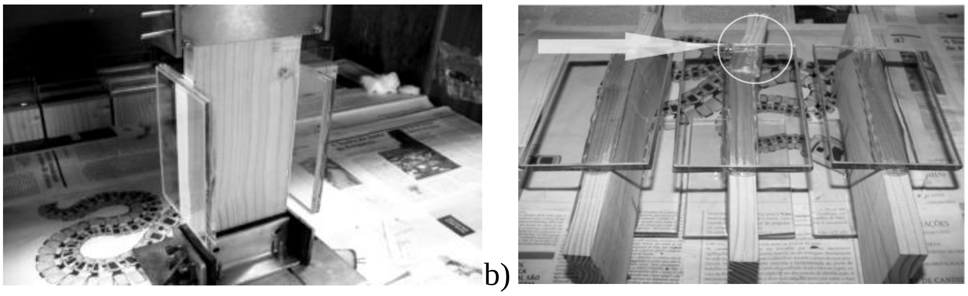


Figure 2.50a and b: Timber reinforcement with transversal glass plates [29]

The timber-glass walls have five theoretically possible failure modes (Figure 2.51) when loaded in-plane: (1) failure of corner hold-downs; (2) failure of shear brackets; (3) failure of the adhesive joint between glass and timber; (4) failure of the glass panel and (5) failure of the columns. In the loading tests on four single-story and four two-story timber-glass structures combining different types of timber-frame wall elements with fixed glazing, the tested specimens exhibited a rocking type of behaviour, dissipating the seismic energy in the corner hold-downs. The shear slip of the panels in the ground floor was minimal. The shear slip in the adhesive line was present however no damage occurred. [36]

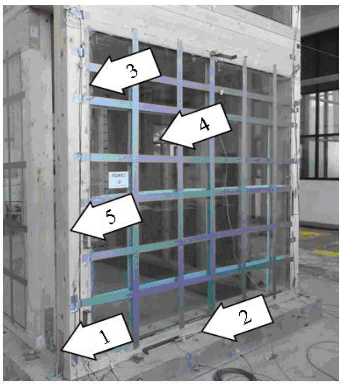


Figure 2.51: Theoretically possible failure modes [36]

After analysing the test results of researches that have been done previously, some important advantages for timber-glass type of composite structure were found. In response to the question why timber structurally combined with glass, these reasons can be mentioned: [21]

- Ductility: With glass alone, no deformation of this level would be possible unless overloading point is achieved;
- Safety: It prevents brittle failure of the constructive system;
- Strength: The mechanical resistance capacity is enhanced;
- Evenly distribution of loadings due to the action of the structural bonding;
- Reinforcement of glass elements: Timber presents low variability in its longitudinal axis and this may play an important role in the lower flange;
- Lateral restraint of glass plate;
- Complementary characteristics, which gives meaning to composite behaviour. Glass is compression stress resistant; timber is tensile (in grain direction) stress resistant;
- Protection of the edges of glass, its most sensitive area;
- Possibility of creating a secondary structure for independent support.

Also, there is the possibility of using the high peak load capacity of glass after collapse of the adhesive. The integration of a metallic plate inside the timber structure, or a U profile, able to resist tension transmitted by the edge of the glass, will assure the redistribution of tension towards a larger timber surface. Another example is correlated with the geometrical misalignment of glass in relation to the edge of the timber flanges (Figure 2.52a), as to apply load on the surface of timber, thus protecting the edge of the glass plate from accumulated stresses. One last example relates to the integration of timber flanges in a discrete restraint system, as to assure the stability of the structure. This is the solution to the buckling effect on glass (Figure 2.52b and 2.52c). [21]

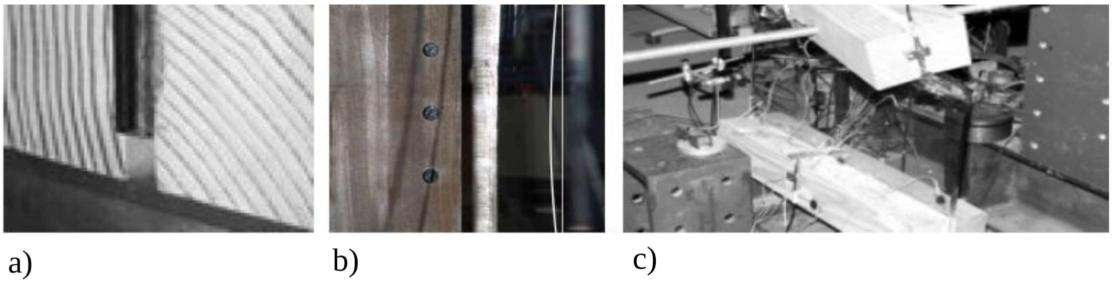


Figure 2.52a, b and c: Misaligned timber-glass geometry(a); buckling effect(b); laterally unrestrained beam(c) [21]

2.4.2 Design Methods of Stiffening Timber-Glass Constructions

At the new construction approach, the glass panels are connected to the loadbearing construction using a structural sealant system. A possible cross-section is represented in Figure 2.53. The construction shows the special feature that, in addition to the main function of stiffening the load-bearing construction, optimizations in physical points of view are possible (Figure 2.54). The construction can be equipped with insulating glass units, with thermal breaks and aluminium covers and may thus fulfill all physical requirements valid at present. [26]

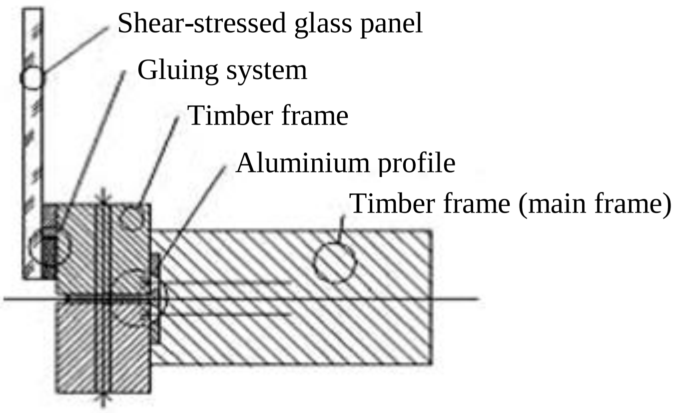


Figure 2.53: A possible design method of stiffening timber-glass-constructions [26]

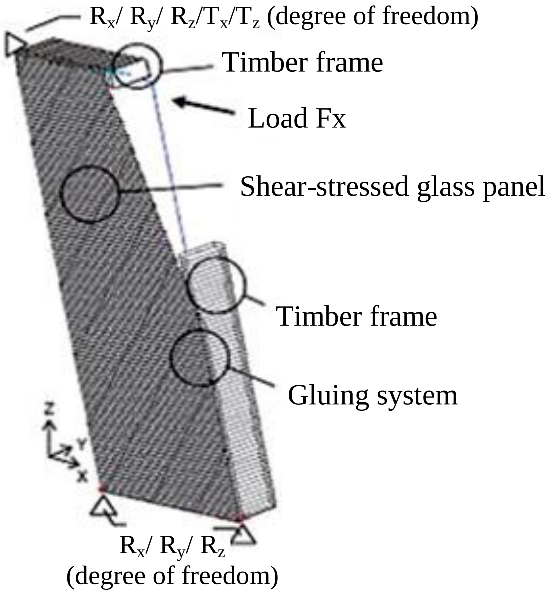


Figure 2.54: Model of a stiffening timber-glass-construction [26]

2.4.3 Examples of Timber-Glass Components

Hotel Palafitte in Switzerland is built with timber-glass composite girders to support the roof [40] (Figure 2.55). These girders have an I-section with flanges of timber and a web of glass. An adhesive referred to as 'HGV 125 glue' was used. A test to establish the long-term deformation was performed on prototypes of the hotel Palafitte girders. In this test, the 'assumed maximum loads' were applied on the element. Deflection is claimed to be stable at 12 mm after four weeks, except for deformations caused by 'day and night cycle temperature differences'. From deformation measures on site, after the hotel was built, the deflection was shown to be stable at 4 mm, i.e. one third of the deflection from the test. [41] This result shows that the displacement was less than the measure expected and this is a positive feature of the composite.

Figure 2.55: Timber-glass composite beams in the conference room in the Palafitte hotel [42]

Copper Market at Bursa is about 120 years old and was recently covered with a timber-glass roof structure. Laminated timber beams with a cross-section of 15 cm x 40 cm were used and the total length of beams was 4000 meters (Figure 2.56). [55]

Figure 2.56: Copper Market in Bursa [55]

Architect Vedat Tokyay‟ s office has designed a roof that is covering a swimming pool in Bursa in 2003 (Figure 2.57). The roof was built with laminated timber beams and glass. [35]

Figure 2.57: Roof over a swimming pool in Bursa by Oran Architecture, from archive of Vedat Tokyay

Timber and glass are also used together in two buildings for having an effect of a transparent box in the nature (Figure 2.58). [35]

Figure 2.58: Summer House, Dikil from archive of Şevki Pekin [35]

The office building has been designed in Istanbul, Turkey, as a prismatic mass which is ranging to a gap by the help of the cantilevers that lyed on the south and west façades. South façade is placed in front of a glass surface as a seconday façade. Geometric timber panels strengthen the perception of the building from the main road and the solid-void relationship brings a comfortable office ambiance by the control of sunlight and sound. The space which is in between with timber panels and glass façade, turns into terraces that provide natural air condition. By the sharp geometric combination of the materials; natural stone, glass and timber, are creating the general character of the building (Figure 2.59). [56]

Figure 2.59: The office building in Istanbul, Turkey [56]

Another example project has been designed by the architect Ahmet Alataş with respecting the current architectural fabric, infrastructure, natural conditions, climate and sun movements, and developing socio-economic conditions. The building was built around a design that uses today’s technology to offer new solutions to respond to well-known architectural problems. To describe it simply, the building is constructed around two blind walls made of fine concrete and a glass façade and timber shell that cover the fully transparent living quarters. Perceived as a giant blind façade from an angle, the timber surface can be seen as a tulle curtain that filters the light and works as an element that controls the sunlight. The timber components on the front elevation run parallel to the glass façade that evolves into a saddle roof and entirely cover the front and back of the building (Figure 2.60). [57]

Figure 2.60: The building is located in the historic and protected district of Istanbul's Galata [57]

The properties of timber structural material, the properties, bearing capacity and the deformation behaviour of glass panels, the issues related to adhesives have been described and relevant influence parameters have been explained for use of structural stiffening timber-glass constructions. The next chapter describes the performed experiments.

3. EXPERIMENTAL TESTS

As mentioned at the intoroduction part of thesis, the research was carried out as a part of European Project, EUWOODWISDOM-NET research program. The Turkish group of the project headed by the Istanbul Technical University (ITU), analyzed the structural silicone sealant Ottocoll S660. The experimental tests consist of two parts; small-sized and medium-sized tests. Small-sized tests include durability tests (freezing-thawing, wetting-drying, UV effect, resistance to high temperature and acids) that were done in order to investigate the behavior of the material under the effect of accelerated aging. The mechanical strength of the timber-glass composites was measured by adhesion and shear strength tests. Influence of the durability tests on strengths was measured afterwards. Small-sized experimental tests were performed at Istanbul Technical University, Faculty of Architecture Laboratory. First, the small-sized tests are described.

3.1 Scope

The aim of small-sized tests is to investigate the behavior of adhesion and the properties of timber-structural silicone joints in order to understand the failure modes and strength of this bonding. For this purpose, adhesion and shear strength tests on the timber-glass small-sized specimens were carried out in order to investigate the adhesion strength. The objective of the long-term testing of medium-size specimens is to investigate the environmental and long-term loading effects on the timber-glass composite elements.

3.2 Method

In this section, the materials that were used in the experiments are described firstly. Afterwards the procedures of tests are explained.

3.2.1 Materials

Birch plywood is characterised by its excellent strength, stiffness and resistance to creep. It has a high planar shear strength and impact resistance, which make it especially suitable for heavy-duty floor and wall structures. Birch plywood has excellent surface hardness, damage and wear resistance. Typical end uses of birch plywood are concrete formwork systems, floors, walls and roofs in transport vehicles, container floors, floors subjected to heavy wear in various buildings and factories, scaffolding materials, load bearing special structures. [45] Since the adapter frame seems a promising concept the shear strength was also assessed using birch plywood (Figure 3.1). The plywood classified surface grade III (EN 635-2) and water boiled proof (EN 314-2). The plywood specimens were stored at a constant climate of +20 °C and 80 % relative humidity prior to bonding. A moisture content of approx. 10 % was measured on random samples. Cleaning of the timber surface involved blowing clear using compressed air.

Figure 3.1: Plywood samples used in the experiments

Tempered soda-lime glass was used as substrate material of small-scale specimen (Figure 3.2). The properties of tempered glass was described in Chapter 2. The higher strength compared to standard float glass minimizes glass failure during testing. The tempering of the glass does not change the adhesive characteristic of its surface. For this test sequence glass is always glued on the air-side. The surface was cleaned by a cloth. No further surface treatments were executed. The tempered glass for the experiments in Istanbul is produced in the Trakya Glass Industry fabric (Trakya Cam Sanayii A.S.).

Figure 3.2: Glass samples used in the experiments

The sealant Ottocoll S660 is a type of 2-component silicone adhesive and was specifically developed for timber-glass composites. The adhesive manufacturer is Otto Chemie. This type of silicone adhesive was used for experiments and was applied manually (Figure 3.3). The timber, with the adhesive on, and the glass were then pressed together in a press.

Figure 3.3: The adhesive used in the experiments [46]

The main characteristics of Ottocoll S660 are as following: [46]

• Extremely UV-resistant, crack and notch resistant
• Non-corrosive
• Excellent adhesion on timber and glass
• High expansion-tension value guarantees high stability bonding
• Cures at room temperature
• Minimal odour nuisance

• Reduced cycle times - due to the fast curing bonded parts can be further processed extremely soon
• High mechanical capability
• Low shrinkage during vulcanization (approx. 4 %)
• Very good temperature resistance
• Excellent resistance to water and moisture

As mentioned, the elastic adhesive Ottocoll S660 exhibits good durability, although it is rather soft. This may limit its applicability for shear walls and other structural purposes with high loads. Nevertheless, it is important to gain further knowledge on its behavior in durability tests, mechanical strength tests and also its creep behavior which will be discussed in this Chapter.

3.2.2 Specimen for Shear Tests

Shear test specimens shall conform to the form and dimensions which are defined in ASTM D1002 (Standard Test Method for Apparent Shear Strength of Single-Lap-Joint Adhesively Bonded Metal Specimens by Tension Loading). The thicknesses of the plywood and the glass are 18 mm and 8 mm, respectively (Figure 3.4). The length of the overlap between the timber and glass, where the adhesive is applied, is 12 mm and the thickness of the adhesive is 3 mm.

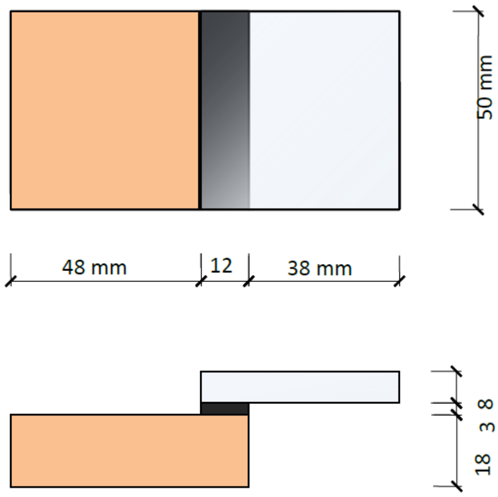


Figure 3.4: Dimensions of shear specimen

ASTM D1002 specifies the dimensions of the adhesion interface between the timber and glass. Therefore, small-scale specimens were prepared (Figure 3.5) and one of them is shown in Figure 3.6.

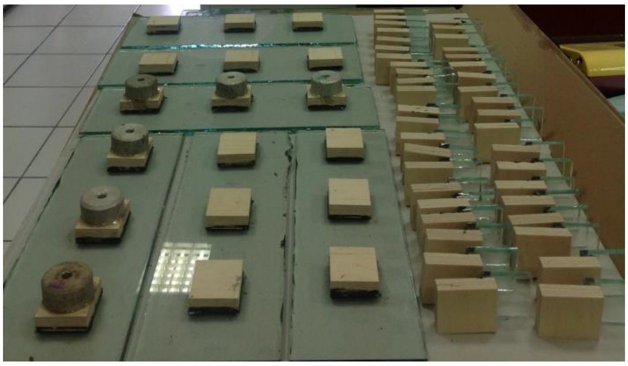


Figure 3.5: Small-scale specimens were prepared at ITU, Faculty of Architecture Laboratory

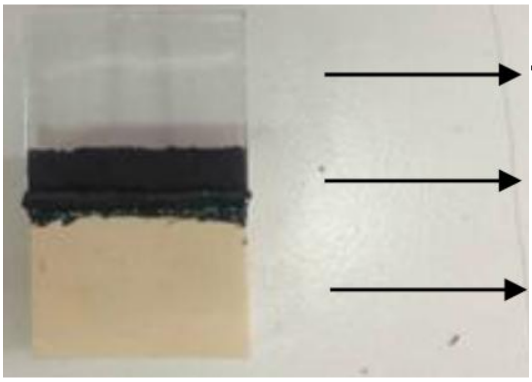


Figure 3.6: A shear specimen

3.2.3 Shear Test

The specimens were placed in the Universal Test Equipment to apply the shear load (Figure 3.7). The loading rate is 50 N/s. The deformations were recorded with 1/1000 mm digital indicator for every 50 N. The maximum load at failure was recorded. The shear strength is calculated by dividing the failure load by the shear area.

Figure 3.7: Loading device for shear tests

Shear tests of timber-glass specimens were performed for different testing conditions. Initially six specimens were tested under laboratory conditions. The rest of the timber-glass shear specimens were used for durability tests, such as wetting and drying, freezing and thawing, UV effect, high temperature and resistance to acids. After the durability tests have been finished, these specimens were tested for shear strength as well. The number of the shear specimens tested for each testing conditions is given in Table 3.1.

Table 3.1: The number of timber-glass shear specimens for testing

Test Conditions	**No of shear specimens**
Laboratory conditions (23C°, 50% humidity)	6
Wetting-drying	6
Freezing-thawing	6
UV effect	6
High temperature	6
Resistance to acids (HCl)	3
Resistance to acids (SO_2)	3

3.2.4 Specimen for Adhesion Tests

As shown in Figure 3.8, 50 mm x 50 mm plywood specimens were glued on 450 mm x 450 mm glass plates with the 2-component silicone Ottocoll S660. After drying of the silicone pull-off headings were attached to timber-glass specimens with a 2-component epoxy resin (Figure 3.9).

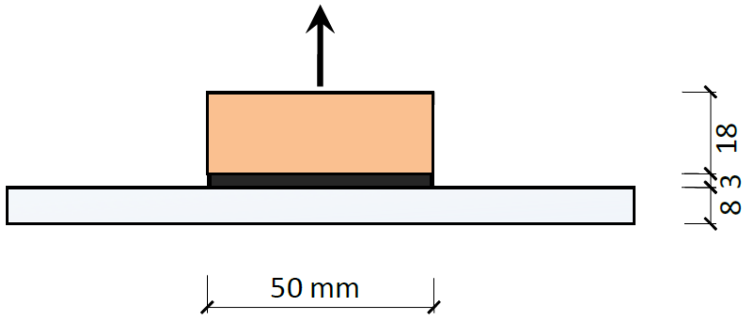


Figure 3.8: Dimensions of adhesion specimen

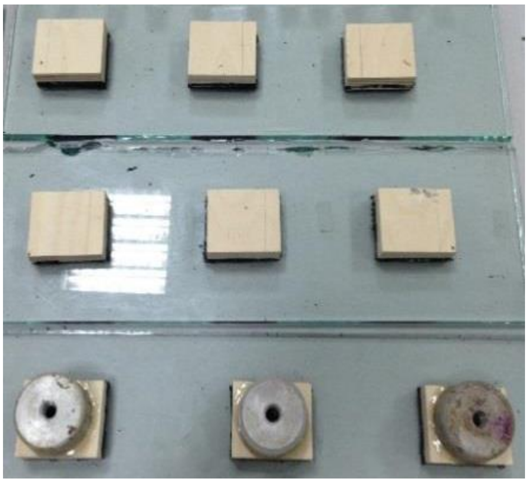


Figure 3.9: Prepared samples in the laboratory

3.2.5 Adhesion Test

Timber-glass specimens were fabricated according to ASTM d4541 - 09E1. The specimens were dried under 20°C and 45% RH. After drying, the pull-off headings were attached to the specimens with the 2-component epoxy resin. When the resin was cured, a tensile force of 250 ± 50 N/s was applied to the specimens via the pull-off headings of the Pull-off instrument. Maximum tensile forces at the failure were recorded (Figure 3.10).

Figure 3.10: Test set-up of the adhesion test

According to EN 1348, adhesion strength is calculated by the following formula:

$A_s = L / A$

where,

A_s = Adhesion strength (N/mm^2)

L = Failure load (N)

A = Adhesion area (mm^2)

According to EN 12004, the tensile adhesion strength for each set of conditions shall be determined as following:

- Determine the mean of the ten values;
- Discard the values falling outside the range of ± 20 % from the mean value;
- If five or more than five values remain, determine the new mean value;
- If less than five values remain, repeat the test;
- Determine the types and shapes of failure.

The number of the adhesion specimens tested for each testing conditions is given in Table 3.2.

Table 3.2: The number of timber-glass adhesion specimens for testing

Test conditions	No of adhesion specimens
Laboratory conditions (23C°, 50% humidity)	6
Wetting-drying	6
Freezing-thawing	6
UV effect	-
High temperature	-
Resistance to acids (HCl)	-
Resistance to acids (SO_2)	-

3.2.6 Durability Tests

The aim of the durability tests is to determine the effects of environmental conditions on the mechanical properties and volume stability of the timber-glass composites. In Turkey, severe weather conditions have essential effects on the performance of buildings. The use of timber-glass composites in atmosphere would result in deformation and rotting of timber. Therefore, the durability tests are important for the performance determination of the timber-glass composites. After the durability tests, the weight loss and the deformations of the specimens have been determined. As mentioned before, the effect of the durability tests on the mechanical strength of timber-glass specimens were obtained by shear and adhesion tests afterwards. Durability tests were performed in a 225 liters Climate Chamber. The interior dimensions of the chamber are 750mm x 500mm x 600mm (Figure 3.11).

Figure 3.11: Climate Chamber

3.2.6.1 Wetting-Drying Test

For wetting-drying test, in one cycle, six timber-glass shear specimens were held in 25°C water for 18 hours and then were dried in the oven at 50°C for 6 hours. Seven wetting-drying cycles were completed during the test procedure (ASTM D2559 - 12a Standard specification for adhesives for bonded structural wood products for use under exterior exposure conditions).

3.2.6.2 Freezing-Thawing Test

According to ASTM C1262-05a (Standard test method for evaluating the freeze-thaw durability of manufactured concrete masonry units and related concrete units) freezing-thawing test of six timber-glass specimens was performed between –20°C and +25°C. One cycle was completed within 18 hours of freezing and 6 hours of thawing. 25 cycles were completed during the test procedure.

3.2.6.3 UV-Light Test

UV test was performed to determine the level of degradation of the material after being exposed to ultraviolet light. The climate chamber having UV test facilities, simulates the effect of sunlight with fluorescent ultraviolet (UV) lamps, while rain and dew are simulated by the condensation of humidity (Figure 3.12). UV light represents roughly 5% of the sunlight, but this percentage causes the most of the polymer degradation. In this study, degradation by UV light was evaluated by spectrophotometer measurement and visual investigation. For this purpose the ASTM D7032 - 14 was used.

Figure 3.12: UV test in the climate chamber

3.2.6.3.1 Spectrophotometer Measurement

ASTM D7032 - 14 (Standard specification for establishing performance ratings for wood-plastic composite deck boards and guardrail systems (Guards or Handrails)) was used for the determination of colour changes with spectrophotometer. Three timber-glass specimens were held at 20^{o}C and 50% RH for 24 hours. After 24 hours, the colorimetric coordinates $a_{(o)}$ of the specimens were measured with the spectrophotometer. Then the specimens were placed 75 cm away from the 400 W UV lamp and they were exposed for four hours. The colorimetric coordinates $a_{(4)}$ of the specimens were again measured at the end of four hours exposion. The specimens were replaced under UV lamp for 26 hours and the colorimetric coordinates $a_{(26)}$ of the specimens were measured. The duration of the test was 28 days. At 28th day, colorimetric coordinates $a_{(final)}$ of the specimens were measured by spectrophotometer (Figure 3.13).

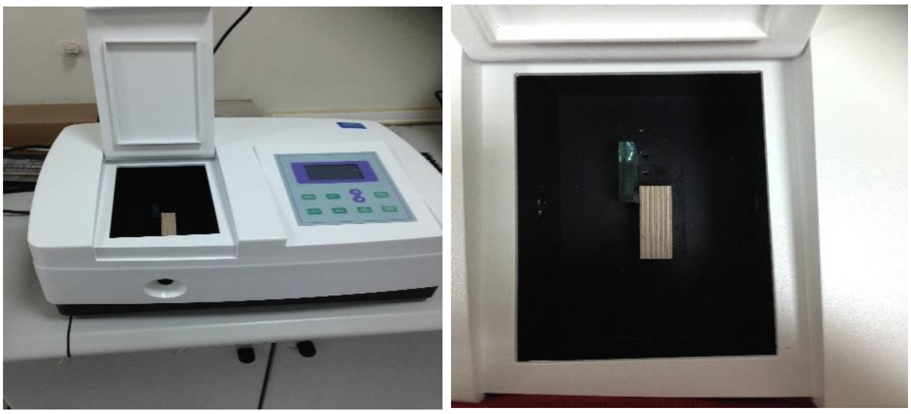


Figure 3.13: The spectrophotometer used in UV effect test

Spectrophotometer CM2600-d of which system is CIE L*a*b*2 with D65/10^{o}C radiance and veren 8^{o} spherical geometry. In this system, L* is the brightness, a* ve b* are the colometric cooordinates of the dimension of the colour of 2D surface. When a* coordinate is positive (+), it goes to red . When a* coordinate is negative (-), it goes to green. When b* coordinate is positive (+), it goes to yellow. When b* coordinate is negative (-), it goes to blue.
The photocatalytic property of the material is calculated as;

$$R_4 = \frac{a_{(0)} - a_{(4)}}{a_{(0)}} \text{ x } 100$$

$R_{26} = \frac{a_{(0)} - a_{(26)}}{a_{(0)}}$ x 100

$R_{final} = \frac{a_{(0)} - a_{(son)}}{a_{(0)}}$ x 100

where,

$R_{(4)}$: The percentage of the colour lost after 4 hours

$R_{(26)}$: The percentage of the colour lost after 26 hours

$R_{(final)}$: The percentage of the colour lost after 28 days

$a_{(0)}$: The colorimetric coordinates before exposed to UV lamp

$a_{(4)}$: The colorimetric coordinates after exposed to UV lamp for 4 hours

$a_{(26)}$: The colorimetric coordinates after exposed to UV lamp for 26 hours

$a_{(final)}$: The colorimetric coordinates after exposed to UV lamp for 28 days

- **Visual Investigation**

The colour change is also detected according to the ASTM D4329-05. Half of the specimens were covered with the aluminum foil and they were placed 75 cm away from the 400 W UV lamp for 28 days. After 28 days, the colour change was determined and evaluated by uncovering the specimens.

3.2.6.4 Resistance to High Temperature Test

Six timber-glass shear specimens were tested for the inflammability test according to DIN 4102-1:1998. The specimens were placed into the oven after their weights have been measured (Figure 3.14). The temperature for the plywood was determined as 150°C according to the chemical composition of the plywood. Inner temperature of the oven was also measured during the test. When excessive smoke is produced or the temperature reaches to 150°C, the test has been completed. After the specimens were taken out from the oven, they were left to cool down and weighed again. The shear strength of the specimens was measured afterwards.

Figure 3.14: The timber-glass specimens for high temperature test

3.2.6.5 Resistance to Acids Test

Effect of the underground water with the sulphate (SO_2) are hazardous for the structures. The sulphate decreases durability of materials. It is essential to determine the durability of the timber-glass composites against sulphate in order to prevent it from the hazardous effects. Three timber-glass shear specimens were hung over the solution concentrated with 5% SO_2 for 28 days (Figure 3.15a). Every 7 days and after 28 days, three specimens were removed away and compared with the reference specimens regarding the change in their color and visual appearance. Reference specimens were kept in the desiccator. For investigating the resistance to the effects of atmosphere, three timber-glass shear specimens were placed into the water solution with 1% HCl (Figure 3.15b). The specimens were taken out of the solvent after seven days. Their appearances were compared with the reference specimens regarding color and visual appearance.

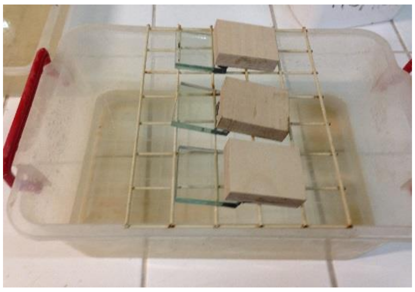
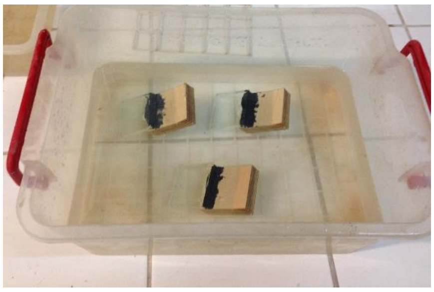
a)  b) 

Figure 3.15a, b: a) the timber-glass specimens placed over the sulphate acid concentration b) the timber-glass composites in HCl concentration

3.3 Results

3.3.1 Shear Test

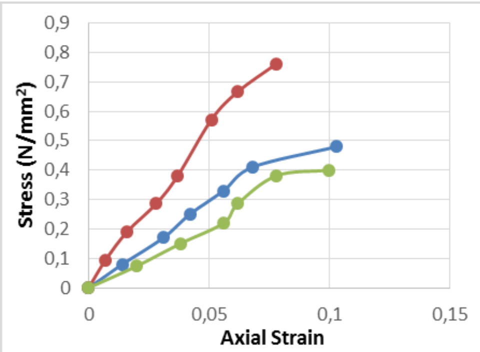
Shear strengths of timber-glass specimens have been determined under different conditions such as laboratory conditions, wetting-drying, freezing-thawing, UV effect, high temperature and resistance to acids. The results are given in Table 3.3 together with failure modes.

Table 3.3: Shear test results of timber-glass specimens

Test Conditions	**Shear strength (N/mm^2)**	**Failure mode**
Laboratory conditions (23°C, 50% humidity)	0.91	Mixed Breakage-Failure in adhesion to timber and cohesive failure in adhesive
Wetting-drying	0.54	Mixed Breakage-Failure in adhesion to timber and cohesive failure in adhesive
Freezing-thawing	0.60	Cohesive failure in adhesive
UV effect	0.51	Mixed Breakage-Failure in adhesion to timber and cohesive failure in adhesive
High temperature	0.49	Mixed Breakage-Failure in adhesion to timber and cohesive failure in adhesive
Resistance to acids (HCl)	0.11	Cohesive failure in adhesive
Resistance to acids (SO_2)	0.43	Mixed Breakage-Failure in adhesion to timber and cohesive failure in adhesive

Shear strength of the timber-glass specimens under laboratory conditions is highest whereas shear strength of specimens under HCl effect is lowest. According to the results of shear tests under different conditions, it can be concluded that the highest to lowest effects on specimens are effects of HCl and SO_2 acids, high temperature, UV Effect, wetting-drying and freezing-thawing, respectively. Shear strengths of the specimens under high temperature and acid effect are lower than 0.5 N/mm^2 which is defined as the minimum shear value in EN 12004. The failure modes are mostly mixed breakage (failure in adhesion to timber and cohesive failure in adhesive). Failure modes of the specimens of freezing-thawing and resistance to HCl are cohesive failure in adhesive.

Stress-strain curves of the three timber-glass specimens tested under laboratory conditions are given in Figure 3.16a. The stress-strain curve obtained by averaging values of these three specimens is given in Figure 3.16b. Deformations have been recorded with the 1/1000 mm digital indicator for every 50 N. Failure modes of the specimens for all test procedures are shown in Figure 3.17 to Figure 3.20.

a) 

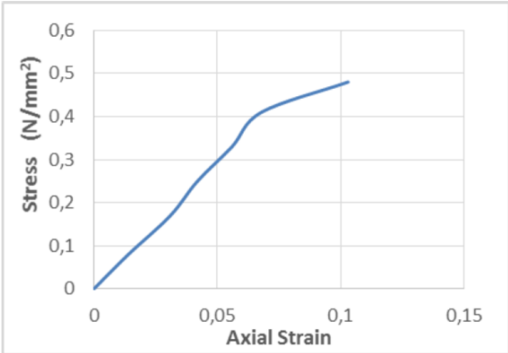
b) 

Figure 3.16a, b: a) stress-strain curves of three shear specimens tested under laboratory conditions b) average stress-strain curve of three shear specimens tested under laboratory conditions

Figure 3.17: Mixed breakage-failure in adhesion to timber and cohesive failure in adhesive (laboratory conditions)

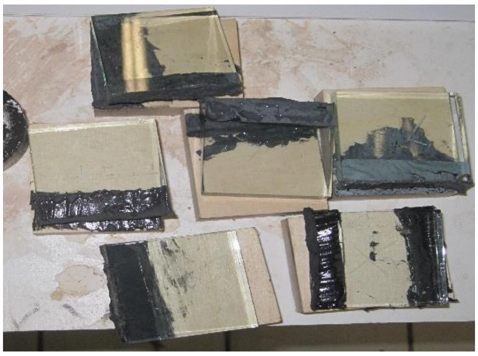
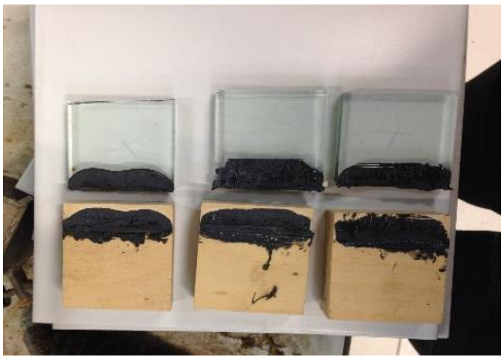
a)  b) 

Figure 3.18a, b: a) mixed breakage-failure in adhesion to timber and cohesive failure in adhesive (wetting-drying) b) cohesive failure in adhesive (freezing-thawing)

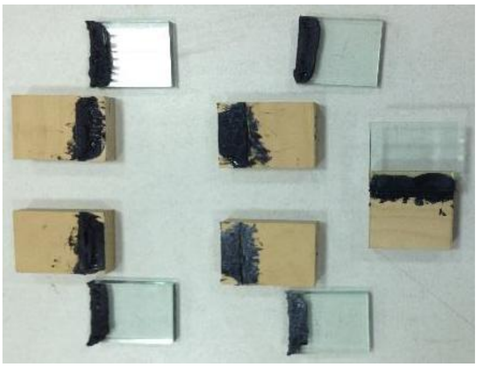
a)  b) 

Figure 3.19a, b: a) mixed breakage-failure in adhesion to timber and cohesive failure in adhesive (high temperature) b) mixed breakage-failure in adhesion to timber and cohesive failure in adhesive (UV resistance)

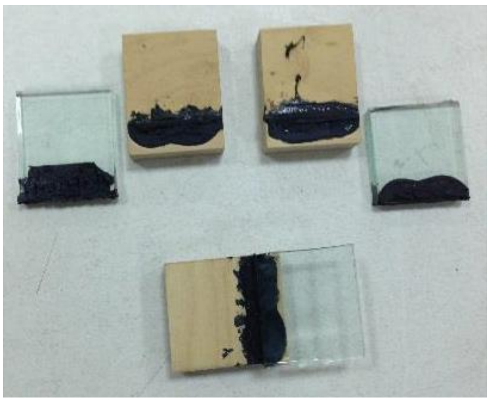
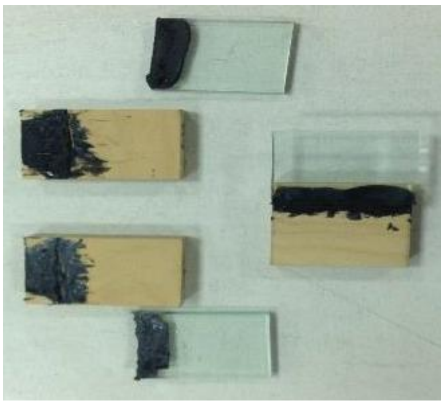
a)  b) 

Figure 3.20a, b: a) cohesive failure in adhesive (HCl resistance) b) mixed breakage-failure in adhesion to timber and cohesive failure in adhesive (SO_2 resistance)

3.3.2 Adhesion Test

Adhesion strength values and failure modes of adhesion specimens are given in Table 3.4. The specimens which were kept under laboratory conditions have the highest adhesion strength. The adhesion strengths of the specimens for all test conditions are higher than 0.5 N/mm^2 which is the minimum value given in EN 12004. The specimens under wetting-drying and freezing-thawing has lower adhesion strength because durability of the plywood is low when exposed to water. Failure of the specimens under laboratory conditions and freezing-thawing specimens are between adhesive and timber. As seen in Figure 3.21 and Figure 3.22b, the timber fibers are on the adhesive whereas failure of the wetting-drying specimens are in the timber (Figure 3.22a). The lowest adhesion strength value in wetting-drying specimens is due to direct contact of specimens with water during the durability test.

Table 3.4: Adhesion strength values and failure modes

Test conditions	**Adhesion strength (N/mm^2)**	**Failure modes**
Laboratory conditions (23°C, 50% humidity)	1.19	Failure in adhesion to timber cohesive failure in timber
Wetting-drying	0.93	Cohesive failure within the timber
Freezing-thawing	1.04	Failure in adhesion to timber cohesive failure in timber

Figure 3.21: Failure in adhesion to timber cohesive failure in timber (laboratory conditions)

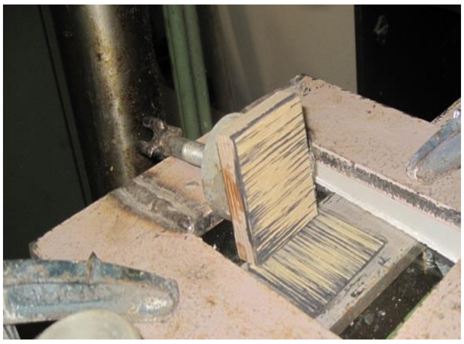
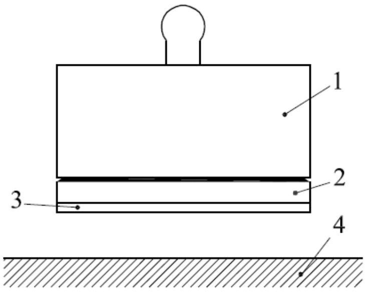
a) 
b) 

Figure 3.22a, b: a) cohesive failure within the timber (wetting-drying) b) failure in adhesion to timber cohesive failure in timber (freezing-thawing)

3.3.2.1 Failure Patterns of Adhesive Strength Test in Timber-Glass Composites

According to TS EN 12004, failure patterns of adhesive strength test in timber-glass composites are as following (Figure 3.23, 3.24, 3.25);

Key: (1) Pull-off heading (2) Plywood (3) Ottocoll S660 (4) Tempered glass

a) 

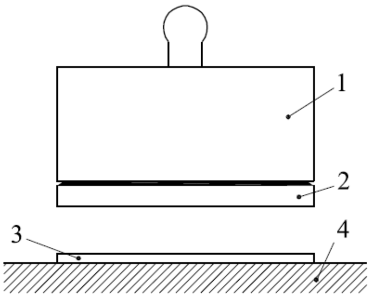
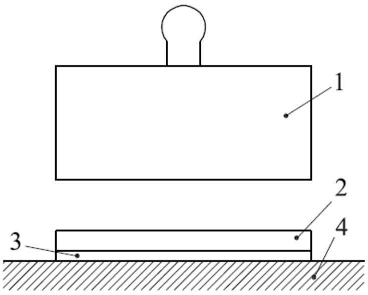
b) 

Figure 3.23a, b: a) adhesive failure between adhesive and glass b) adhesive failure between plywood and adhesive

a) 

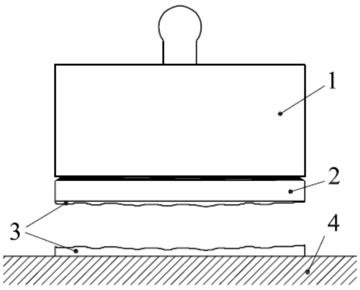
b) 

Figure 3.24a, b: a) adhesive failure between plywood and pull-off heading b) cohesive failure within the adhesive

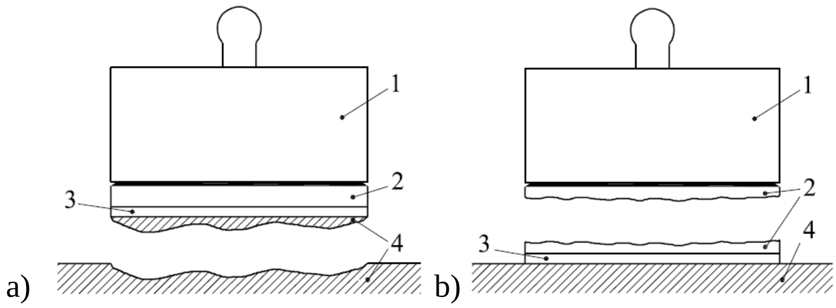


Figure 3.25a, b: a) cohesive failure within the glass b) cohesive failure within the plywood

3.3.3 Durability Tests

The results of durability tests which consist of freezing-thawing, wetting-drying, UV Spectrophotometer, high temperature and resistance to acids are given in this part.

3.3.3.1 Wetting-Drying Test

A wetting-drying cycle consists of 18 hours in 25°C water and six hours for drying in the oven at 50°C. These cycles continue for 7 days. The weights of the specimens were measured before and after test. Although no change in the weights of the specimens has been observed, the plywood gets darker in color. This is due to the fact that water settles in the upper level of the plywood, deforming the inner structure of it by swelling and shrinking.

3.3.3.2 Freezing-Thawing Test

A freezing-thawing cycle consists of 18 hours at -20°C and six hours at +25°C. These cycles continue for 28 days. The weights of the specimens were measured before and after test. Test results show that there is no change in the weight specimens. However, plywood gets darker in color because water settles in the upper level of plywood, deforming the inner structure by swelling and shrinking.

3.3.3.3 UV Spectrophotometer Test

Under UV light, the structure of the polymer of plywood deforms and plywood gets darker in color. The color lost and variation wave lengths were measured using spectrophotometer and the results are given in Table 3.5 and Table 3.6. The color of the plywood gets darker under the UV effects and the color lost values differ from positive to negative. This result supports the deformation of the plywood. The white wave length variation supports these results.

Table 3.5: Average values of color variations of all UV specimens

	$\mathbf{R_4}$	$\mathbf{R_{26}}$	$\mathbf{R_{final}}$
Timber-glass specimens	1,9	2,24	-1,62

Table 3.6: Average values of white wave length of all UV specimens

	$\mathbf{T_{0h}}$	$\mathbf{T_{116h}}$	$\mathbf{T_{28d}}$
Timber-glass specimens	50,2	48,2	23,3

3.3.3.4 Resistance to High Temperature Test

Six timber-glass shear specimens were weighed and then settled in the oven at 150°C. After 30 minutes, the specimens were taken out from the oven and cooled in a glass jar. At the end of the test it has been observed that the timber and glass elements of one specimen separated from each other. However, there are no deformations, weight and color changes at the rest of the specimens (Figure 3.26).

Figure 3.26: Timber-glass shear specimens after high temperature test

3.3.3.5 Resistance to Acids Test

The shear specimens were put into 1% HCl solvent for 7 days to determine the resistance to acid. After 7 days, the specimens were compared with the reference specimens visually. It has been observed that the color of plywood and the glue darkens. The color change of the specimens shows that the durability of the specimens against HCl is very low.

The same process is made for SO_2. After 4 weeks, the specimens were compared with the reference specimens visually. There is no deformation and no darkening at the specimens which means that the durability of the specimens against SO_2 is high (Figure 3.27).

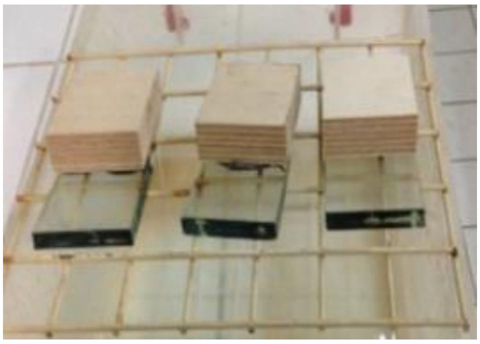


Figure 3.27: The timber-glass specimens at the end of SO_2 test

3.3.4 Long-Term Loading Test of Medium Size Specimens

The second part of the experiments is test of the long-term behaviour of the timber-glass composite elements with the adhesive bond. The objective of the long-term testing is to investigate the environmental and long-term loading effects on the timber-glass composite building elements. With the purpose of evaluating the behavior of the bonding between timber and glass materials, this experimental test has been carried out at the campus of Istanbul Technical University, Faculty of Architecture.

The aim of medium size test is to determine the creep behavior of timber-glass composite elements under long-term loading at outdoor conditions. For the medium size specimens, birch plywood, tempered soda-lime glass with a thickness of 8 mm and two-component silicone adhesive Ottocoll S660 were used. The plywood was classified as surface grade III (EN 635-2) and water boiled proof (EN 314-2 class 3). The tempered glass was a production of Trakya Glass Industry (Trakya Cam Sanayii A.S.). “Properties that affect the load-bearing capacity of a bond-line are cohesive strength of the adhesive, adhesive strength to timber, adhesive strength to glass, deformation capacity and load distribution ability”. [27] Many adhesives are sensitive to environmental changes, such as moisture, temperature and light (especially UV-light) etc. The strength of the adhesive bond is therefore dependent on the service environment. [19]

The details of L-shaped sections of plywood are given in Figure 3.28. The dimensions of medium size specimens are given in Figure 3.29. L-sectioned timber elements were bonded to the both sides of the glass by silicone adhesive. Fabrication of all specimens was done by ITU team with the help of professional workers from Metal Yapı A.S. (Figure 3.30).

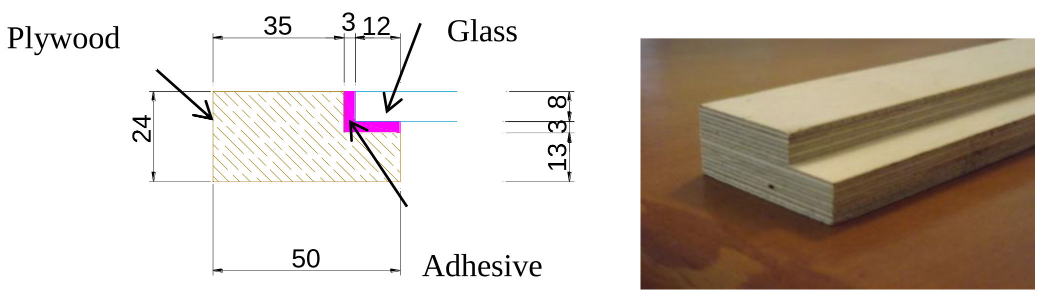


Figure 3.28: Section properties of timber-glass specimens (Units are in mm.)

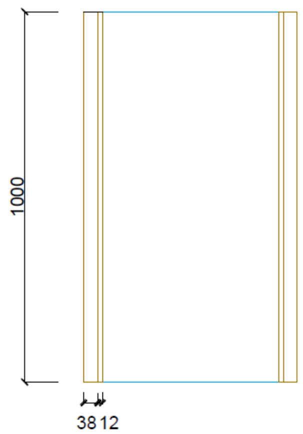


Figure 3.29: Dimensions of medium-size specimens (Units are in mm.)

Figure 3.30: Fabrication of medium-size timber-glass specimens

Eight medium size specimens were exposed to long-term loading at exterior conditions. The specimens were partially protected from environmental effects by being covered with a shelter (Figure 3.31).

Figure 3.31: Medium-size timber-glass specimens at exterior conditions

The experimental setup for long-term loading was prepared in the form of wooden boxes (Figure 3.32). Loading of the specimens were performed by filling the wooden container with sand. Timber-glass composite specimens were attached to the loading boxes via pins from their plywood components. For each box, two timber-glass composite specimens were placed: one on the front and the other at the back side. Two different long term load levels were as 0,028 MPa and 0,035 MPa. Even though two different long term load levels were decided as 0,04 MPa and 0,05MPa, due to some difficulties during preparation of test setup real loading levels were 0,028 MPa and 0,035 MPa. By this manner, four of the specimens were loaded under 0,028 MPa, while the other four specimens were subjected to 0,035 MPa during the first

174 days. The dimensions of test setup are given in Figure 3.33. Layout plan of the specimens placed at exterior conditions is given in Figure 3.34.

Figure 3.32: Loading box details of medium size specimen tests

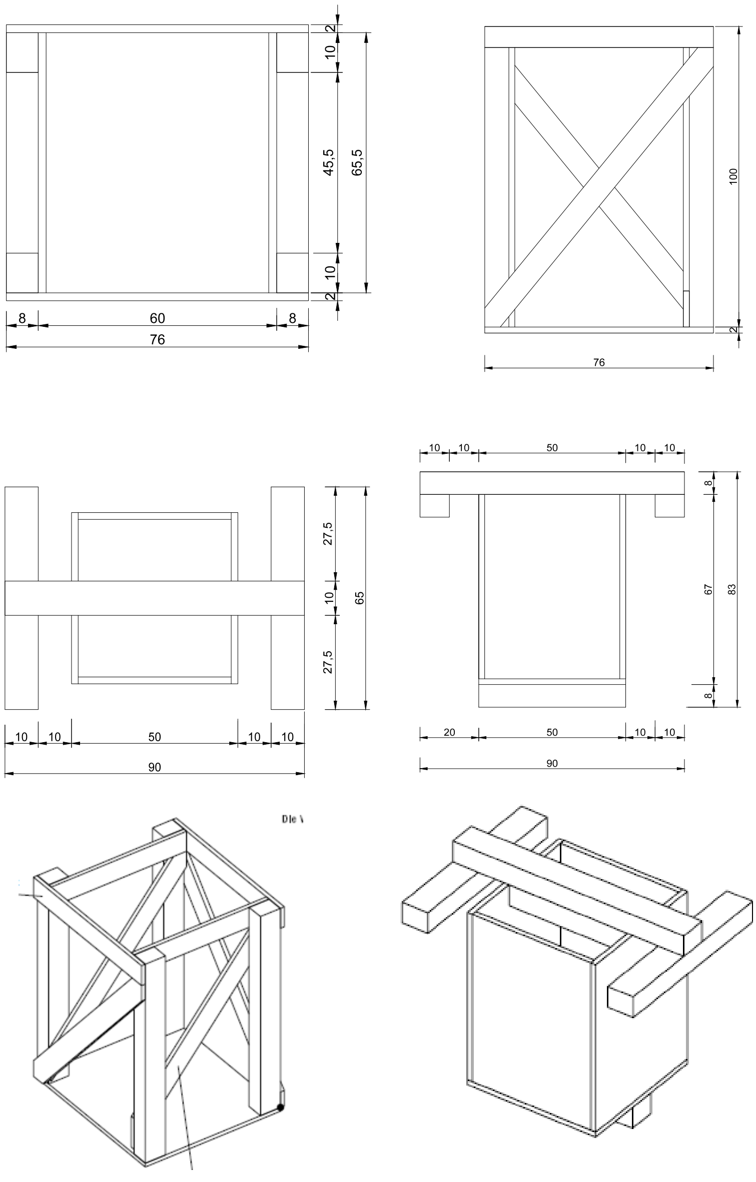


Figure 3.33: Dimensions of the long term loading test setup (Units are in cm.)

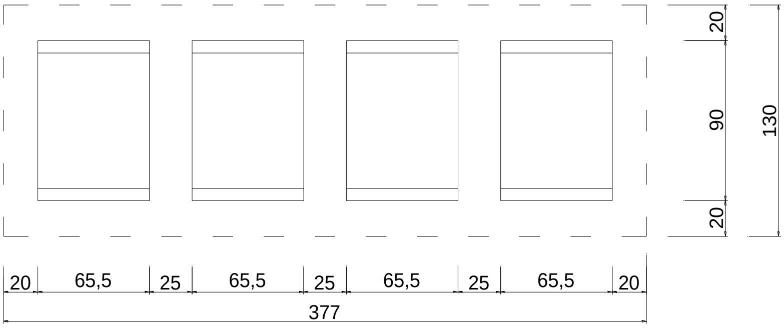


Figure 3.34: Layout plan of medium-size specimens placed at exterior conditions. (Units are of cm.)

During the test, vertical displacement of the glass was recorded once a day at the same time each day (Figure 3.35a). Displacements were measured by mechanical displacement sensors (comparameters) placed on middle level of specimen. In addition, the temperature and humidity were daily measured by automatic measuring device (Figure 3.35b).

a)  b) 

Figure 3.35a, b: a) displacement measuring device b) automatic humidity and temperature measuring device

The variation of temperature and relative humidity during the first 174 days of loading are given in Figure 3.36. Temperature changes were between -2°C and 34.6 °C. Relative humidity was between 39% and 92%. Total vertical displacement values of specimens under long-term vertical loading measured at the end of 174 days are given in Table 3.7.

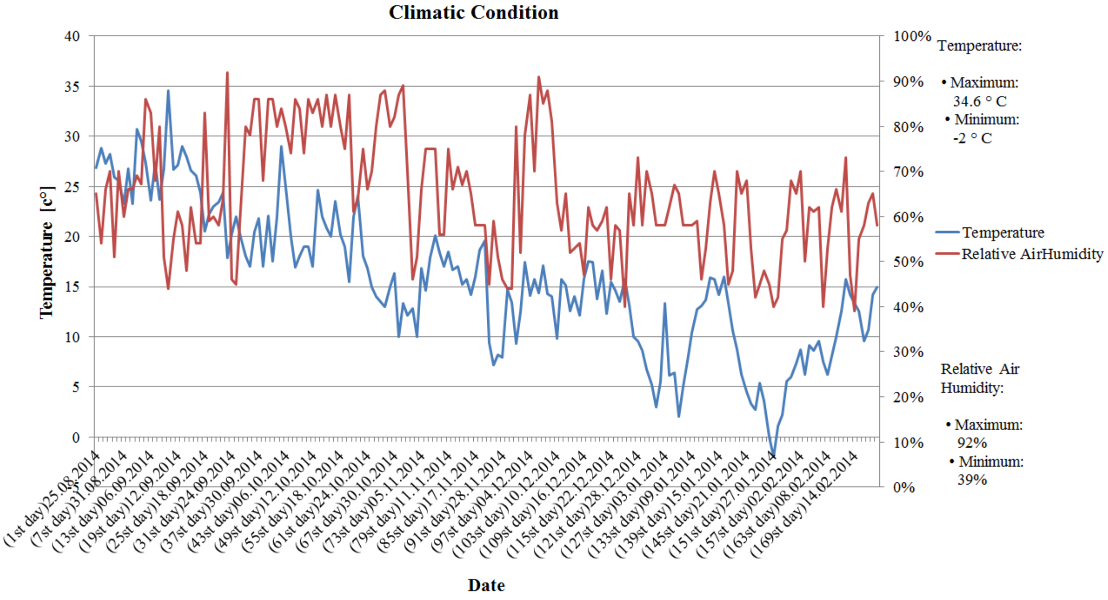


Figure 3.36: Climatic variations diagram

Table 3.7: Total vertical displacement values of medium-size specimens at the end of first 174 days

Specimen No	**Loading [1] (MPa)**	**Measurement Period [2] (Day)**	**Total Vertical Displacement (mm)**
1	0.028	174	1.09
2	0.028	174	1.24
3	0.035	174	1.71
4	0.035	174	1.69
5	0.035	174	1.35
6	0.035	174	1.12
7	0.028	174	0.83
8	0.028	174	0.65

[1] Loading shows the amount of shear stress on each adhesive surface for specimens.

[2] Measurement period is the number of days between the first loading day and the final day of measurement.

At the beginning of the experiment, the long-term loading test of medium-size timber-glass composite specimens was aimed to perform for three months. After 174 days of measurement, it was decided to increase the load on four of the specimens to 0,05 Mpa which was 0,028 MPa before (Figure 3.37). For this, the specimens attached to the first loading box were replaced by the reference specimens that had been kept in laboratory conditions beforehand. The load of second box were also increased from 0,028 MPa to 0,05 MPa as well, but the specimens attached to this box were not changed. The measurement of other loaded specimens (0.035 MPa) continued as before.

Figure 3.37: Increased load on the medium size specimens for long term loading at exterior conditions

While the modifications were made for the loading of Box 1 and Box 2, the measuring setup of the tests were also modified. Displacements are measured daily by digital comparameters to obtain more precise values (Figure 3.38a). The moisture percentage of plywood in each specimen is measured and recorded by an automatic device once a week (Figure 3.38b).

a)  b) 

Figure 3.38a, b: a) digital displacement measuring device b) automatic moisture measuring device

After revision of experimental setup, two different long term load levels were as 0,04 MPa and 0,05 MPa. At the end of second 84 days measurement, total vertical displacement value ofmedium-size specimens which were under 0,04 MPa loading is nearly 0.25 mm and displacement of the specimens which were under 0,05 MPa loading is nearly 0.40 mm (Figure 3.39).

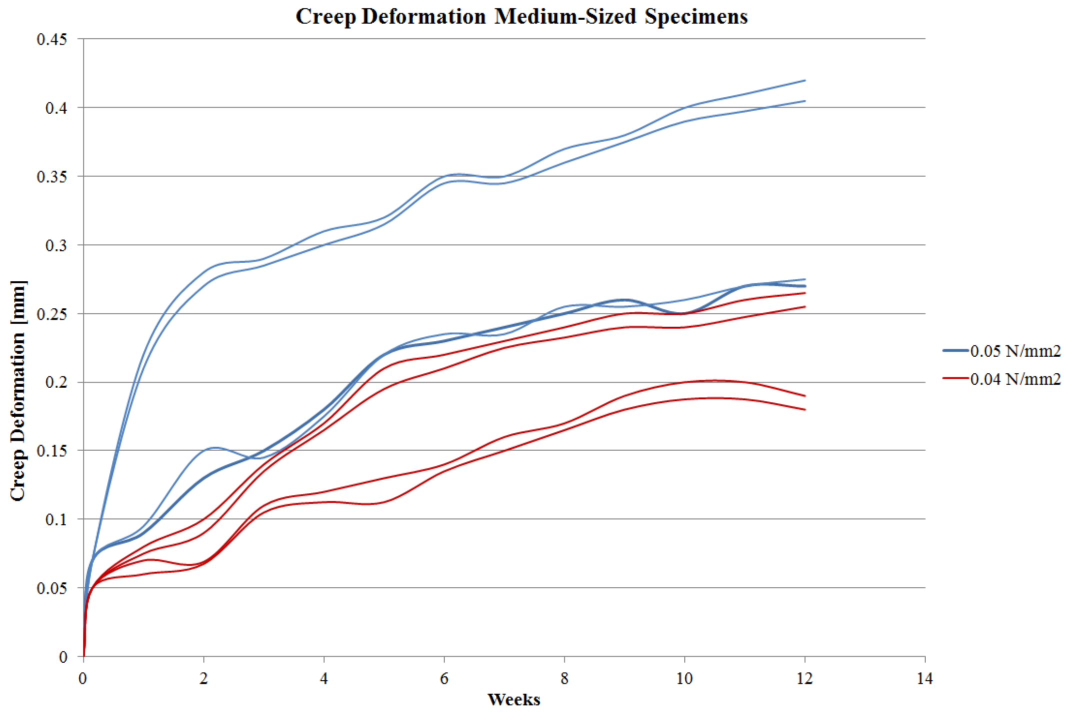


Figure 3.39: Creep deformation of medium sized specimens after revision at the end of second 84 days

The variation of temperature and relative humidity during the second 84 days of loading are given in Figure 3.40. Temperature changes were between 6.7°C and 26.1 °C. Relative humidity was between 73% and 33%. Also, As mentioned, the moisture percentage of plywood in each specimen is measured by the automatic device once a week. The moisture percentage of all specimens are varying between minimum %10 and %18 maximum.

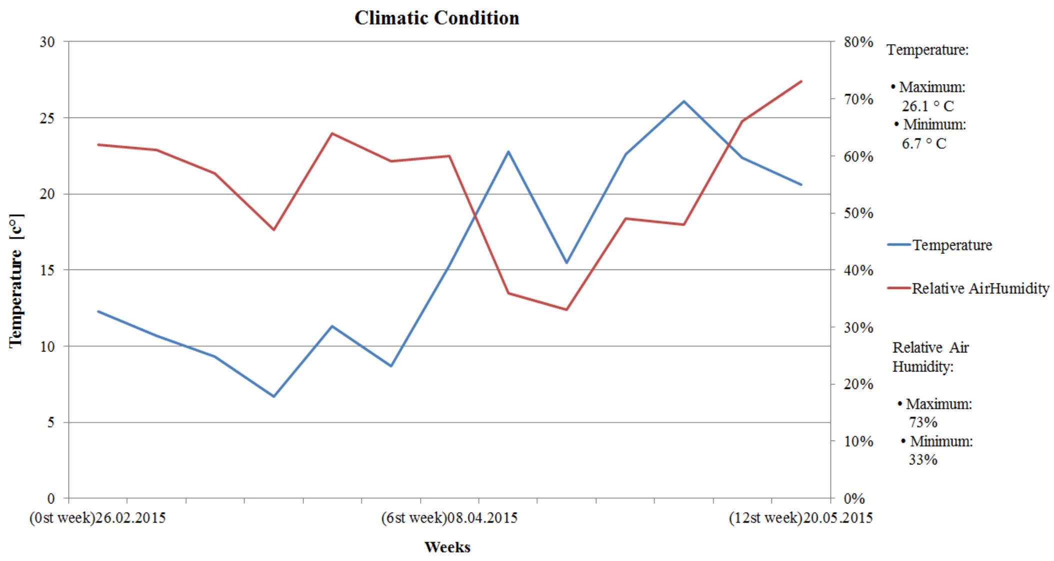


Figure 3.40: Climatic variations diagram during the second 84 days of loading

With the aim of measure load-bearing capacity of timber-glass composite elements which are held under effects of long-term loading and climatic conditions, specimens will be taken from the experimental setup and will be loaded until failure in the laboratory. For it, monotonic vertical load will be applied with use of load-controlled experimental setup.

In order to fully benefit from timber-glass composite cross sections, an adequate bonding between timber and glass elements is essential. With the purpose of achieving the ideal balance between strength and flexibility, an extensive set of experimental tests were carried out in this part of research. The previous part of this chapter focused on the analysis of results regarding shear and adhesive strength tests. Afterwards, the creep test of timber-glass composite elements has been described. In the medium size test, displacements were measured in all climatic conditions, such as: Cold, warm and rainy weathers. Under the Istanbul's severe weather conditions, the specimens have shown rather high resistance. As the graphic shows, displacement of glass in the specimens with higher load is more than specimens with lower load. Also, the glass of timber-glass composite specimens which were placed on the front side of boxes have less displacement than the others at the back side. This is due to they have been exposed to sunlight. Sunlight causes to decrease the moisture content of plywood. The specimens which were placed on the back side of boxes are more affected by moisture because they were exposed to shadow. This issue affects the adhesion between the timber and glass. High humidity affects adhesion on the negative side. As a conclusion of this experiment, it can be deduced that the little displacements of the medium-size specimens, is an appropriate result for using the elements in the structures of buildings.

4. PILOT PROJECTS

This chapter comprises an overview of possible architectural design applications of timber and glass as composite structural materials. Initiation of pilot projects will provide the possibility to experience the practicality and applicability of developed composite systems, and create different design and application solutions. One of the main goals of this research is to provide a marketable component system for buildings. The association of mechanical capacity of timber and glass, environmental sustainability and recyclability let believe that projects that were designed with timber-glass composite elements have a lot of structural potentials.

Possible applications of this product in architecture of Turkey could include kiosk, resting place, tourist information center and a canopy. The dimensions and detail of single panel has been used in pilot projects are as follows (Figure 4.1a, b). The shear wall is made of tempered glass with a thickness of 8 mm and plywood. Both materials are bonded via silicone adhesive glue lines.

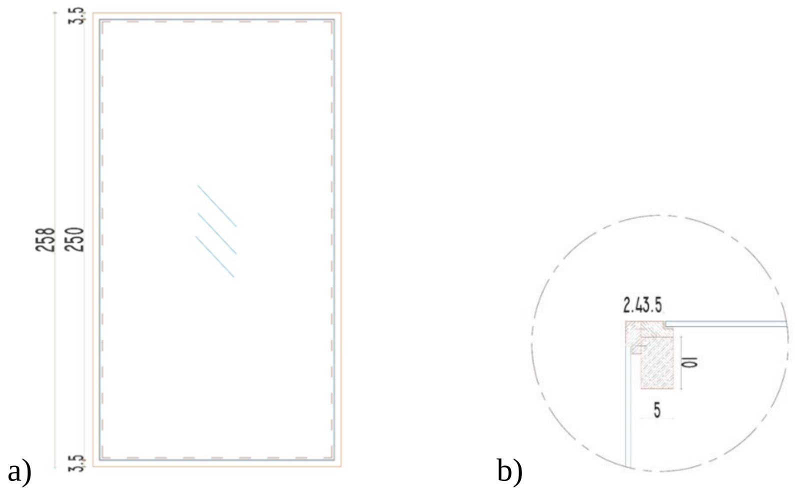


Figure 4.1a, b: a) dimensions of single panel b) detail of panel

4.1 Kiosk Design

This pilot project is designed to sell newspaper. Total area is 6.25 m^2. The main purpose of design is to use advantages of glass. Indoor space can be lighted up with natural light. Glass façades enable users to see inside easily and make the kiosk environmentally compatible. The roof which is a combination of timber and glass enables light and shadow to pass through and it prevents direct contact of light of the employee. Furthermore, the details on right and left sides are used as newspaper holders (Figure 4.2a, b).

a) b)

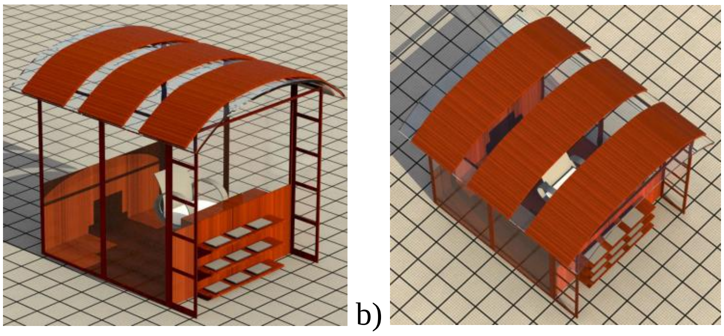


Figure 4.2a, b: a) perspective view of kiosk b) top view of kiosk

For the materials of the kiosk, birch plywood and tempered soda-lime glass with a thickness of 8 mm will be used. The plywood is classified surface grade III (EN 635-2) and water boiled proof (EN 314-2 class 3). Also, for the construction of the kiosk, four panels of timber-glass shear walls (125x250cm) are used. Each panel is connected to load bearing timber frame with column dimensions of 10x10cm. One panel is made openable for entrance (Figure 4.3a, b).

a) b)

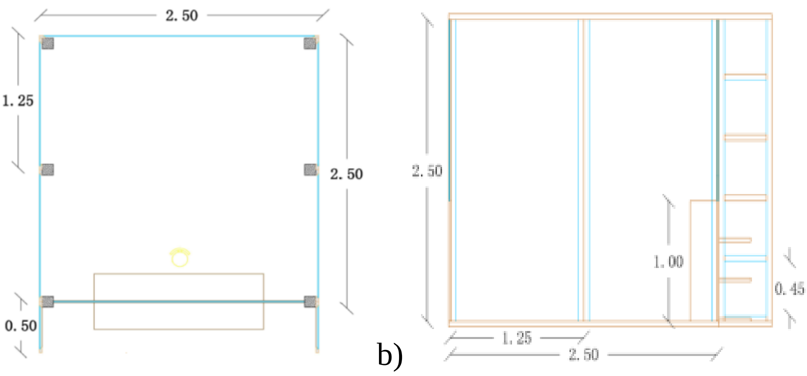
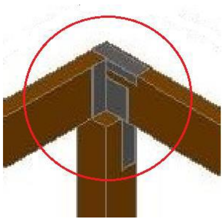


Figure 4.3a, b: a) plan of kiosk b) side view of kiosk

Some possible connection details for beam-to-beam and beam-to-column are given in the Figures 4.4a, b.

a)



b)

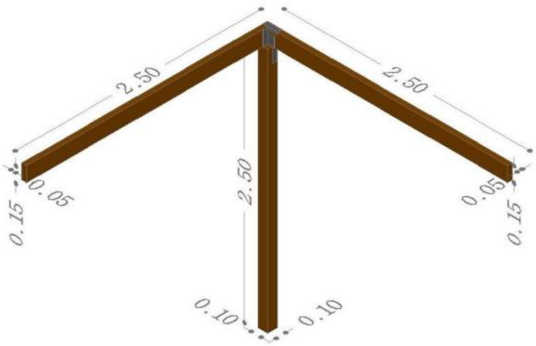


Figure 4.4a, b: a) timber construction connector detail b) connection detail of column to beam

A typical foundation detail for column-to-base is given in the Figure 4.5.

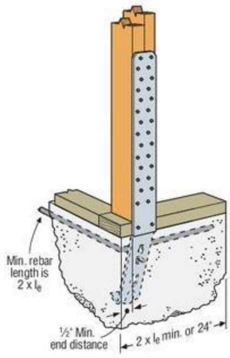
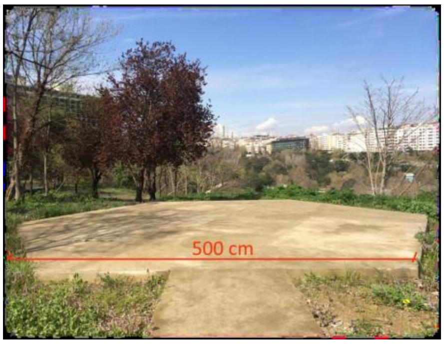


Figure 4.5: Typical STHD Corner Installation detail [59]

4.2 Resting Place Design

The other design project topic is a resting place. For the hexagonal-shape platform that is located in ITU-Faculty of Architecture campus, a resting place for academic members is designed. The site has a beautiful view of surrounding landscape and total area of the platform is nearly 65 m^2. The design concept is a spider web. Its roof is designed as a combination of timber and glass, to bring daylight and transparency to the space (Figure 4.6a, b).

a) 

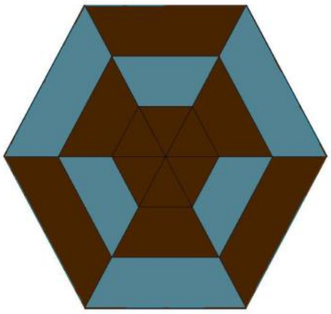
b) 

Figure 4.6a, b: a) hexagon place b) top view of resting place

The place has six glass façades which provide transparency. Fourteen panels of timber-glass shear walls (125x250cm) are planned to be used. Several windows are placed for ventilation purposes (Figure 4.7, 4.8).

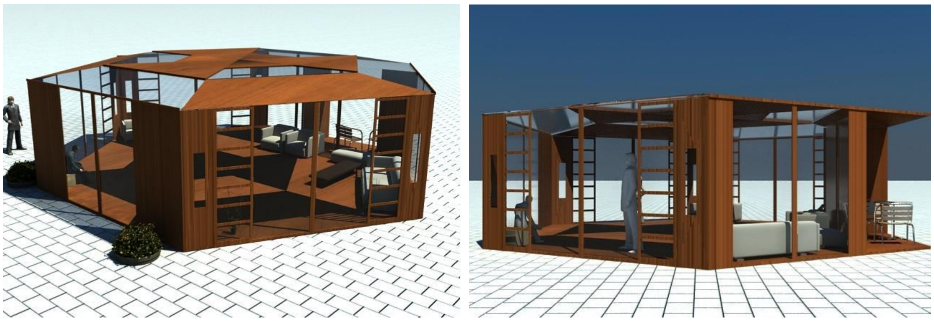


Figure 4.7: Perspective views of resting place

a) 

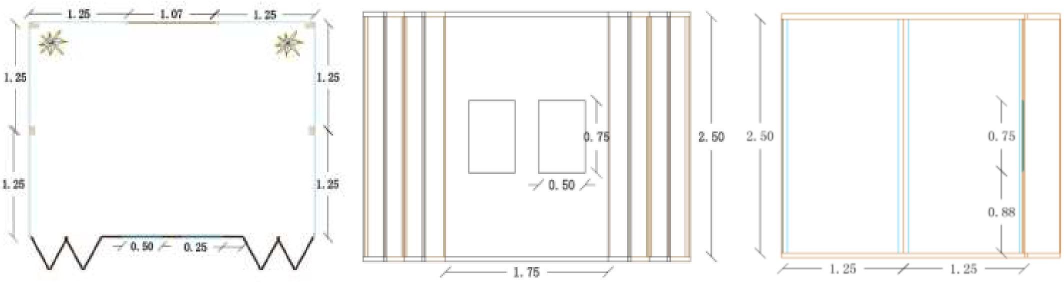
b) 

Figure 4.8a, b: a) side view of resting place b) plan of resting place

4.3 Tourist Information Center Design

The next pilot project is a tourist information center. It is designed with three glass façades. Glass façades enables users to see inside easily. Area of the place is 9 m^2.

Six panels of timber-glass are used as shear walls. The structure is 2.5 m height. The ceiling and front façades are made of timber which add aesthetic value to the structure (Figure 4.9, 4.10).



a) b)

Figure 4.9a, b: a) plan of Tourist information center b) tourist information center front view and side view

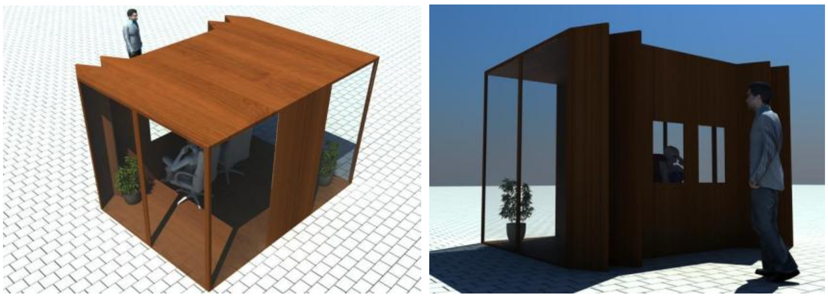


Figure 4.10: Tourist information center perspective views

4.4 Canopy Design

The next project is a canopy. This pilot project is designed for a school entrance to protect children from climatic conditions. Six panels of timber-glass shear walls (125x250cm) are used (Figure 4.11a, b).

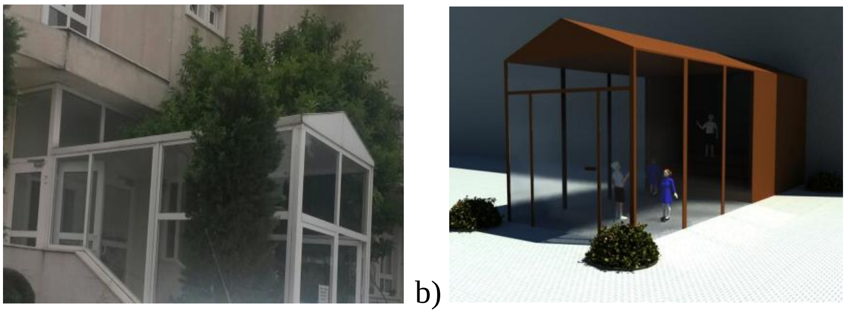
a)  b)

Figure 4.11a, b: a) entrance door of A school in Istanbul b) an example of canopy

The examples show, that the practical application of innovative and challenging glass structures can be realized with less cost, time and effort than in case of regular buildings. It is seen that by creating different design and application solutions, these new composite elements will provide the possibility to experience practical and applicable developed composite systems. Timber-glass composite structural elements combine the advantages of both materials. Combining glass with the ductile material timber improves the structural performance after failure and expands the scope of applications beyond the initial limits. It is an important advantage of timber-glass composites that manufacturing of these structural elements doesn`t demand heavy industrial facilities. The suitability of timber-glass composites to ecological structures also empowers the value of these systems.

5. QUESTIONNAIRE STUDY

One goal of this research is to intorduce timber-glass composite structural element as a new product to the Turkish market in order to take a place between other structural systems. The intention of this research is to contribute to the knowledge required for the industry to be willing to produce timber-glass components for the market. For this purpose, by questionnaire method has been communicated with the timber and glass industries. The results of questionnaires have analysed graphically. In addition, the companies reviews are also given.

5.1 Timber Questionnaire

1. What is your first impression related to the use of timber-glass composite structural element in the load-bearing system?

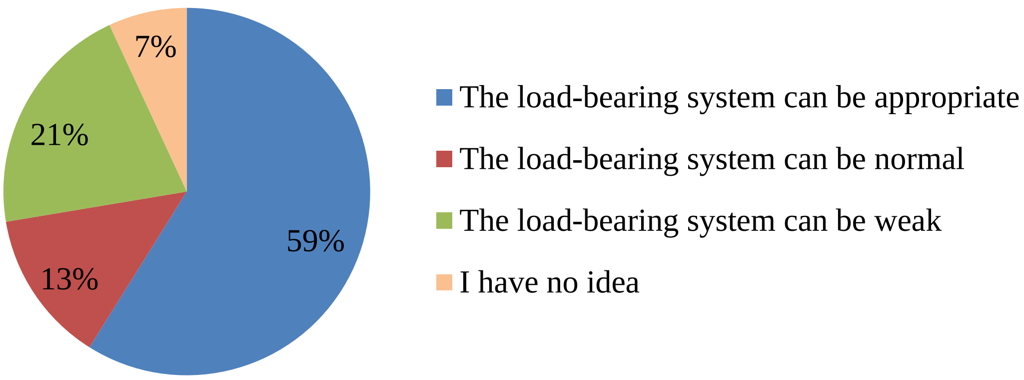


Figure 5.1: Graphical result of first question, timber questionnaire

A high percentage of surveyors who selected "timber industries" indicates that the bearing capacity of timber-glass composite structural elements can be appropriate. Besides, some respondents to the questionnaire have mentioned that due to the timber is a ductility material and raw material of glass is liquid, bearing capacity of the system can be weak.

2. Nowadays, in which structural element the timber material is used the most?

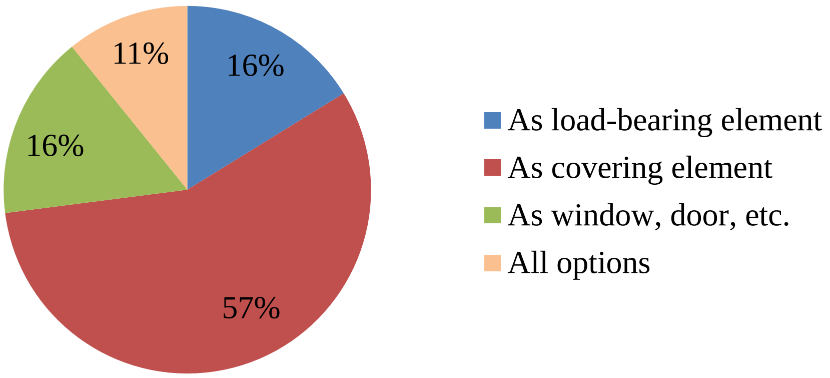


Figure 5.2: Graphical result of second question, timber questionnaire

The most use of timber in constructions is as covering elements, such as; flooring, roofing, ceiling and also is used as the interior and exterior wall cladding. The graphic shows that the use of timber in constructions as load-bearing element like column, beam and as structural element like window, door and decorative items, have equal percentage.

3. Which type of trees is more resistant as a load-bearing building material?

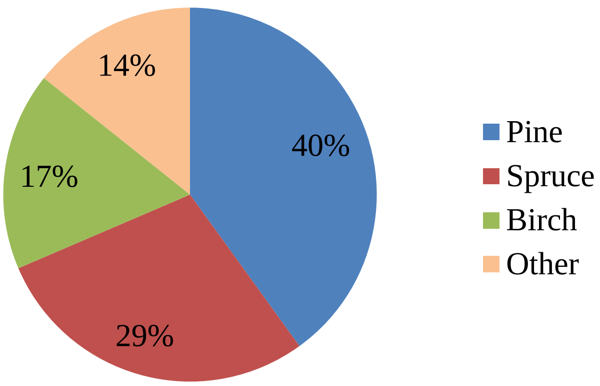


Figure 5.3: Graphical result of third question, timber questionnaire

The tree types used in the buildings are divided into two groups; coniferous (softwood) and broadleaf (hardwoods). The timber industries have proposed the most common type of coniferous tree, Pine tree for the building applications. Pine is being grown almost in everywhere of Turkey. Another type of softwood, Spruce, with its easily processed property for use in structures is in the second row. Also, respondents of timber firms have stated that plywood which is obtained from Birch tree (a type of hardwood) has very high resistance. Oak tree which is another type of hardwood is preferred to use in load-bearing systems due to its stiffness and very durable properties. In addition, Iroko tree with its high resistance against natural decay, insects and moisture has recommended to use in structures but it is a costly tree. Furthermore, many respondents have stated that Teak tree is very durable but the use of it in the load-bearing systems is less.

4. With considering the chemical and physical properties of the timber, how would the strength of timber be when it is combined with glass?

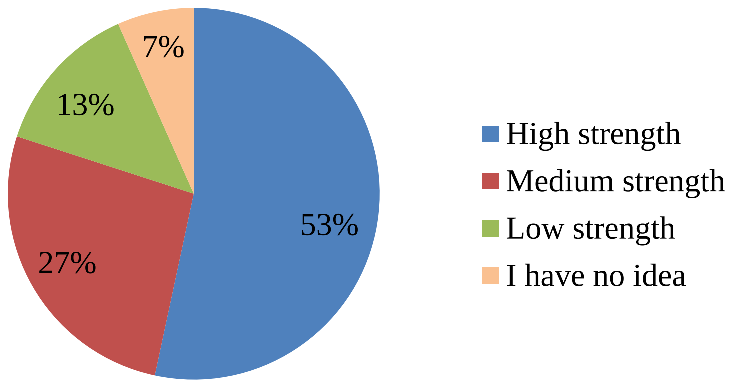


Figure 5.4: Graphical result of fourth question, timber questionnaire

According to the timber industry reviews, if the operation of timber can be controlled as well torsion and buckling of the glass can be prevented, the timber-glass composite element can be a high strength structural element. Also, some respondents of companies have stated that in this composite, the element that has the bearing characteristic is timber and glass is as a carried element.

5. Is the preservation of timber necessary when it is used in the load-bearing system? If necessary what methods can be used?

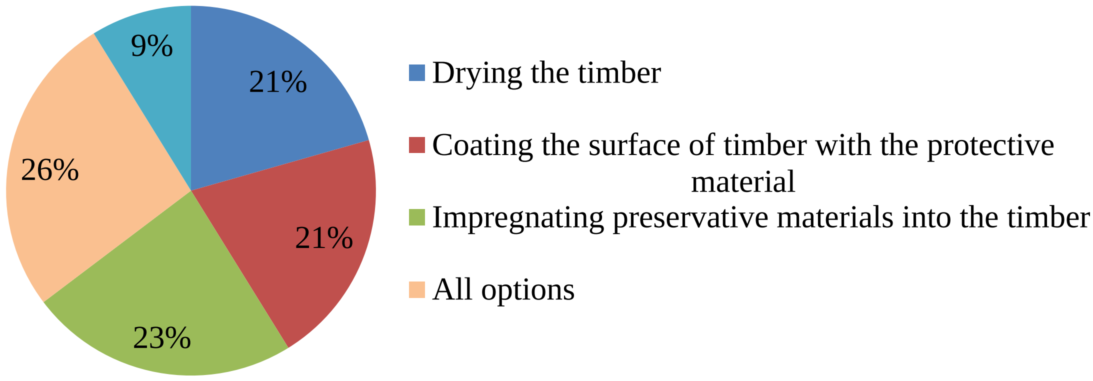


Figure 5.5: Graphical result of fifth question, timber questionnaire

Respondents of questionnaire have stated that the preservation methods of timber to prolong the life and durability of it, sometimes together, sometimes individually can be used. Particularly, drying the timber is very important and by this method it is protected against insect and fungi. Surface protection is preferably done to protection of timber and as well to retard fire. Thermal processing and removing resin are other methods. Besides, some companies have mentioned that in poducts with very high quality is not necessary to use impregnating.

6. In our research project, named "Load Bearing Timber-Glass Composite Structures", plywood is used. How is the strength of plywood when it is used as a load-bearing material?

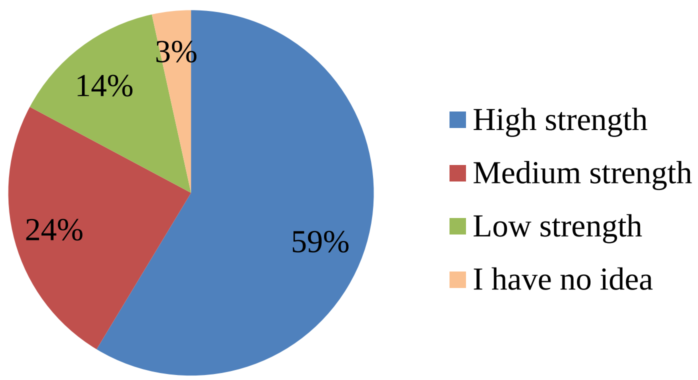


Figure 5.6: Graphical result of sixth question, timber questionnaire

The respondents of timber industry have indicated that the plywood has higher strength than solid wood. Also, some companies stated that strength of the plywood structural panels can be determined by the company.

7. As a solution for the housing problem, how much would the use of timber-glass composite elements be appropriate?

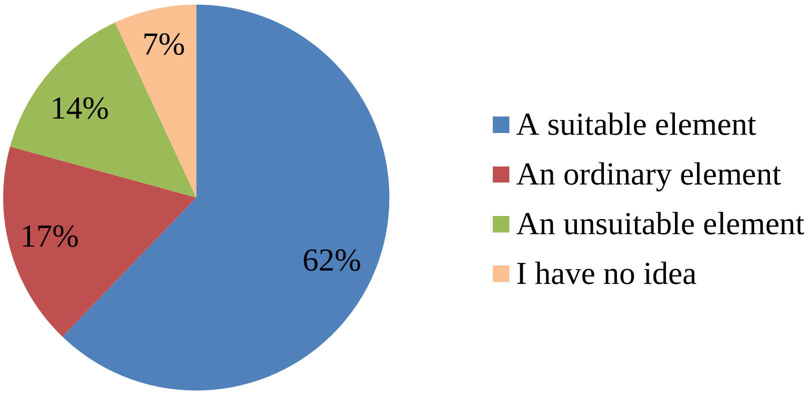


Figure 5.7: Graphical result of seventh question, timber questionnaire

Most of firms have stated that the use of timber-glass composite structural elements is an appropriate solution for the housing problem but they have emphasized that it should be tested.

8. In non-residential buildings, in which building(s) ,with different functions, this structural element is a good solution? (Multiple options can be marked)

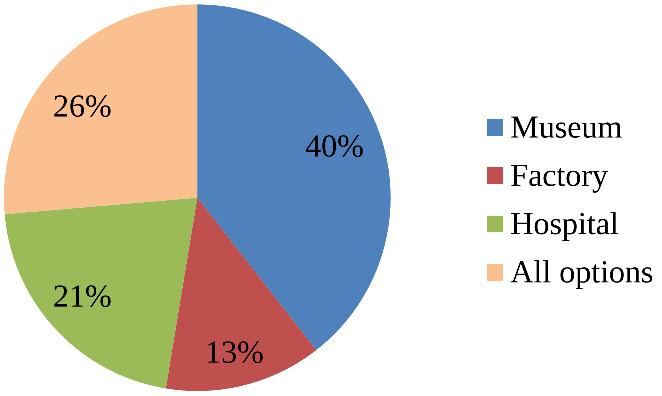


Figure 5.8: Graphical result of eighth question ,timber questionnaire

According to respondents of timber industry, timber as an ecological material when combined with glass and formed timber-glass composite element, it can be used almost everywhere. Except for the specified structures, it has also been proposed to use in schools, villas, sport halls, workshops, office buildings and places like dormitories.

9. Do you think this new structural element can be used and competed with other alternative materials in Turkey?

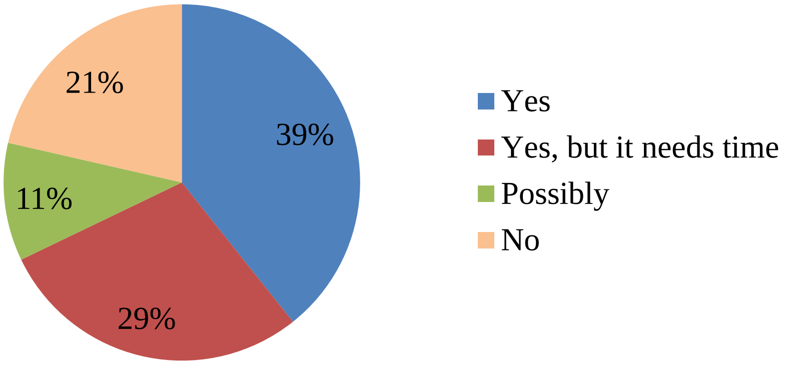


Figure 5.9: Graphical result of ninth question, timber questionnaire

A high percentage of timber firms have stated that this new structural element can be used in Turkey and as well it would be able to compete with other alternative structural elements. Besides, some companies have specified that timber needs preservation and due to it is expensive, cannot compete with other products also it would be preferred by architects and aesthetic concerns in special projects.

10. If your company has plywood production, it is performed according to which standards?

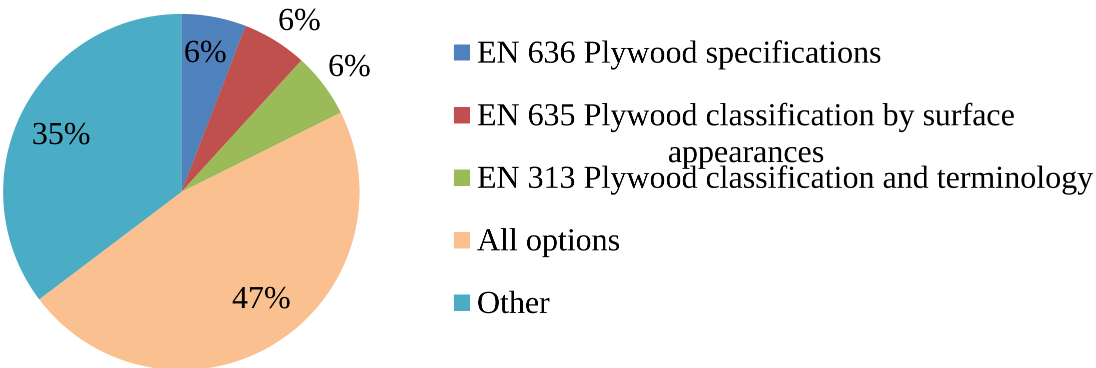


Figure 5.10: Graphical result of tenth question, timber questionnaire

Timber companies are used almost all of the specified standards. Furthermore, EN 1995-1: 2004 ‘Design of Timber Structures’, EN ISO 17225 ‘Solid biofuels fuel specifications and classes’, ASTM D1037 ‘Standart Test Method for Evaluating Properties of Wood-Base Fiber and Particle Panel Materıals’, DIN 1052 ‘Design of

Timber Structures', TS 446 'Kerestelik iğne yapraklı tomruklar', BS EN 14080: 2013 'Timber Structures, Glued laminated timber and glued solid timber' standards and E1 Health Certificate are used by the companies.

11. If your company is a plywood seller, the required timbers are supplied from your own production or importing?

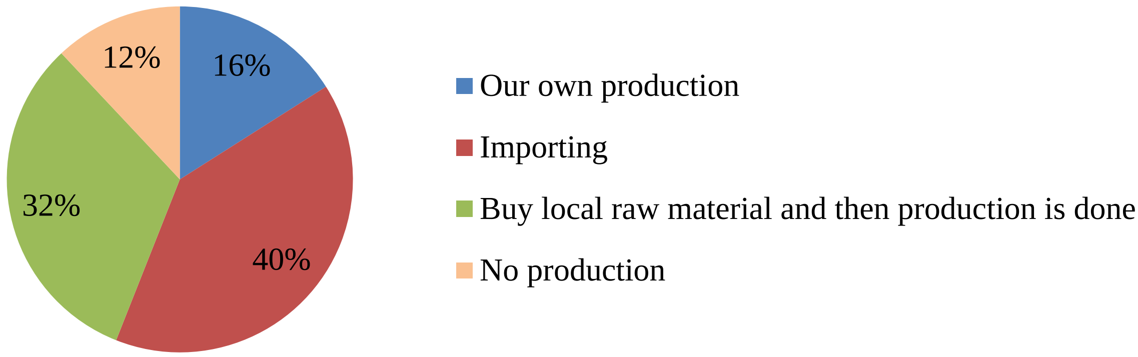


Figure 5.11: Graphical result of eleventh question, timber questionnaire

Most of the timber companies supply big part of required timbers by imports. In additon, many companies buy raw material from local companies and sell after developing the product.

12. As long as this new product becomes available and can be a reliable construction element, it needs to conduct researches to produce prototypes. With considered this process, would you support this research?

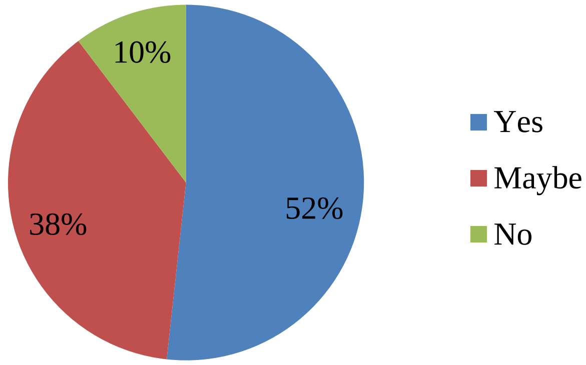


Figure 5.12: Graphical result of twelfth question, timber questionnaire

Most of timber companies have stated that they can support the use of this new structural element and the research related to this topic. Besides, some companies have specified that they do not support this product due to the brittle behavior of glass.

As a result, many timber industries have stated that timber-glass composite structural elements can have high load-bearing capacity. The most use of timber material in buildings is as the covering element and big part of required timbers are supplied by imports. Timber companies have proposed the Pine tree for building applications and the tree is being grown almost anywhere in Turkey. According to the timber componies reviews, if the operation of timber can be controlled and disadvantageous properties of glass can be prevented, timber-glass composite can be a structural element with high strength. Respondents of timber industry have specified that drying the timber, coating the surface of timber with the protective materials, impregnating preservative materials into the timber are the methods to prolong the life and durability of timber which sometimes together, sometimes individually can be used. Also, the firms have stated that the plywood has a high strength and can be used in housing or many other places. In addition, this new structural element can be used in Turkey and as well it would be able to compete with other alternative structural elements.

5.2 Glass Questionnaire

1.What is your first impression related to the use of timber-glass composite structural element in the load-bearing system?

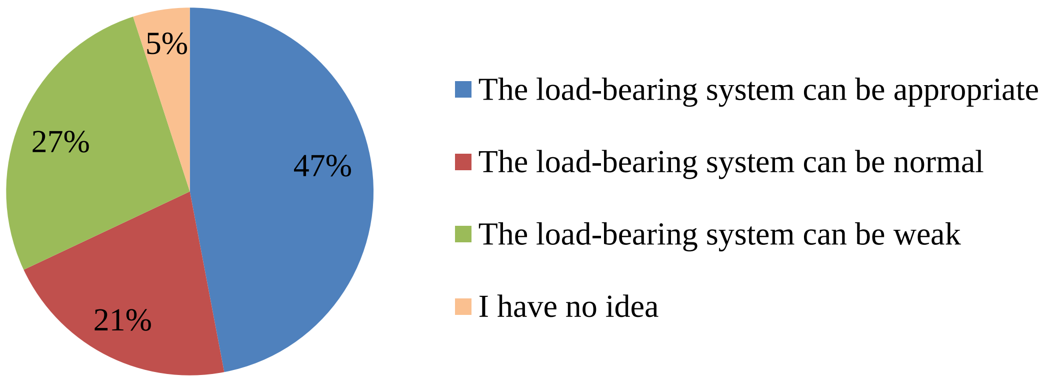


Figure 5.13: Graphical result of first question, glass questionnaire

The glass componies which have stated that the use of timber-glass composite structural elements in the load-bearing systems can be appropriate are the most.

Many firms have specified that the use of timber-glass composite system in constructions is appropriate due to the strength of silicone adhesive which brings two materials together. The durability of adhesive affects the system positively. Also, some companies have stated that this system can be weak owning to problematic brittle behaviour of glass, and the fact that in failure time it shatters into a multitude of sharp pieces which represent a further potential danger.

2. Nowadays, in which field the glass material is used the most?

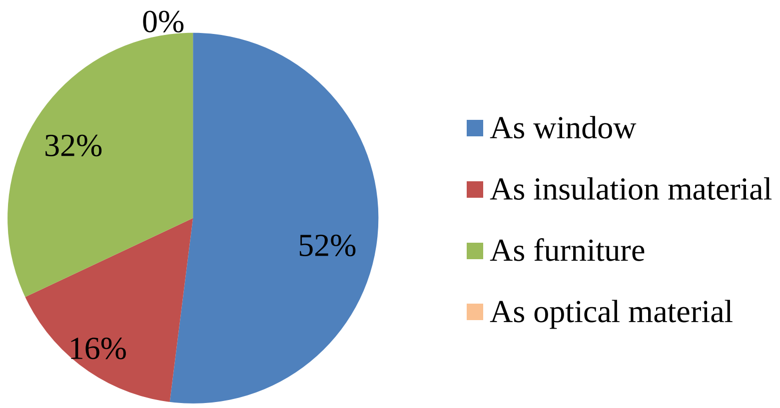


Figure 5.14: Graphical result of second question, glass questionnaire

Nowadays, the most use of glass material is as windows, doors, balconies and railing of stairs. Also, many companies have stated that the majority use of glass is in façades. In addition, the structural element of glass is also used by the automotive industry abundantly. Besides, glass is used as insulating material, furniture and optical material.

3. Which type of glass is more resistant as a load-bearing building material?

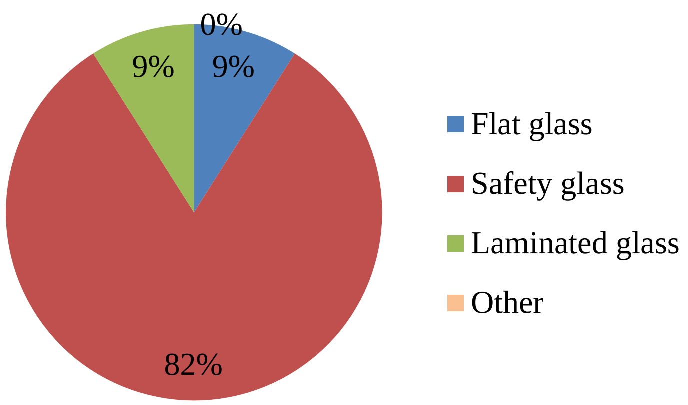


Figure 5.15: Graphical result of third question, glass questionnaire

The respondents of glass firms have specified that glass is a brittle material and the standard flat glass has low resistance to impacts. Secondary operations on glass add safety and security features to increase the strength of it against shocks. Therefore, tempered glass and laminated glass with their highest strength are indicated by the companies as safety glasses. In addition, many companies have stated that by increasing thickness of glass, high resistance glasses can be obtained.

4. With considering the chemical and physical properties of the glass, how would the strength of glass be when it is combined with timber?

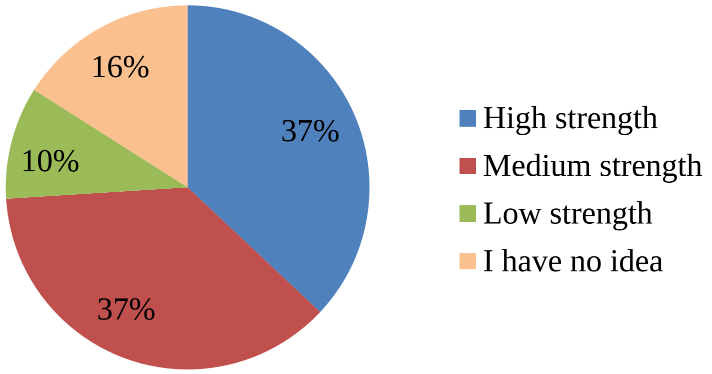


Figure 5.16: Graphical result of fourth question, glass questionnaire

Many companies have stated that due to timber provides ductility and glass offers stiffness, when they are combined together the strength is increased. Besides, some respondents have mentioned that the strength of this system is not as much as strength of metal constructions. They also stated that strength of the material may vary according to the size and usage.

5. What can be done to strengthen the glass against impacts when using in the load-bearing system?

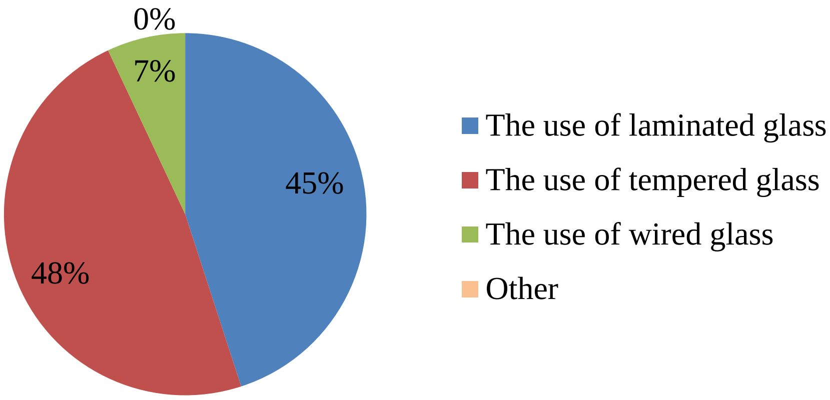


Figure 5.17: Graphical result of fifth question, glass questionnaire

Most of glass companies have specified that two common methods are used for the strengthening of glass; laminating and tempering. By these methods broken pieces are held together and injury risks are reduced. Furthermore, very few companies have mentioned that by compressing the wire mesh into the hot glass, wired glass is formed and it is resistant against the dangers.

6. In our research project, named “Load Bearing Timber-Glass Composite Structures”, tempered glass is used. How is the strength of tempered glass when it is used as a load-bearing material?

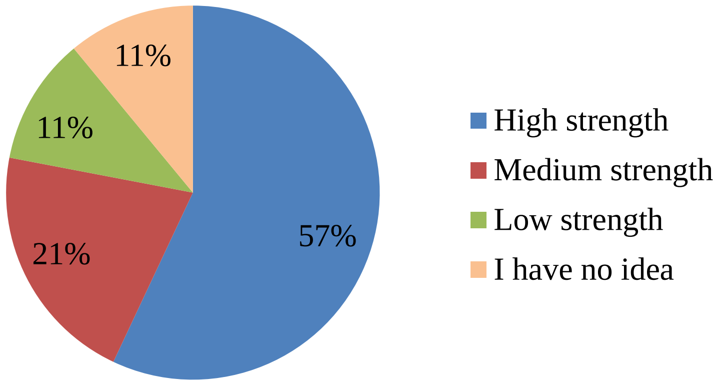


Figure 5.18: Graphical result of sixth question, glass questionnaire

High percentage of answers by companies is that the use of tempered glass in load-bearing system has high-strength. Besides, they have specified that it depends on the applied load on the glass and it should be tested. Also, it is detected that when the glass is tempered its strength increased five times more. In addition, by the Polyvinyl butyral (PVB) layer, two or more tempered glass are laminated and it can be used as the column structural element.

7. As a solution for the housing problem, how much would the use of timber-glass composite elements be appropriate?

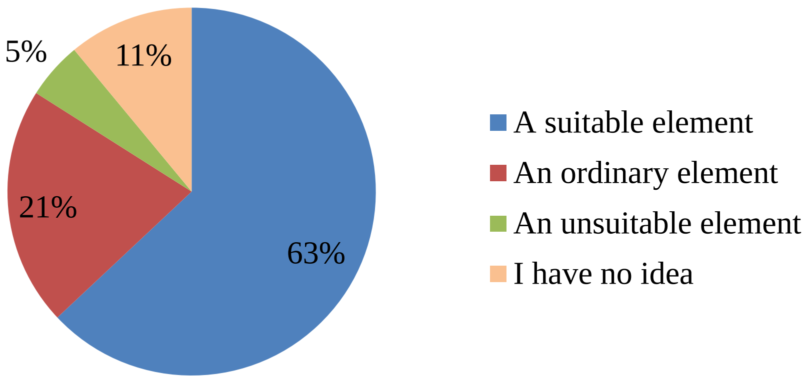


Figure 5.19: Graphical result of seventh question, glass questionnaire

Most of glass firms have stated that the use of timber-glass composite structural elements is an appropriate solution for the housing problem. Some componies have mentioned that this system should be used in buildings not more than two-storey. Some of them also stated that the system can be expensive.

8. In non-residential buildings, in which building(s) ,with different functions, this structural element is a good solution? (Multiple options can be marked)

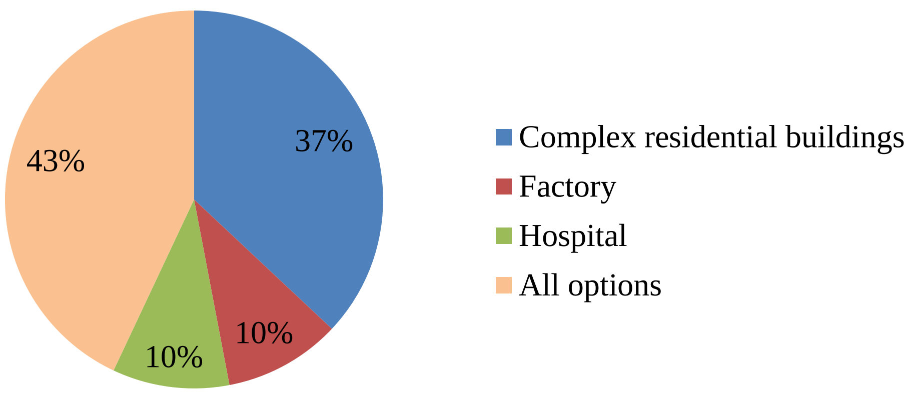


Figure 5.20: Graphical result of eighth question, glass questionnaire

Respondents of questionnaire have stated that timber-glass composite structural element is a suitable material to use everywhere, specially suggested to be used in the complex residential buildings, office, hotel, shopping mall, café, resturant and winter garden.

9. Do you think this new structural element can be used and competed with other alternative materials in Turkey?

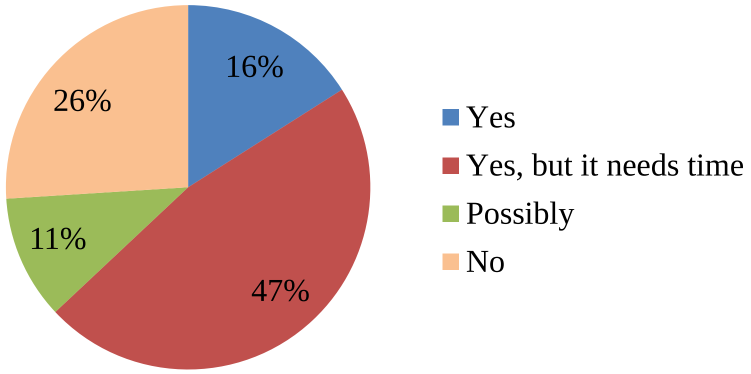


Figure 5.21: Graphical result of ninth question, glass questionnaire

Many glass companies have stated that this new structural element needs time to compete with other alternative structural elements in Turkey. Furthermore, it has been suggested to be integrated with other elements.

10. If your comany is a tempered glass seller, the required glasses are supplied from your own production or importing?

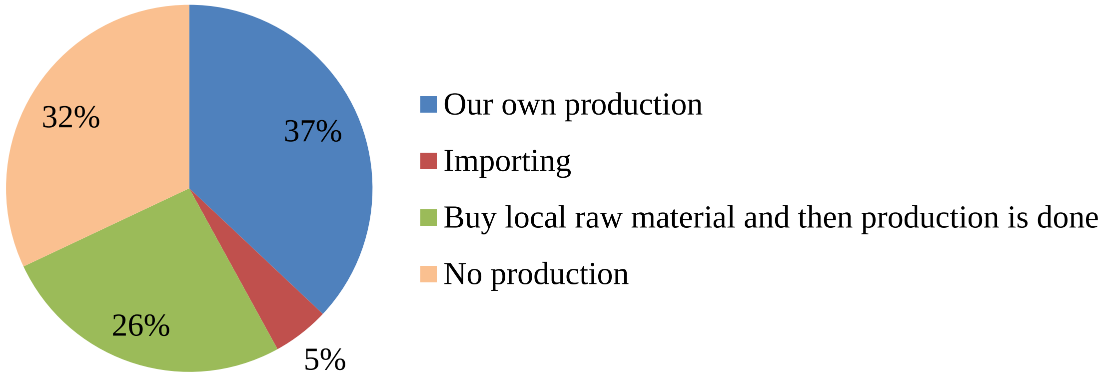


Figure 5.22: Graphical result of tenth question, glass questionnaire

There are only two companies produce glass as raw material in Turkey. Many companies buy raw materials from these firms and sell after processing on the materials. In addition, the firms which imported glass are also available.

11. If your company has tempered glass production, it is performed according to which standards?

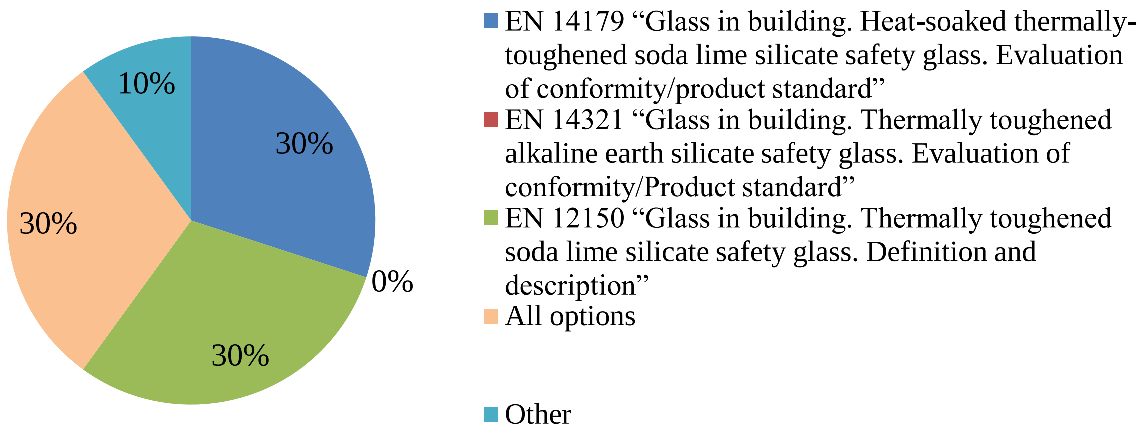


Figure 5.23: Graphical result of eleventh question, glass questionnaire

Many glass companies are using almost all of these standards for production of glass. In addition, EN 1863 “Glass in building. Heat strengthened soda lime silicate glass definition and description” standard is used by some companies to produce tempered glass.

12. As long as this new product becomes available and can be a reliable construction element, it needs to conduct researches to produce prototypes. With considered this process, would you support this research?

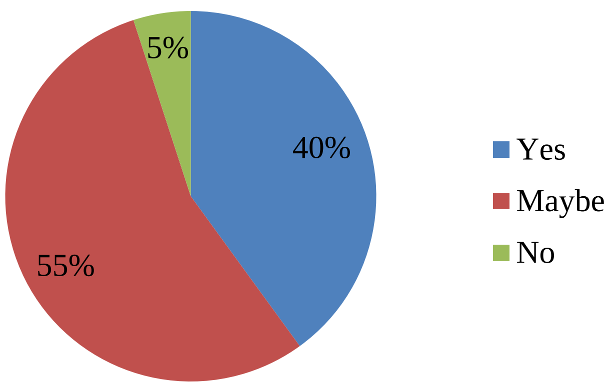


Figure 5.24: Graphical result of twelfth question, glass questionnaire

Most of glass companies have stated that they can support the use of this new structural element and the research related to this topic.

As a result, the glass componies which have stated that the use of timber-glass composite structural elements in the load-bearing systems can be appropriate are the most. Also, the most use of glass material is as windows, doors, etc. Tempered and laminated glasses which indicated by the companies as safety glasses are more resistant as a load-bearing building material. Also, according to reviews of glass firms the strength of glass when it is combined with timber is high. In addition, glass companies have stated that timber-glass composite structural element is a suitable material to use everywhere but this new structural element needs time to compete with other alternative structural elements in Turkey. Also, the result of glass questionnaire shows that many companies buy the raw materials of glass from two firms and sell after developing the materials. Most of glass companies have stated that they can support the use of this new structural element and the research related to this topic.

A wide variety of different timber frame systems, methods of construction and manufacturing options are possible. However, the system which is discussed in this thesis is maybe a good suited to niche market situations where the purchaser is looking for something different in terms of appearance, traditional or modern, or in terms of performance, a building that is particularly energy efficient, or perhaps site requirements dictate a particular approach, for example a remote site where prefabricated building systems may become desirable.

6. CONCLUSION

Today timber is an important material for the engineer, the architect, and the builder by reason of improved technology. The durability of timber has increased by modern technology. With new timber products such as plywood, particleboard, and other panel products, largely removed the limitation of size and form through the glue-laminating process, and developed improved fasteners with greater load-bearing capacity. Building with timber is building for the future because timber is a renewable building material. The scientific research on joints composed by timber-silicone-glass is still at infancy. Timber-glass composite elements meet modern architecture´s demands and can help to increase the use of timber as building material as well as the statically use of glass panels and plates. The system materialises in a multistructural modular panel which can be applied horizontally, as a slab, and vertically, as a resistant wall. The glass material is preferred to use in timber-glass composite structures due to aesthetics, architectural expressivity, transparency and natural lighting. Also, advantages of timber-glass composite system are: Aesthetic value, ecological system, energy saving system, load-bearing value, lightweight structure, composite system enables smaller timber cross-sections, prefabricated system of building and better precision in dimensions. Since glass is a brittle material, an important task for the timber is the redundancy. A glass failure should not lead to a catastrophic failure of the entire structural element. As previously mentioned, glass in such composites behaves as a structural reinforcement. The main characteristic of this composite system is that timber provides ductility and glass offers resistance and stiffness. The bonding system is also very important. Because, the adhesive brings together strength and flexibility. When glass cracks, the adhesive bonding transfers the tensile force. The adhesive has to service under all conditions and for a significant period of time. Adhesive bonding with an appropriate adhesive could provide a uniform stress distribution at the transition between the materials. As a result, it is possible to state that, with the bonding technology, the mechanical capacity of the composite system is substantially higher than the sum of the individual behaviours of the composing materials, which confirms its structural capacity. Reduction of materials fragilization by avoiding drilling, averting of high peak stresses and aim at the ductility in the unity of the set are the criterias behind the decision of using adhesive as structural bonding system. Regarding to different tests on adhesives which were performed in several universities, silicone adhesive is the most advisable, as it allows greater indexes of flexibility, thus assuring the needed structural mechanical resistance. A set of experimental tests were carried out in this research. The small sized tests focused on the analysis of results regarding durability, shear and adhesive strength tests. In most durability tests, the plywood gets darker in color. This is due to the fact that water settles in the upper level of the plywood, deforming the inner structure of it by swelling and shrinking. Also, in shear and strength tests, the effect of humidity on adhesion is clearly seen. In the medium sized test, displacements were measured under the Istanbul’s all weather conditions. Although, the specimens have shown rather high resistance. Displacement of glass in the specimens with higher load is more than specimens with lower load. Also, the glass of timber-glass composite specimens which were placed on the front side of boxes have less displacement than the others at the back side. This is due to they have been exposed to sunlight. Sunlight causes to decrease the moisture content of plywood. The specimens which were placed on the back side of boxes are more affected by moisture because they were exposed to shadow. This issue affects the adhesion between the timber and glass. High humidity affects adhesion on the negative side. As a conclusion of this experiment, it can be deduced that the little displacements of the medium-size specimens, is an appropriate result for using the elements in the structures of buildings. The project results also shall benefit several levels of the Turkish industry. It provides a marketable component system for buildings that optimally uses timber and glass. By means of the use of organic renewable resources the innovative technology provides an alternative to the existing steel glass tradition. The business principle of this research bring out the need of a strategic marketing vision. Prefabrication, control of costs and transport ability are aspects that decisively influence a product which is intended to be modular and largely feasible, and fundamentally capable of offering quality. The association of mechanical capacity of timber and glass, environmental sustainability and recyclability let believe that timber-glass composites have a huge potential in structural applications.

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