Sophisticated Developments and Advanced Applications of Glass Structure: Summary of Recent Research

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ABSTRACT

Glass is used as an emerging structural member in the civil engineering construction industry. Fear and unconsciousness are the main hindrance to apply glass structure practically. Some safety glasses with the elastic interlayer material have the ability to carry higher loads than steel. So, it is high time to adopt this as a major load carrying structural member. At the beginning of this inspection elaborately presents the manufacturing process, basic properties and classification of glass for structural use. Reviewed portion of this work includes the recent research on the basic components of glass structure such as glass beam, glass column, glass slab or pavilion, glass walkway, glass panel, glass façade, curtain wall and glass frame under static or dynamic performances. The specific connection between glass with other materials and special types of different glass related composite structures like glass-concrete, glass-timber, glass-steel and glass-fiber are discussed. Special features of dynamic responses like effect of blast loading, wind born debris attack or cyclic loading and fire hazards of glass structure are also attached. Design guidelines and some practical applications are included to create interest, attention and courage for both structural engineer and architect. In recent years, a large number of glass related sophisticated developments have occurred in Europe. Since, an attempt has been taken to find out the huge research gaps in this sector so that this could fill in the future in order to spread glass design industry all over the world.

Keywords: Glass structure, static performance, blast loading, wind born debris attack, cyclic loading, fire hazards
Preface

Glass can be used as an important structural element in building, bridges, long span truss bridges, hotels etc. because of having the excellent compressive strength than concrete or steel. But fear, unconsciousness, lack of proper guidelines or experts are the main hindrance to apply it practically. Its transparency nature may be the effective solution between the contradiction of architect and structural engineer. Glass is now just used for excellent architectural aspects. In the structural engineering point of view, the movement of practical implementation is very slow. Nowadays laminated glass with elasto-plastic interlayer material is becoming very popular to the practical implementation.

Glass composites with different pre-stressing techniques also show excellent structural performance. But more inspections should be needed at this point of view. The main objectives of this monograph are to create awareness and new idea about the application of glass structure. Recent investigations on different aspects, effects and components of glass structures are also included in this monograph. Actually the glass structure related books, journals, proceedings, magazines or reports are very limited so that these limited documents create a great challenge to complete this monograph. At last all credit goes to the Almighty Allah to finish this monograph properly and carefully.

More fundings donations should be needed to conduct effective glass related research. Glass related industries or different government agencies could play a vital role in this sector. Sufficient applicability of glass structure could reduce its high cost. Self-motivation and extensive interest should be needed to apply this glass structure practically. At this point of view, glass is called the new emerging structural element for the next decades.
Chapter I

INTRODUCTION

1.1. General

Glass is very useful material in many versatile aspects. Beautiful and dangerous are the most common and opposite aspects of glass. Architects love this beautiful nature because of many aesthetic applications. Glass is a very transparent material and can utilize natural energy. Having transparent in nature, it can easily be placed in numerous designs or planning’s through many architectural imaginations. On the other hand, the structural engineer can handle its dangerous character because of having brittleness nature. So, glass is a very brittle material because of the disability of the internal force distribution which may be crossed in its ultimate strength. When it goes in permanent deformation then unstable condition occurs in its inner phase where stress is densely concentrated. Residual stress which is formed at the end of the cooling process of glass is liable to create concentrated stress in the inner phase of glass. As the consequence, first crack appears on the glass surface and then this small crack will spread rapidly until a massive fracture or total collapse of the structure. Actually rapid crack propagation is the main culprit of its brittleness nature. Connection of glass structure is considered as another kind of challenging job. Glued connection is very popular but more researches should be needed on the application techniques of bolt connection in glass without the formation of large stress concentration. The main challenge of any structural engineer is to apply this practically in any sophisticated construction. To know about the actual practice of glass must visit the Stone Age. According to European Stone Age history, the caveman used one kind of transparent volcanic rock in their daily activities where sunlight could pass. This type of transparent volcanic rock is considered as the early version of modern glass [1-3]. After many years, the practice of commercial glass was started in Egypt and Mesopotamia. They used different types of glazing on glass. In their society, glazing was considered one kind of colourful coating in glass which was used in doors, windows or walls for aesthetic beauty.

Nowadays, the useful design guides for glass structural are “Guidance for European Structural Design of glass components” (Eurocode 2014) and “Code of Practice for Structural Use of Glass 2018” (Building department of Hong Kong). From the beginning of the 19th century, the practical application of structural glass had been spread all over in Europe. Many sophisticated creations of glass structures are noticed in many places in Europe where other nations are too much slow to apply this practically. At first glass columns, beams, floors and bricks are used in the construction industry on a small-scale but now these are used in large-scale. Glass is an excellent recyclable material with no need to paint but having better capabilities to take more compressive load than concrete. High cost is one of the main disadvantages of glass structure. If the glass is used elaborately in many construction purposes then the cost will be reduced. Skilled supervision should also be needed to apply this in any kind of construction. Paucity of research on the buckling or flexural behavior of glass column or beam is the main problem for the vast application of glass in construction [4-6]. Some researches have been conducted in Europe but it is high time to spread this worldwide.

A developing country like Bangladesh, glass structure is the brand new concept for the construction industry. More researches should be needed on the behavior of compressive, flexure, bending or buckling of glass structures in Bangladesh so that proper guidelines can be included in Bangladesh building code (BNBC 2016) which can help the structural engineer to design these kinds of glass structures without any hazard [7-9]. At least, small-scale application of the glass
structure might be possible in many beautiful tourism places in Bangladesh which can increase the aesthetic beauty as well as attracts many tourists in such places. This policy will be helped to grow economic rate in Bangladesh.

Fear is another main culprit to the practical application of glass structure. Actually glass is strong in compression but very weak in tension in the real state. Theoretically glass has high tensile strength because silica is the main constituents of glass which is very strong in tension but the reality is different. So, glass is recommended to use as a compression member in construction. Many imperfections or non-crystalline nature may reduce the tensile strength of glass [10-12]. More researches should be needed in order to improve the tensile strength of glass.

A small amount of researches has also been conducted on seismic and fire behavior of different components of glass structure. These types of gaps should be filled. It is high time to create awareness about this glass structure in building construction. This paper reviews the state-of-art for glass structures with recent researches, guidelines and applications. Figure 1.1 represents the pictorial view of the research frameworks of glass structures.

Figure 1.1. Research frameworks of glass structures.

Glass is very strong in compression but very weak in tension. Its compressive strength is more even than concrete and steel. But the cost is the main culprit for glass structure due to the rare implementation criterion. If the proper practice of glass structure is increased then the cost will be decreased. Glass composites (Glass-steel frame, Glass-steel fiber reinforced member, glass-timber frame or glass-concrete composite structures etc.) had higher seismic behavior, fire resistance and long term behavior than normal glass structure. Nowadays laminated glass with elasto-plastic PVB interlayer is being very popular for its better fire, seismic, anti-corrosion or abrasion behavior and its construction ability and way of installation are so good and easy.
Table 1.1. Comparative studies on different types of structures.

<table>
<thead>
<tr>
<th>Content</th>
<th>RC</th>
<th>Steel</th>
<th>Timber</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>Low</td>
<td>Medium</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Compressive behavior</td>
<td>Good</td>
<td>Not bad</td>
<td>Fair</td>
<td>Excellent</td>
</tr>
<tr>
<td>Section size</td>
<td>Big</td>
<td>Small</td>
<td>Big</td>
<td>Medium</td>
</tr>
<tr>
<td>Seismic behaviour</td>
<td>Fair</td>
<td>Excellent</td>
<td>Not bad</td>
<td>Good</td>
</tr>
<tr>
<td>Fire resistance</td>
<td>Excellent</td>
<td>Fair</td>
<td>Bad</td>
<td>Not bad</td>
</tr>
<tr>
<td>Construction ability</td>
<td>Not good</td>
<td>Excellent</td>
<td>Not good</td>
<td>Good</td>
</tr>
<tr>
<td>Anti-corrosion</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Long-term behaviour</td>
<td>Not good</td>
<td>Good</td>
<td>Not good</td>
<td>Good</td>
</tr>
</tbody>
</table>

1.2. Objectives of This Study

1. To create awareness for the implementation of glass structure.
2. To sum up the recent glass structure related researches and investigations.
3. To analyze the mechanism of practically implemented glass structure.
4. To discuss about the glass related design guidelines.

1.3. Organization of This Monograph

This monograph is divided into ten chapters. An overview of each chapter follows. **Chapter 1** It includes the research framework and background, objectives and the scope of the study. **Chapter 2** presents the manufacturing process and basic properties of glass. **Chapter 3** denotes a brief discussion on the classification of glass for structural use. **Chapter 4** represents an elaborate conversation on the different components of glass structure. **Chapter 5** reviews the connection pattern of glass structure. **Chapter 6** briefly discusses the basic characteristics, applicability and investigations of glass-concrete, glass-steel and glass-timber composite structures. **Chapter 7** explores the behavior and failure pattern of glass structures under different dynamic responses and fire hazards. **Chapter 8** also includes the design guidelines of glass structures (Eurocode 2014 and Hong Kong building code 2018). **Chapter 9** picks the pictorial view and the structural mechanism of practically implemented glass structure. Finally, the summary and conclusions of the work along with the recommendations for future research have been included in **Chapter 10**.
Chapter II
MATERIAL PROPERTIES OF GLASS

2.1. General

Glass is inorganic, transparent, homogenous and amorphous or non-crystalline material. The manufacturing process of glass is not critical. Sometimes, glass is defined as a supercool material because of its rigid nature from liquid to solid after the rapid cooling process. The first step is fusion of raw materials. This is the initial step of the whole manufacturing process. In this step, soda ash (Na$_2$CO$_3$), limestone (CaCO$_3$) and sand (SiO$_2$) are mixed and batched. These are also mixed with cullet. Cullet is the broken wasted glass or recycled glass. This cullet also helps to reduce the melting temperature of these raw materials. Then 1000 °C temperature is applied to create the liquid state of all these materials [13-14]. Flow ability is the basic property of this liquid solution. A whitish scum can be floated on the top surface of this liquid solution which is called glass gall. This glass gall should be removed before the final manufacturing process. The name of the last step of the manufacturing process is annealing. In this process, ultimate operation is done and rigid solid glass is formed. So, the chemical reaction of the whole process is:

$$\text{Na}_2\text{CO}_3 + \text{CaCO}_3 + 4\text{SiO}_2 \rightarrow \text{Na}_2\text{SiO}_3\cdot\text{CaSiO}_3\cdot4\text{SiO}_2 + 2\text{CO}_2$$

<table>
<thead>
<tr>
<th>Chemical Name</th>
<th>Chemical Formula</th>
<th>Weight Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica</td>
<td>SiO$_2$</td>
<td>69 – 74</td>
</tr>
<tr>
<td>Lime</td>
<td>CaO</td>
<td>5 – 14</td>
</tr>
<tr>
<td>Soda</td>
<td>Na$_2$O</td>
<td>10 – 16</td>
</tr>
</tbody>
</table>

With small amounts of magnesium, aluminium, iron and other elements

2.2. Physical Properties of Glass

Glass was used as a structural material for the first time in the 19th century in palm and greenhouses in England. Comparing with the regular structural materials like concrete, steel or timber, glass is considered more valuable especially in case of the transparency requirements. Besides the secondary structure like stair or roof or walkway, glass is being used in primary structures like beam, wall, column etc. Glass is solid, homogenous, inorganic, isotropic and impermeable in nature. The isotropic characteristics refer that stress remains same in three perpendicular directions of corresponding materials.

Glass is one kind of slender structure which sustains more lateral load. Although adequate dynamic loading or lateral loading sustainability related researches had not been conducted yet. Having fragile in nature, it can carry higher loads than steel if the compressive behavior of glass is considered. Glass is one kind of recycled materials. So, it has not any harmful effect on the environment. And recycling process does not hamper the actual quality of glass. But glass is very
weak in tension. From the analysis of the stress-strain diagram of tensile test, steel has elastic zone, plastic zone, yield point, ultimate point and strain hardening characteristics. On the other hand glass has only an elastic zone. No plastic zone or no yield point exists in glass. So, for this reason glass is brittle and easily fails in tension. But the laminated glass plates with interlayer adhesive materials are used to obtain non linearity and safe failure characteristics of glass. The theoretical tensile strength of glass is high due to presence of silicon oxide, which is super strong in tensile strength of 8 kN/mm² (1160 ksi), which is about 70 times the yield strength of Steel. But in real life testing, even a close value for this cannot be achieved. The widely accepted tensile strength of annealed glass is only 25-30 N/mm² (2.9-4.35 ksi). In the production process of float glass a bed of molten tin is used onto which molten glass is poured. The flexural strength is larger on the “air side” that in “tin side”. The actual tensile strength of glass is much lower than the theoretical one due to many imperfections [15-18]. Generally laminated and thermally strengthened glasses are mostly used in building structure. Table 2.2 refers the combination of physical properties of soda lime silicate glass.

Glass is very strong in compression. Recently in many heavy weighted building construction, glass column with 1000 MPa strength is used. On the other hand, at room temperature, mild steel shows 250 MPa stress under compression.

Now a day’s laminated glass column is being popular in many construction projects. Two or more thicken glass panes are attached with a thin interlayer whose are called laminated glass.

Table 2.2. Physical properties of soda lime silicate glass.

<table>
<thead>
<tr>
<th>Name of the properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 18 ºC</td>
<td>2500 kg/m³</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>70-74 GPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>30 GPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.22</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>3600 MPa (Theoretical Value) but behavior is governed by fracture</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>Vary widely with the sources, because glass is governed by tension, thus will break during the test because of a tensile failure and not because of compression. In Structural Use of Glass in buildings &gt;1000 MPa</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>Varies between 40 MPa (Annealed glass) to 120 MPa (Toughened glass)</td>
</tr>
<tr>
<td>Tensile Ductility</td>
<td>0</td>
</tr>
</tbody>
</table>

But glass is very weak in tension, the ranges of the average values are 40 MPa to 200 MPa under tension according to the various types of glasses. The thermal conductivity of glass is very low [19-21]. So, glass is considered as a thermally insulated material. Cooling or heating operation in glass can create stresses in glass sheet which creates the thermal breakage. Direct solar radiant...
heat can also occur the thermal breakage on the exposed portion of glass structures. In this case, heat absorbent solar control glasses are used to avoid such type of problems. Glass is a stiff material because its initial stiffness is very high and can resist plastic limit. Figure 2.1 represents the comparative stress-strain diagrams of steel, glass and timber.

![Stress-strain diagrams of steel, glass and timber](image)

**Figure 2.1.** Typical comparative stress-strain diagrams of steel, glass and timber.

### 2.3. Conclusions

Transparency, impermeability and strength are the common advantageous property of glass. Due to advanced production techniques glass can handle high compressive stresses. The weakness of the material lies in its inability to handle large tensile stresses. Moreover the transparency properties of buildings increase the Utilization natural energy. It is possible to connect glass to almost all kinds of architectural component of a building like steel beams, Masonry walls, concrete columns, glass columns and fins. The transparency property of glass sometimes causes the problem by limiting privacy. If a crack travels with explosive violence, smaller breaks will grow throughout the glass. The brittleness also creates problem with redistribution of stress, which causes stress concentrations which is one of the reason of failures in glass. The massive failure of glass may be occurred without any kind of warning. So to avoid such kind of hazards, laminated safety glass with the interlayer material is used.
Chapter III

CLASSIFICATION OF GLASS FOR STRUCTURAL USE

3.1. General

Glass is used for many versatile purposes. Classification is conducted according to its sizes, shapes and chemical or physical properties. The special type of glass which is used in construction purposes is called architectural glass. Transparent glazing is the main features of this type of glass. Glazing is the process of the adjustment of the glass in the window frame. It derives from the word “glass”. One, two and three unit glazing’s are used in the window. In building construction, this type of glass can remove darkness and also provides privacy. Architectural glass can be used in windows, external walls or internal partitions. So, some types of architectural glasses are discussed below. Figure 3.1 denotes the pictorial view of the classification of structural glass.

![Classification of architectural glass](image)

**Figure 3.1.** The pictorial view of the classification of structural glass.

3.2. Annealed Glass

Another name of this glass is float glass. Sir Alastair Pilkington invented the manufacturing process of annealed glass. At the first of this process, 60% sand, 20% lime dolomite and 20% soda are mixed during 50 hours at 1770 K. Then the molten glass is poured in the tin bath. Then the hot molten mixture is kept in a gradual cooling process so that no residual stress could form. This process is known as annealing. Then the cold glass sheet is coated with titanium dioxide which increases the self-cleaning property of this glass.

Float glass has an anti-reflective and solar controlling property. So, it is used in solar panel technology, car windows, building surfaces and screen of smart products. But this kind of glass can be broken because of the large temperature difference, impact loading or large imposed strain.
Then it splits into large pieces which are very dangerous in nature. So, this type of glass is prohibited in some places such as bathroom, door, fire exit or school to avoid the risk of injury. Instead of annealed glass, laminated or tempered glass is strongly recommended to such places because of having small pieces splinting property which protects from injury.

### 3.3. Chemically Strengthened Glass

Chemically strengthened glass is such a kind of glass where strength is increased by a special chemical process. Its failure pattern is the same as float glass but strength is 5 to 6 times larger than float glass. It is kept in potassium salt solution at 300 °C temperature so that potassium ion can replace the sodium ion at the glass surface which forms potassium nitrate coating [22]. This type of coating can increase compressive and bending strength of glass. This type of glass is used in the canopy of fighter aircraft.

### 3.4. Heat Strengthened Glass

Annealed glass is cut to the desired shape then kept under a thermal cycle to produce heat strengthened glass. So, the heating and cooling processes cause the surface of the glass to be cooled and solidified first. The shrinkage and hardening induced compressive stress at the surface of the glass. On the other hand, when the inside part of the glass gets cooled and then shrink tension is induced in this interior part. After the heat treatment process, the surface compressive stress is to be greater than 24 MPa but less than 52 MPa [23]. Just like annealed glass, Heat-treated glass is also not considered as a safety glass because of its risky broken patterns with sharp pieces. In heat strength glass, the strength is larger than float glass. But float glass contains a high redundancy value.

### 3.5. Tempered Glass

Another name of the tempered glass is “thermally toughened” or “fully toughened” glass. Tempered glass is one kind of safety glass which is processed by a special kind of chemical treatment that increases its strength and stability than annealed glass. After such tempering process, its outer surface goes compression rather than its tensile inner surface.

Because of having such kind of stresses, tempered glass breaks into granular small solid or circular pieces rather than irregular fragments whose reduce injury. It is used in building window, car window glass, mobile screen, bullet and explosive proof surface [24-30]. Thus prestressing process of tempered glass should increase its strength at least 4 to 5 times than annealed glass. Figure 3.2 defines the stress distribution of tempered glass.

### 3.6. Laminated Glass

Two or more glass panes are placed and bonded together to form laminated glass. The panes of glass can be strengthened, annealed or combined. Bonding of these panes is provided by a thin interlayer that keeps them together. PVB (polyvinyl butyral) or EVA (ethylene vinyl acetate) or sentry-glass plus is used as a thin interlayer in the laminated glass where PVB and sentry-glass plus are the common polymers but EVA is used only for solar industrial laminated glass. If the glass gets broken, this type of assemblies keeps the pieces of glass together and do not let them fly around and harm people and properties.

The assemblies can also bear some load depending on the number of layers broken. That is the reason why laminated is considered safety glass. Recently these types of glasses have been
used as a glass column or beam and girder or glass slab in the construction industry. In the recent, investigation on the compressive behavior of laminate glass had been conducted with the variation of sizes, shapes or thin interlayers.

Figure 3.2. Stress distribution of tempered glass.

The maximum standard size of the laminated glass is 3000 mm × 7500 mm and the minimum is 300 mm × 300 mm. It is very difficult to cut laminated glass window. So, it protects the attempt of a criminal attack [25]. It helps to protect unnecessary sounds from party songs, traffic noises etc. It also defends UV ray and sustains in dynamic loading conditions. Insulated laminated glass is used for its thermal insulation property. Figures 3.3 and 3.4 define the pros and cons of laminated glass. Figure 3.5 depicts the uses of laminated glass in roof panel and staircase. And finally, Figure 3.6 represents the safe failure mode of the laminated glass.
Figure 3.3. Details of standard laminated window glass [32].

Figure 3.4. Insulated laminated glass.

Figure 3.5. Uses of laminated glass [25].
3.6.1. PVB

The major components of PVB are butenal, butyraldehyde, water and acetic acid. After recycling and bending operation, PVB can be reused. Equation 3.1 denotes the formation process of PVB.

\[
\text{Condensed polyvinyl alcohol + n butyraldehyde} \xrightarrow{\text{Pressure}} \text{PVB} \xrightarrow{\text{Acid catalyst}} \text{PVB}
\]

Actual 65% PVB is used in the architectural glass industry. PVB laminated glass is used in the car shield in order to absorb the impact load and handicap the crack propagation. Under cyclic loading condition, PVB shows better hysteresis and hypo elastic response and steep initial rise before failure. The standard thickness of PVB which is used in many practical implementations is 0.76 mm and it behaves as an elasto-plastic or viscoelastic material.

The tangent Young’s modulus of PVB varies from 2.15 MPa to 14.9 MPa and the value of Poisson’s ratio is 0.5. The standard displacement control tensile loading speed rate of PVB is 10 mm/min. PVB shows better elastic behavior than sentry-glass plus interlayer. Figure 3.7 denotes that the typical tensile stress-strain diagrams of PVB.

Figure 3.6. Safe failure pattern of laminated glass [25].
3.6.2. Sentry-Glass Plus (SGP) Interlayer

The physical and chemical properties of SGP are quite different from PVB and ethylene or methacrylic acid because of having metal salt copolymers. It also behaves as an elasto-plastic material. The initial stiffness, ductility and deformability of SGP are higher than PVB and the standard value of the initial stiffness of SGP is almost 480 MPa. And the standard tensile loading speed rate varies from 1 to 100 mm/min. Figure 3.8 represents that the typical comparative stress-strain diagrams of PVB and SGP.
3.7. Low-Emissivity Glass

This type of glass is coated by such a kind of material which can reflect the infrared radiation of the sun but light can pass through it. In summer, this type of glass can keep the room temperature cool.

3.8. Insulating Glass Unit (IGU)

The production process involves two or more panes of glass. They are spaced apart and hermetically sealed to form a single-glazed unit. Generally spacer bar with desiccant filled is inserted into the arrangement. Primary seal and secondary seal are commonly incorporated in IGU. The function of the less permeable Primary seal is to prevent the water and gas between the glass panes of IGU. Secondary seal protects spacers properly by not allowing any voids. For sound insulating purposes, gas like hexafluoride is used. So, Insulating glass Unit can be used for heat and sound insulation.

![Typical features of IGU (edge view)](image)

3.9. Fire Rated Glass

In a Fire-rated glass commonly an intumescent interlayer “gel” in laminated or multi-laminated glass arrangements works as a fire shield when the temperature rises. The intumescent material is such a kind of material which protects the structure from fire. It can swell up at the contact of fire and decrease its own density. So, fire rated glass can be sustained more in the fire than other normal glasses. To increase the aesthetic beauty of any structure, many types of decorative glasses are used. Acid etching, sand-blasting, fritting, screen printing, ink-jet printing, body tinting, embossing and abrading are the most popular way of decorating treatment. On the other hand, the concave shape of glass should be avoided in window glass because it can create injury or damage.

3.10. Conclusions

Laminated glass is used for safety purposes. Laminated glass is very popular in many sophisticated structures like buildings, bridges, museums or any type of aesthetic implementations. This type of glass offers safe failure behavior under any kind of static or dynamic loading conditions. Its elastic interlayer material could retain the scattered pieces of broken glass under
any type of major dynamic loading condition. Annealed laminated safety glass has lower tensile strength (45 MPa) than toughened laminated safety glass (120 MPa).

So, fatal injuries could be reduced with the use of the laminated glass.
Chapter IV

COMPONENTS OF GLASS STRUCTURE

4.1. General

Glass is strong in compression but weak in tension. Avoiding the weakness of tension, a steel frame is used in building frontage where glass façade is fixed up there. And also in many truss bridges, steel manufacturing rope is used as a tension member where glass is used as a compression member. Having a strong tension side, steel supports the glass in any sophisticated structures. Heat strengthened and tempered glasses are stronger than annealed glass but those are not considered the safety glass because of having the crumble failure nature. So, laminated glass is the ideal safety glass for any kind of structural application. The fire performance of laminated glass is very good. So glass column, glass beam, glass floor, glass panel, glass brick, glass wall, glass stair and glass fin are considered the structural components of glass. Figure 4.1 denotes the pictorial view of the components of glass structure.

![Components of glass structure diagram](image)

Figure 4.1. The pictorial view of the components of glass structure.

4.2. Glass Column

Column is one of the most important structural elements of a building structure as it works as a compression member and can transfer the building load to the foundation. But from the Architects and clients view, the presence of columns is considered as a disturbance because it blocks the view and stands in the way. Glass columns bring a solution to these conflicting desires of architects and structural engineers. Besides most common concrete and steel columns,
nowadays the glass column is getting popular for these reasons. Structural engineers are gaining confidence to use glass as a structural material day by day by doing many experimental tests. Design and construction of small glass structures are influencing structural engineers to use glass in a greater extent. Figure 4.2 represents the different transverse cross sections of glass column.

**Figure 4.2.** The different transverse cross-sections of glass column.

Most common failures of a column are crumbling, shear and buckling. Crumbling failure occurs when column can no longer withstand the compression and this is the least desired method of failure. Shear failure occurs when shear force is too large. Buckling means the bending of the column until it breaks in the middle. Figure 4.3 denotes the Common failure modes of glass column.

**Figure 4.3.** Common failure modes of glass column.

Typically glass column is slender in nature. Generally laminated glass is used as a column because of having buckling and lateral resistance property. Designers use four special types of laminated glass columns. These types of columns are described sequentially.
4.2.1. Circular shaped bundle column

The total numbers of glass columns in the circularly shaped bundle are six where the middle one is surrounded by five columns. The diameter of each column is 3.5 inch. UV-activated glue is used to bind together these columns. And the length of these bundle column is 9.5 feet and can carry 35 kN load. If such types of columns are used in heavy structures then the diameter or number can be increased. (Here, and below: original length units are used).

4.2.2. Cylindrical shaped column

Another name of this column is laminated cylindrical glass column. The diameter of the outer cylinder is 4 inch and the inner is 3 inch. And the thickness of the inner cylinder is 0.4 inch. The remaining gap between the outer cylinder and the inner cylinder is filled with epoxy glue. This specification is perfect for lightweight structure. This type of column is used in the spiral staircase. But for heavy weighted structure, three cylindrical laminated glass columns are attached together by transparent glue having the diameter of 9.84 inch, 8.86 inch and 7.87 inch. The thickness of each column is 0.3 inch. For safety issue, perfect positioning of such columns is not necessary.

4.2.3. Rectangular shaped glass panel or column

In this type of column, suitable rectangular size, shape and thickness of 5 or 7 rectangular annealed or laminated glass columns are connected with resin. Basically this type of column is used in many commercial projects.

4.2.4. Crossed shaped column

This type of column is used in the heavy weighted structure. And this type of column is used in Saint-Germain-en-Laye which is situated in Paris. The cross - shaped column can resist bending. The height of this column is 10.5 feet and can carry 15500 lb or 70 kN load. Each section consists of three layers where the diameter of the outer layer is 0.4 inch and the middle layer is 0.6 inch.

![Figure 4.4](image)

(a) Circular shaped bundle column (top view)  (b) Rectangular shaped column (front view)  (c) Crossed shaped column (top view)

Figure 4.4. Types of laminated glass column.

Generally, very few researches have been conducted on glass column. Aiello et al. (2011) [33] conducted six compressive tests on laminated and monolithic glass column. Buckling is the
main concerning issue for any kind of design. They considered 4 mm thick laminated glass with 1 mm PVB layer. They also compared the tested results of laminated glass panel having varying heights (400 mm, 500 mm and 600 mm) with constant width and thickness. T and X shaped glass columns were joined by structural silicon connection. Deformation controlled UTM machine was used. The capacity and loading rate of this UTM machine were 600 kN and 1 mm/min. Four point bending test of glass panel was also conducted. After the completion of the experiment, maximum crack was observed in the middle and end portion of glass column.

They concluded that the increase of the slenderness ratio could reduce the capacity and create the local buckling of glass column and the performance of the laminated glass column was more than a monolithic glass column or panel. Figure 4.5 shows that the typical load-deformation curves for laminated glass column (any shape).

![Figure 4.5. Typical load-deformation curves for laminated glass column (any shape).](image)

Jakab et al. (2016) [34] conducted research on the buckling condition of I-Shaped laminated and annealed glass column. They used LVDT’s to measure the horizontal displacement and axial shortening. They also used strain gauges for the monitoring of axial and transverse strain. It was found that the laminated glass column could sustain high vertical and horizontal displacement. It was also observed that the possibility of creating local buckling could very small in I-Shaped laminated glass column.

Campione and Rodello (2014) [35] inspected on the effect of load carrying capacity of laminated glass column for the different cross-section in a transverse plane. They adopted tee (T), rectangular and X (cruciform) type cross-sections. Glue connection was applied to connect the glass panels. Their targeted observations were the progressive behavior of torsional and flexural buckling.

They noticed that the rectangular section had higher ability to carry more load than X or T cross section because of having the resisting capability of flexural buckling. On the other hand, torsional buckling effect was observed on the connection zone of X or T cross-section. So at this consequence, a fracture was observed in the glue connection zone of X or T cross-section.
Amadio and Bedon (2013) [36] approached to detect the buckling behavior of monolithic and laminated glass column under concentric and eccentric loading condition. They proposed a model for interaction curve and used ABAQUS software to predict the buckling strength. Eccentric compression on the structure may be occurred by any kind of additional load due to different boundary condition.

Figure 4.6. Flexural buckling and torsional buckling observation in T and X cross-sectional tested glass column [35].

Veer and Pastunink (2000) [36] tried to observe the failure behavior of the tubular transparent laminated column with float glass plies and resin as an interlayer material. They observed that the tubular transparent laminated glass column showed good failure behavior as compared to steel column. The compressive strength of their prototype column (length = 550 mm, diameter = 40 mm and thickness = 4 mm) was 30 kN.

Aşık (2003) [37] found that the laminated glass plate showed complex non-linear behavior with PVB interlayer under simply supported condition. He used Von Karman plate theory for theoretical approach.

Van Nieuwenhuijzen et al. (2005) [39] investigated of the laminated (two float glass tube with resin interlayer) tubular transparent column under concentric compression loading. They observed that this column showed higher strength and safe failure because of the presence of resin which could hamper the crack propagation. No destructive failure was noticed in the experiment which was conducted on prototype sample column under the displacement control UTM machine. Careful curing must be needed for the installation of resin. Due to the presence of resin, it increased the strength and safety of sophisticated laminated glass tubular transparent column.

The architect wants to increase the aesthetic beauty of the building by disappearing the column which is considered as the main challenging issue for the structural engineer to calculate safe load transferring capability. So, transparent glass may be a great solution for such kind of contradiction between structural engineer and architect. Bundled glass column can be acted as a single unit. But this is rarely used because of the paucity of proper experimental investigation, the process of installation and having the brittleness behavior. Oikonomopoulou et al. (2017) [38] investigated the compressive behavior of the bundled glass column with or without borosilicate
rod. It was found that borosilicate glass rod increased the ductility, load-carrying capacity, strain hardening property and safe post failure behaviour. This type of column can be easily installed. This type of column was applied in TU Delft campus as a 14 m long pedestrian bridge. The suitable connection pattern of the top and bottom of this column should be investigated. Cruciform (X) shaped column was used in Saint-Germain-en-Laye (3.2 m) at France and Danfoss headquarter (5.5 m) at Denmark.

![Bundled glass column with or without a prestressing technique](image1)

**Figure 4.7.** Bundled glass column with or without a prestressing technique [38].

![Practical application of glass column in Danfoss headquarter at Denmark](image2)

**Figure 4.8.** Practical application of glass column in Danfoss headquarter at Denmark [36].

### 4.3. Glass Beam

Sometimes an obstruction such as steel beam or girder can hamper architectural visual beauty. To overcome such type of problem, glass beam is used instead of steel beam. In most common cases, laminated glass panel (rectangular, square or I-Shaped) is used with three or more panel layers. These layers are to be designed in such a way that inner layer can carry more loads. So, outer layer is thinned to create the support of the inner layer. This type of glass beam is directly
connected with an insulated glass roof. This connection design is conducted in such a way that the whole structure can carry gravity and wind load. Actually laminated glass beam has no standard size but the length can vary from 14 feet to 23 feet [38-40]. For continuous laminated glass beam, staggered joint is used.

Pešek and Melcher (2017) [41] inspected on the buckling bahaviour of laminated glass beam with constant length (2400 mm) and width (280 mm) but the variation of thickness (12 mm, 16 mm and 20 mm). Vertical deflection, lateral deflection and torsional angle were measured by LVDT’s. And mid-span strain on both sides was also calculated by strain gauges. The test frame was constructed in such a way that the specimen could be subjected to bending at the contact of four-point condition. One kind of hydraulic press was used in test frame which could be operated by electric power.

To avoid concentrated stress at the contact of glass and steel, special timber pad was used to ensure safety issue. Figure 4.9 shows the overall investigated test frame.

Figure 4.9. Experimental test set-up for four point bending test of laminated glass beam [41].

Biolzi et al. (2010) [42] investigated the consequent damage of laminated glass beam. They used annealed float glass and fully tempered glass as glass plies and PVB and SGP as interlayer materials. They conducted three point bending tests on three beam specimens with considering the variations of interlayer material and glass ply.

It was concluded that the laminated beam having float glass plies with SGP showed higher strain hardening property or deformability than tempered glass plies with PVB. And fan-shaped
fracture was also noticed in the laminated beam with tempered glass plies. Considering the rectangular cross-sectional beam, the equation of the critical moment for torsional buckling is,

\[ M_{CRT} = 1.36 \left( \pi^2 EI_Z \right) \left( L_{LT}^2 \right) \left[ (0.55Z_a + \left( GKL^2_{LT}/\pi^2 EI_Z \right) + 0.55Z_a \right] \] (4.1)

- \( EI_Z \): Bending stiffness
- \( GK \): Torsional stiffness
- \( L_{LT} \): Length of unrestrained beam
- \( Z_a \): Gap between applied load and center of gravity

They also used bracing at the top of laminated glass beam for reducing extra bending in the test set-up arrangement. The three point bending test was conducted in displacement control electromechanical instron load frame having capacity of 100 kN. Figure 4.11 shows the typical load-deformation curves for laminated glass beam.

**Figure 4.10.** Fan shaped crack pattern of the tested laminated glass beam [42].

**Figure 4.11.** Typical load-deformation curves for laminated glass beam.
Buckling is considered the major concerning issue of any kind of structural component. So Belis et al. (2011) [43] also investigated on the buckling behavior of laminated and monolithic glass beam with considering the parameters of height, length, glass type and thickness.

A time dependent progressive failure mechanism and behavior of laminated glass beam were investigated by four point bending test with PVB and SGP interlayer where SGP showed better buckling resistance [44].

Bedon and Louter (2018) [45] used GFRP (Glass fiber reinforced polymer) prestressing rod in laminated glass beam in order to investigate the bending behavior. They concluded that such prestressing technique in laminated glass beam showed higher ductility, deformability, strain hardening property, post and initial cracking resistance, flexibility and elastic-plastic property than normal laminated glass beam. Figure 4.11 denotes the typical redundancy of laminated glass beam.

4.3.1. Restrained Beam Condition

There are acute research gaps in the restrained beam condition of glass structures. Bedon et al. (2015) [46] proposed a torsional buckling design in restrained laminated glass beam with continuous sealant joint. And they also conducted FEM analysis on such condition of laminated glass beam. More experimental investigations should be needed for this condition of glass beam or column. Figure 4.12 denotes the typical redundancy of laminated glass beam.

![Figure 4.12. The typical redundancy of laminated glass beam.](image)

4.4. Glass Pavilion

The main objective of glass pavilion is to increase the transversal and lateral stability of structure. In general the configurations of glass pavilion, two glass columns are used to transfer the steel truss load to the concrete foundation. A glass roof can be constructed on the top of glass pavilion. But some portion of glass pavilion can be made opaque for two psychological factors which are fear and privacy.

Laminated glass consists of two or more layers of glass panel which are attached by interlayer material like PVB. The main advantages of such material (PVB) are to increase the load carrying capacity of glass panel and to remove the spreading of small sharp pieces of broken glass. So, laminated glass is used in many important structural components and can be recognized as a safety glass. Akter and Khani (2013) [48] investigated on the effect of different layer of glass panel.
and different interlayer material on standard laminated glass. They found that single layered glass is more brittle than multi-layered laminated glass. They used three interlayer materials such as PVB foil, Solutia DG 41 and SGP (sentry glass plus). They noticed that the stiffness of PVB foil was less than 13 to 15 times of other and it showed non-linear behavior. Three point flexural tests were also conducted in this investigation. And two LVDT’s (Linear variable differential transformer) were used in the outer opposite direction to measure the central deflection. Finite element analysis in ABAQUS software was also conducted to compare it with the experimental results.

![Figure 4.13](image1.png)

(a) (b)

**Figure 4.13.** Laminated glass beam.

### 4.5. Glass Walkway

![Figure 4.14](image2.png)

**Figure 4.14.** Glass walkway in Hunan province of China [47].
Glass walkway is another kind of glass structure which is used as a hanging transparent suspended bridge in hilly areas to give the thrilling feeling. So the surface of the glass floor or glass walkway is needed to rough because of avoiding uneasy feeling. In this operation, broken pieces of glass and sand are mixed with the molten top surface of glass floor or glass walkway. When these are hardened then the surface is ready to use without hazards. Easy replaceable capability is the main advantage of glass floor.

4.6. Glass Stair

Glass stair treads are made of laminated glass and can carry more dynamic energy. The height of glass threads is 2 inch and it can be connected with steel. If steel cable is inserted in any glass structure, it can increase tensile strength, lateral stability and fire resistivity of this structure. Nowadays, glass cladding is very popular in building façade in order to reduce the steel portion of the steel frame. On the other hand, glass fin is used to support the glass panel and can protect the structural frontage from the extra moment and wind force.

4.7. Glass Brick

Glass brick is used for architectural purposes. It is opaque in nature. It is used in lightweight construction. The size and shape of this glass brick are quite similar to standard brick. It is so attractive and it has high load-bearing capacity. On the other hand, glass balustrade is also used to give the strength of the railing of stair and glass roof.

Standard size glass brick (200 mm × 300 mm × 700 mm) is cast in the mould as hot molten condition and then rapid cooling system is applied. Usually, glass brick is produced because of its good transparent look. Actually glass is a very stiff material. When glass brick is stacked to one by one then transparent adhesive (polyvinyl chloride or polyurethane) is used between them in order to reduce the local stress concentration or extra tensile stresses [48-49]. If the interlayer thickness of the transparent adhesive is increased then the strain softening property is also increased. Transparent adhesive is also used in filling the crack of glass brick which may be applied at the first step of glass brick cooling. Extra ceramic strip is used on the outer surface of glass brick to furnish its aesthetic beauty. In Amsterdam, 6500 glass bricks were used in the façade of the townhouse hotel. This glass brick is very popular in an architectural application. Size and temperature effect of glass brick should be studied.

(a) Mould of glass brick

(b) Cooled glass brick
4.8. Glass Façade, Curtain Wall and Glass Fin

Glass façade is one kind of aesthetic outside which is totally covered by glass. Glass façade is installed on the front or back side of a building. Curtain wall is a thin outward wall of a building that just carries its own dead weight. Glass curtain wall may install on all sides of a building. In spite of being constructed with glass, curtain wall may be made with any low cost materials. Glass curtain wall can pass lateral wind load from outside to beam or column through connection [46]. So glass in façade or curtain wall is considered as a “member” of building. To increase the transparent aesthetic beauty and to protect from wind load, a transverse rib is installed perpendicularly to act as a supporting bar in glass wall [50-53]. Such kind of arrangement is called glass fin. Figure 4.16 defines the Practical applications of glass fin.

4.9. Conclusions

It is thought that glass is very risky material for its fragile property. Being brittle in nature crack propagation is the main dis-advantage of glass. So PVB and SGP are used as interlayer material in laminated glass. Laminated glass has higher strength, flexibility and energy absorption capability than monolithic glass. It is largely used in many construction projects. There are still huge research gaps in a special type of glass-concrete composite (fully encased, partially encased or concrete filled glass tube) columns. So, special attention should be given in such type of this research field.
Figure 4.16. Practical applications of glass fin [46].
Chapter V
CONNECTIONS OF GLASS STRUCTURE

5.1. General

Connection is considered as a challenging job for any kind of construction. Connection is one kind of load transferring medium which can transfer the load from one member to another. So, structural engineer faces a great challenge for the connection of glass structure because of having no sufficient and relevant researches and guidelines in this field. Temperature change can create a great thread to the connection of glass structure. This effect is very harmful to the exposed glass façade of building construction. To avoid such kind of problem, polyurethane coating is used in an aluminium portion of glass façade which can protect the connection from temperature change. Different types of connection are discussed below.

5.2. Point Supported Connection

![Diagram of Point Supported Connection]

**Figure 5.1.** The detailing of the insulated glass panel to glass beam connection.

Drilling of holes is necessary for the bolted connection of steel and glass member. Improper drilling operation may cause stress concentration to the glass member. Stress concentration is
regarded as the great hindrance of stress distribution. So, tensile stress is induced which may exceed the tensile yield of this glass member. At the consequence, propagation of crack creates a great damage of the glass. To avoid such kind of problem, a special type of elastic bolted connection is adopted which is regarded as point supported connection. Extra care should be needed for the drilling hole operation. Any type of undulation should be removed to the corner of the hole and the hole is polished to make it smooth. This operation can hamper the creation of stress concentrated condition. An elastic plug which is made of nylon or polyoxymethylated (POM) is fixed in this hole by a thin layer of glue. At last bolt is tightened by applying torque. Glass column and angle of steel beam can easily be joined by this technique without any kind of hazard. Some guidelines are available for the placement of the hole for this connection.

An accident occurred in Netherland (2002) where the drilling operation was occurred in glass for creating bolted connections between glass beam and glass floor. But the smoothing operation on the corner of the hole was not conducted. So, concentrated and localized stresses were induced and the failure was occurred after half an hour of erection.

![Figure 5.2. Point Fixing Glazing Connection in Munich airport.](image)
In most cases, Grade 316 stainless steel and ASTM A276 bolt are used for connection purposes. In order to avoid moisture penetration, silicon is used to seal the gap between glass and bolt. Apple computer store in New York, titanium bolt was used in glass stair for connection issue. Figure 5.1 shows the detailing of the insulated glass panel to glass beam connection.

5.3. Point Fixing Glazing Connection

Steel plate is attached to the glass panel in this connection so that lateral force can be resisted. This type of connection is used in hotel Kenpinski at Munich airport which is attached in Figure 5.2.

Figure 5.3. Typical glass-truss connection.

5.4. Linear Supported Connection

Linear supports are mainly applied to the glazing. Figure 5.4 shows an example of linear supported connection details between a glass panel and a substructure. In drying period, spacers can protect the adhesive.

5.5. Glued Connection

The strength of a glued connection depends the adhesive and cohesive properties of bond material. Selection of adhesive for materials depends on various factors such as curing, bonding, resistance to water and shear strength. The glued connection system is denoted as the best joining technique for glass and it makes a solution to the problems like visualization and stress concentrations that occurs in mechanical connections (Figure 5.5).
5.6. Physical Connections

In structural sectors, the physical connection system is not that popular for various difficulties. In Large joints, for welding it needs extreme perfections in temperature control that can’t be possible.

Netusile and Eliasova (2010) [53] used the glued joint in steel-glass hybrid beam (steel flange + glass web) and also investigated on tension, shear and failure behavior of this beam. They conducted four point bending tests. Actually there are two types of joints which are used in glass to steel connection. One is bolted joint and other is adhesive. Bolted joint has too much risk to create stress concentration. On the other hand, glued joint behaves elasto-plastic (polyurethane, silicon and modified silicon) and rigid (acrylic and epoxy) with low weight but having high aesthetic aspects. Rigid adhesive has higher strength and lower elongation than elasto-plastic
adhesive. And this is very effective for point connection and long term loading condition. On the other hand, elasto-plastic adhesive is effective in short, dynamic loading and linear bonded condition.

Figure 5.6. Glued connection between glass web and steel flange of glass-steel hybrid beam.

Fiore (2016) et al. [54] inspected on the pull-off strength behavior of glass-steel composites in salt-fog environment (5% NaCl solution in 35 °C temperature). Basalt interlayer and frosted condition was applied in this glass surface in order to barricade the water penetration and delay the whole degradation process. They found that the epoxy resin’s joint had higher durability and strength than polyurethane adhesive joint. And higher mechanical degradation period was found

Figure 5.7. Typical stress-strain diagrams of acrylic, polyurethane and silicon adhesives.
in epoxy adhesive joints. They concluded that the failure occurred due to the steel corrosion in glass-steel composites.

![Pull force diagram](image)

**Figure 5.8.** Pull-off test configuration.

Overend (2011) et al. [55] investigated on the performance of glued adhesive in framed supported glass-steel curtain wall. They selected polyurethane, silicone, epoxy and acrylic adhesive for this experiment. They found that acrylic and epoxy adhesive showed better stiffness, strength, visco-elastic (time dependent), elasto-plastic and hysteresis behavior under cyclic loading condition than silicone adhesive. The inverse relation between the adhesive thickness and mean shear strength were also briefly discussed. Further investigations should be needed in the mechanical performance of the glued joint in glass-steel composites. Figure 5.9 shows the allowable movements of bolt in bolted connection. Figure 5.11 and 5.12 show the required guidelines for the placement of holes in glass for bolted connection and standard diameter of hole which are taken from “Code of Practice for Structural Use of Glass 2018” (Building department of Hong Kong).

![Allowable movements of bolt](image)

**Figure 5.9.** The allowable movements of bolt in bolted connection.
Figure 5.10. Typical glass pane which is infilled by clipping connection.

Figure 5.11. Vertical placement of hole.

Figure 5.12. Inclined placement and standard dimension of hole for bolted connection.
5.7. Conclusions

Due to the production of stress concentration, connection in glass structure needs to properly design so that failure does not occur. Connection may transfer forces from one element to another. Glued adhesive is used instead of bolted connection in the middle of glass and steel (Glass-steel hybrid beam) so that it can avoid concentrated stresses. Acrylic and epoxy are considered the suitable adhesives for glued connection because of having better stiffness, high strength, ductility and durability.

So, more investigations should be needed to improve the mechanical properties of glued connection.
Chapter VI

DIFFERENT GLASS COMPOSITE STRUCTURES

6.1. General

Glass is very weak in tension but strong in compression. To overcome such kind of weakness different glass related composite structures are adopted. Such glass related composite structures improve overall structural rigidity, stiffness, deformability, energy dissipation capacity, tensile property etc. But there are huge research gaps in these structures. Detached researches were conducted on beam, frame or column but whose are not enough to apply such kind of structures practically. So, more and details researches should be needed in glass-concrete, glass-steel and glass-timber composite structures on the practical applicability in each part of building, bridges, foundations etc.

6.2. Glass-Concrete Composite Structure

Waste glass powder can be used as the partial replacement of fine aggregate in concrete. Ismail and AL-Hasmi (2009) [56] investigated the mechanical properties of concrete with waste glass powder. 10-20% sand was replaced by waste glass powder. They observed that the waste glass powder increased the compressive, flexural and pozzolanic strength of concrete and also decreased ASR expansion. On the other hand, Shayan and Xu (2006) [57] used 30% glass powder instead of cement in concrete mixture and noticed that it increased the mechanical properties of concrete. They suggested that up to 40 MPa concrete mixture, glass powder (less than 100 µm) shows good mechanical performance without ASR expansion. But decreasing workability and slump are considered the major negative aspects of waste glass content in concrete.

Self-consolidating concrete is such a kind of concrete which has a self-consolidation and better flowability property. It reduces the improper honeycomb structure. Wang and Huang (2010) [58] inspected the mechanical property of self-consolidating glass concrete where LCD TV monitor glass powder was used instead of 0-30% sand with various admixtures. Having the high hydrophobic nature of LCD glass powder, it reduced the water absorption and drying shrinkage of concrete but increased the slump flow. At last, they concluded that the glass content with more than 20% reduced the strength of concrete but increased the setting time of cement paste.

At first Jin et al. (2000) [59] proposed the identity “Glasscrete” which means concrete with glass aggregate. They investigated ASR expansion of different parameters like glass content, glass type, glass colour and particle size. They also found that the mortar bar expansion rate was proportional to the glass content. Soda-lime white glass was liable to ASR expansion but the green glass had no effect on this because of having Cr₂O₃ content. They concluded that the glass aggregate which was passed through the U.S. standard Sieve No.50 having less ASR expansion.

Lee et al. (2008) [60] used such kind of special reinforced bar which was produced by the polymer of glass fiber in concrete having high compressive strength to observe the interbond behavior of this rebar. The results were found that the internal bond strength increased with the increase of compressive strength of concrete. They observed anchorage, rupture and splitting failure pattern of concrete. They concluded that the bond strength of GFRP (Glass fiber reinforced polymer) was 0.3 power of concrete compressive strength where the value of this power was 0.5 in case of normal fiber reinforced polymer bar.
Taha and Nounu (2008) [61] investigated the overall behavior of concrete by using colourful recycled crushed glass in lieu of sand and cement. But the output was not up to the mark. Bleeding, segregation, micro-crack and the reduction of the compressive strength were observed.

Borhan (2012) [62] adopted a new basalt fiber in glass concrete which was found from volcanic rock. Being such kind of special nature, its temperature and ASR expansion resistivity are high. He discovered that such kind of basalt fiber glass concrete had higher compressive and splitting tensile strength as the 40% replacement of sand. On the other hand, the thermal and mechanical properties of recycled carpet fiber reinforced glass concrete are very high.

Freytag (2004) [63] connected the laminated glass web to high strength concrete flange to meet up the structural challenges of glass as a load bearing member. Such kind of glass concrete composite beam showed very little brittle behavior with high ductile behavior.

He used three glass panes in laminated glass web with high load carrying capacity. Five specimens were tested with 8.1m length and failure patterns were also analyzed. He also suggested that multiple tendons or reinforcing bars might be used in pre-stressed condition in concrete flange. More and more researches would be needed in such kind of condition. Outer pane destructions occurred due to the smaller tensile strength but crushing and spalling were observed as a common failure mode in the compressive connection zone on glass web.

Figure 6.1. Standard glass-concrete composite beam according to Freytag’s experiment.

Glass fiber reinforced polymer (GFRP) rod is such kind of special rebar which is constructed from glass fiber. GFRP has better corrosion protectiveness (heavily use in seawater), tensile ability, non-conductive and non-magnetic property than steel rebar. But high initial cost, lower ductility and modulus of elasticity are the main disadvantages of GFRP. GFRP is very popular in
the transportation industry and can sustain a very long time in the pavement. There are acute scarcities in proper design guidelines for GFRP. So, more inspections should be needed in this field.

High productions of different types of wasted glass content are considered as the major concerning issue in our new civilized world. Lacking’s of proper recycling process or strict rules or regulations, most of these contents are used for landfill activities. So, many attempts have been conducted to reuse these items in the concrete industry.

Glass pellets are one kind of painting materials which are produced from glass fiber and used in roadway and highway with reflection, fire protection and colour matching principle.

Shao and Mirmiran (2004) [71] investigated the non-linearity of cyclic response of the concrete filled GFRP tube and propose a model to find out this which was conveyed good agreement with experimental approaches.

**Figure 6.2.** Different features of glass-concrete composite structure.

NO\textsubscript{x} (Nitrogen oxide) and VOC (Volatile organic compound) are considered the main air polluting agents by many researchers whose are liable to many inhalation diseases. Highly cementitious concrete block produces such kind of agents. Poon and Cheung (2007) [64] used recycled glass aggregate with 10% TiO\textsubscript{2} in concrete block so that sunlight could enter the satisfactory depth of this block to activate the TiO\textsubscript{2}. This activation process of TiO\textsubscript{2} removes the NO\textsubscript{x} and VOC. Then Chen and Poon (2009) [65] illustrated this mechanism for two layer paving block structure. Figure 6.3 defines the Mechanism for the removal of NO\textsubscript{2} and VOC in the paving block surface.

Alkali silica reaction is one kind of chemical process but attacks physically and causes mechanical damage. Having the presence of highly reactive silica, aggregates are attacked chemically by Na\textsuperscript{+}, K\textsuperscript{+}, Ca\textsuperscript{2+} or other ions in dissolved high alkali condition which is produced by hydrated cement paste. And at the consequence of this phenomenon, expanded alkali-silica gel is produced. Such kind of ASR expansion causes the hydrostatic pressure in cement which depends on the elastic modulus, interfacial transition zone and viscosity of materials. When this internal hydrostatic pressure is greater than the tensile strength of the matrix then the ultimate micro crack has occurred. So, ASR expansion creates the elastic and inelastic deformation of concrete. This microcrack is liable to reduce the elastic modulus of concrete and leads to long detrimental effect. Having high silica-rich and amorphous nature, waste glass coarse particles up to mixed with concrete 100 µm are faced with ASR expansion.
So, particle size influences the ASR expansion. Naturally finer silica reactive aggregates show less ASR expansion. Electrochemical method and vacuum absorption are the popular ASR expansion reduction techniques which are used worldwide. Figure 6.4 defines the Relation between ASR expansion and particle size.

**Figure 6.3.** Mechanism for the removal of NO$_2$ and VOC in the paving block surface.

**Figure 6.4.** Relation between ASR expansion and particle size.

Although glass concrete composite structures have too many research gaps such as seismic, fire and blast loading performance etc. More investigations should be needed in this area so that
could be used in the concrete industry and as an important load carrying structural member at large scale. Table 6.1 shows the Recent studies on glass-concrete composite structure.

**Table 6.1.** Recent studies on glass-concrete composite structure.

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Specimen details</th>
<th>Mixing details (Amount)</th>
<th>Variations of parameters consideration</th>
<th>Outputs</th>
<th>Name of the conducted tests</th>
<th>Reference</th>
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<td>80 kg crushed waste glass powder was used instead of 10%, 15% and 20% sand</td>
<td>Overall in 900 kg concrete</td>
<td>Replacement of sand</td>
<td>80% pozzolanic strength, 20% flexural and compressive strength increased and 66% ASR expansion also decreased</td>
<td>Slump, dry density, compressive strength, flexural strength, pozzolanic strength, ASR and mortar bar tests</td>
<td>[56]</td>
</tr>
<tr>
<td>2</td>
<td>Self consolidating LCD glass concrete</td>
<td>Amounts of sand replacement were 0%, 10%, 20% and 30%</td>
<td>Water cement ratio and sand replacement</td>
<td>More than 20% LCD glass content reduced the strength of concrete but increased the setting time of cement</td>
<td>Slump, V-funnel, unit weight, air content, setting time and U tests</td>
<td>[58]</td>
</tr>
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<td>3</td>
<td>Glasscrete (concrete with glass aggregate)</td>
<td>10% aggregate and 10% cement were replaced by glass content</td>
<td>Glass content and particle size</td>
<td>Green glass and particle passing No. 50 sieve had less effect on ASR expansion</td>
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<td>54 cubic concrete specimens</td>
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<td>[60]</td>
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<tr>
<td>6</td>
<td>Basalt fiber reinforced glass concrete</td>
<td>20%, 40% and 60% sand were replaced by colourful wasted glass powder and extra addition of 0%, 0.1%, 0.3% and 0.55 of basalt fibers</td>
<td>Sand replacement and adding of basalt fiber</td>
<td>Tensile and compressive strength increased by more than 20% waste glass powder content with lower ASR expansion</td>
<td>Slump, unit weight, compressive strength, splitting tensile strength and heat transfer tests</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Coarse (4-16 mm) waste glass used in concrete</td>
<td>0-60% coarse was replaced</td>
<td>Coarse aggregate replacement</td>
<td>Very little reduction of strength and other properties</td>
<td>Slump, unit weight, compressive, flexural, tensile strength and dynamic modulus of elasticity</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Glass fiber reinforced plastic bar (GFRP)</td>
<td>15 beams were tested in five groups</td>
<td>Types of rebar and effective depth of beam</td>
<td>Proposed design guidelines for the use of GFRP in beam</td>
<td>Four point bending tests</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Concrete filled tubular glass fiber reinforced beams (for partially and totally filled condition) and short columns (under concentric and eccentric loading condition)</td>
<td>3 beams and 5 columns were tested where coarse silica was used to rough the outer surface and 15 mm corner radius was considered</td>
<td>Reinforcement ratio</td>
<td>Lower bulging effect, higher initial stiffness, non-linearity before failure and better confinement were observed. Concrete crushing and short outward local buckling were also observed</td>
<td>Four point bending tests for beam and axial loading (concentric and eccentric) for columns</td>
<td></td>
</tr>
</tbody>
</table>

### 6.3. Glass-Timber Composite Structure

Timber structure has low weight with high strength and do not need any kind of formwork at the time of the construction process which reduces the time and cost. Timber acts as an insulator and having the resistivity of corrosion or oxidation. Actually the strength of timber depends on the moisture content, orientation of grain, knot and termite attack. So, load carrying capacity of timber varies in different direction of the same log. Using glass fiber reinforced polymer rod in timber and glued laminated timber are the major common techniques to improve the bearing capacity of
solid timber. So, more investigations should be needed to use the GFRP rod in timber beam or column.

Timber is one kind of anisotropic material which means that its material property changes along all its direction. On the other hand, glass is isotropic material. At the time of tree’s growth, annual ring is created in radial or tangential direction. This type of direction may be parallel or perpendicular to the grain which can increase or decrease the strength and stiffness of timber. Timber is one kind of orthotropic material and the propagation of different kinds of knots are the strength reduction agents of timber. Having the natural appearance of timber and transparency of glass, glass-timber composite structure has high load carrying capacity with low cost. Energy efficiency and environmentally friendly properties are the other features of this structure. Timber is considered as the recyclable, sustainable and CO\(_2\) neutral building material. Hotel Palafitte complex in Switzerland, glass-timber composite girder was established to enhance the transparency and architectural aspects [72]. There lake view glass façade was adopted and heavy tree trunk was used to make timber column. The tensile rigidity and ductility of timber frame are very high. Hot melting polyurethane glued connection was used between composite girder to timber rather than point supported connection. High economic and ductile prestressing glass pane was used in the web of glass-timber composite girder. Generally glued connection is used to connect the glass timber composite structure. Steel screw is also used as a connection with an elastic coating so that it can reduce the stress concentration related problems. The bearing capacity of this bolted connection is very high but ductility is very low. On the other hand, glued connection has satisfactory capacity with high ductility. The tensile strength of glass-timber composite frame is very high. An excellent renovation work of timber railroad bridge was done in Moorefield at West Virginia [73]. Pile, pile cap and sleeper were wrapped and refashioned with glass composite fabric or polymer coating.

Winter et al. (2010) [77] investigated on the load bearing capacity of timber-glass composite frame. They found that timber-glass composite structure increased transparency and load carrying capacity. They also presented an outstanding review on about timber-glass composite girder and its application. Different aspects of elastic adhesives were also discussed.

Valee et al. (2016) [74] proposed a detailed model of timber-glass pedestrian hybrid bridge. The girder of this bridge was proposed to make with glued laminated timber.

Schleicher (2016) [78] discussed about different fire protection techniques of timber glass composite frame. A special type of bracing system and automatic sprinkler system were considered as the most effective fire protective systems. He observed that timber-glass composite structure showed higher deformability and elasticity than reinforced concrete structure under fire. He also suggested to use epoxy or acrylic adhesive as a glued connection because of having the special ability to absorb the shear stress. Timber glass composite frame could be used as a double façade system in different multistory buildings because of having the better sustainability to withstand the worse climate or fire than normal RCC structure. At last, He concluded that the bearing capacity of timber-glass composite girder or bracing system was very high.

Rosliakova (2014) [79] estimated that the timber glass composite structure reduced the emission of CO\(_2\) almost 16 times. And there was no need of any kind of bracing system in timber-glass composite frame to resist lateral force.

Figure 6.6 shows the typical load-displacement diagram of timber-glass composite member with silicon adhesive.

Although several research works have been conducted on glass-timber composite beams and frames but still now glass-timber composite columns are untouched. So, more researches should be conducted at this point of view. Blast loading and fire performances are needed to be conducted on glass-timber composite structure. Figure 6.7 shows the typical stress-strain diagram of timber where grain is adjusted in parallel.
Figure 6.5. Pictorial details of the glass-timber composite girder at Hotel Palafitte complex [72].
**Figure 6.6.** Typical load-displacement diagram of timber-glass composite member with silicon adhesive.

**Figure 6.7.** Typical stress-strain diagram of timber where grain is adjusted in parallel.

**Table 6.2.** Recent studies on glass-timber composite structure.

<table>
<thead>
<tr>
<th>Serial Number</th>
<th>Specimen details</th>
<th>Targeted observations</th>
<th>Variations of parameters consideration</th>
<th>Outputs</th>
<th>Name of the conducted tests</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Timber beam (100 mm × 200 mm × 3000 mm) with or without GFRP rods</td>
<td>Load-strain response, failure modes and flexural strength</td>
<td>Presence of GFRP rods</td>
<td>Timber strengthened beam with GFRP rods increased the stiffness, strength and tensile capacity than solid timber beam</td>
<td>Four point bending tests in 7 specimens</td>
<td>[76]</td>
</tr>
<tr>
<td></td>
<td>Glass-timber composite I beam (glass web and laminated veneer lumber flange) and shear wall (4 storey wall)</td>
<td>Overall behaviour</td>
<td>Adhesives</td>
<td>Acrylic adhesive showed better ductility and aesthetic aspects than silicone or polyurethane</td>
<td>Four point bending tests</td>
<td>[82]</td>
</tr>
<tr>
<td>---</td>
<td>--------------------------------------------------</td>
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<td>-----------------------------------------------------------------</td>
<td>--------------------------</td>
<td>-----</td>
</tr>
<tr>
<td>3</td>
<td>Glass-timber composite wall pannel</td>
<td>Dynamic performance</td>
<td>Adhesives, joints and glass panel thickness</td>
<td>Silicone and polyurethane showed excellent behaviour under seismic dynamic loading condition</td>
<td>Shaking table tests</td>
<td>[79]</td>
</tr>
<tr>
<td>4</td>
<td>Timber beam (pine wood beam) with glass fiber or carbon fiber reinforcement</td>
<td>Bending strength and failure modes</td>
<td>Dimension of beam</td>
<td>Strength and stiffness were increased. First and 2nd crack were observed in tension and compression zone (for GFRP)</td>
<td>Four point bending tests in 9 beams</td>
<td>[77]</td>
</tr>
<tr>
<td>5</td>
<td>Single and two-storey glass-timber composite frame</td>
<td>Ground shaking failure behaviour</td>
<td>Different types of Experimental setup</td>
<td>Glass-timber composite frame acted as a rocking frame with high ductility, energy dissipation capacity and deformability</td>
<td>Vertical, horizontal and combined loading tests</td>
<td>[80]</td>
</tr>
<tr>
<td>6</td>
<td>Glass-timber composite beam (Height = 240 mm, length = 4800 mm) and shear wall (1200 × 2400) mm²</td>
<td>Failure behaviour</td>
<td>Adhesives and loading condition</td>
<td>Heat strengthened glass had high ductility and deformability than annealed float glass</td>
<td>Four point bending tests (beam) and Vertical, horizontal and combined loading tests (for shear wall)</td>
<td>[78]</td>
</tr>
<tr>
<td>7</td>
<td>Timber-glass composite shear wall (laminated heat strengthened glass panel in timber frame)</td>
<td>Cyclic load strain response</td>
<td>Glass panel</td>
<td>Timber-glass composite shear wall showed higher ductility and deformation ability than normal shear wall</td>
<td>Frictional force, buckling and quasi static ranking tests</td>
<td>[81]</td>
</tr>
</tbody>
</table>

### 6.4. Glass-Steel Composite Structure

Glass-steel composite structure is regarded as the load bearing and aesthetic structure. The main challenge is to connect the glass web to steel flange. So, connection is the major concerning
issue of glass-steel composite structure. Drilling hole should be prohibited because of forming stress concentration instead of glued connection. So, more researches should be needed in this issue. The main hindrance to use glass as a structural member is fear because of having no plastic deformation and brittleness nature. To overcome this issue, laminated glass member is used with elasto-plastic interlayer material.

Weller et al. (2010) [85] investigated on the torsional buckling and post failure behaviour of glass-stainless steel hybrid beam with acrylic adhesive as an important structural member. They conducted four point bending tests in 10 specimens with 10 N/s loading rate. They adopted displacement transducers at centre to measure outward buckling and linear strain gauges at bottom to measure the elongation. They observed that glass-stainless steel beam showed higher flexural strength and better post-failure behavior than normal laminated glass beam.

Ungermann and Preckwinkel (2010) [86] studied on the structural behavior of glass-steel hybrid beam where I shaped steel flange and glass web were used. They conducted four point bending tests and found that this glass-steel hybrid beam had higher stiffness, transparency, load carrying capacity and better connection efficiency. This kind of glass-steel hybrid structure could be used as girder, column, glass fin or façade bracing. Silicone, polyurethane and epoxy resin are considered as the best adhesives whose are used as the main element in glued connection.

Bos et al. (2004) [87] studied on the post failure behavior of pre-stressed stainless steel reinforced glass beam in glued connection. They also conducted four point bending tests and found that this prestressing techniques delayed the crack formation of such specimens. They concluded that the T shaped glass-steel hybrid beam had higher failure load and strength than box section.

Hoffmeister et al. (2017) [83] investigated on the buckling behavior of laminated glass to cold formed steel frame with polyurethane adhesives. Such kind of composite structure can resist the slender buckling of steel structure.

Santarsiero et al. (2017) [84] used laminated adhesive connection in different glass beam segment and wanted to observe the creep and failure mode under static loading condition. They found that such kind of arrangement increased the ductility, structural stability and safe failure
mode. Steel bar reinforcement was also used at the top and bottom of the glass beam. Top and bottom of the glass beam was found the best position of laminated adhesive connection.

Figure 6.9. Standard four point bending test setup for glass-steel hybrid beam.

Figure 6.10. Typical load-deformation diagram for stainless steel reinforced glass beam (post-tensioned).

6.5. Conclusions

The practical applications of glass-concrete, glass-steel and glass-timber composite structures are not up to the mark because of conducting very few types of research. But these are
very potential structural elements for practical implementation. If waste glass powder is used in the replacement of sand or cement then it increases the mechanical property of concrete and decreases the ASR expansion. Glass fiber reinforced polymer bar (GFRP) is the new potential source of rebar which is used in lieu of steel rebar because of having the corrosion resistance and high tensile ability. Extensive researches have been conducted on glass-concrete composite beam rather than a glass-concrete composite column. So, special attention should be needed in this area. On the other hand, timber-glass composite frame shows higher load carrying capacity, ductility, transparency and fire protectiveness. It also acts as a rocking frame and can resist more cyclic loads. Glass-stainless steel hybrid beam or frame increases flexural and tensile strength rather than single glass beam. Pre-stressed steel rebars are used in a glass frame to improve ductility and safe failure pattern and can also resist slender buckling. Although these outputs look good but more information should be needed to apply such glass related composite structures practically.
Chapter VII

DYNAMIC RESPONSES AND FIRE HAZARDS

7.1. General

Glass is very sensitive under fire and dynamic responses. Blast load, wind-borne debris effect and cyclic load are considered the common features of dynamic responses whose could easily affect the glass. Blast load may be occurred by terrorist bombing attack or gas line explosion without giving any kind of warning. At the consequence, glass splinter may be scattered and injuries are occurred in and out of the glass structure. So, blast load protective techniques should be adopted to reduce any kind of damage. Wind-borne debris may attack the glass window or glass structure during heavy storms and creates great harm to all. Fire and cyclic load are also considered the major concerning issue for glass structure. Several kinds of research and some protective measures of glass structure under fire and dynamic responses are discussed below.

7.2. Dynamic Responses of glass structure

Blast loading may occur by the terrorist bombing attack or gas line explosion. In 1995, an ANFO detonation occurred in Alfred P. Murrah Federal building by a terrorist attack which was situated in Oklahoma City in the USA. The first portion of this damaged building was the curtain wall. A thin glass filling frame which is attached to the surroundings of the main building structures, then this is called curtain wall. When this curtain wall is placed on one face in any direction of the building then this is called glass façade. More than 167 peoples were died in this attack by the scattering of glass splinters. Many peoples were also injured by such kind of abrasion and laceration effect of glass [88-90]. At first terrorist attack occurred at the center position of this building and then large numbers of windows, power circuits and light bulbs were damaged. Many peoples had suffered hearing problem from this event. Most of the damages were occurred by 10ft glazing wall than 5ft. Actually terrorist bombing activity may have occurred without any kind of warning.

So, burst resistance glazing system much be needed to be reduced such kind of incident. After 1995, many attempts and researches had been conducted to establish blast protective glazing system. Laminated glass with elasto-plastic PVB interlayer and polycarbonate glazing have been used as innovative detonation protective techniques in standard glazing system. Table 7.1 defines important glass-related injuries which occurred in many portions of the USA. Fuel tank and gas pipe explosion are considered other destructive features of blast load.

<table>
<thead>
<tr>
<th>No.</th>
<th>Name of structures</th>
<th>Number of inhabitants</th>
<th>Fatal injuries caused by bombing</th>
<th>Fatal injuries caused by glass shards</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Durham Post Office (U.S.A.)</td>
<td>10</td>
<td>7</td>
<td>3</td>
<td>[88]</td>
</tr>
<tr>
<td>2</td>
<td>Water Resources Boar (U.S.A.)</td>
<td>63</td>
<td>39</td>
<td>23</td>
<td>[90]</td>
</tr>
</tbody>
</table>
When any kind of explosion occurs then it releases energy and produces blast air pressure. Positive blast phase has strong damaging capability with short duration than negative phase. At certain long distance blast wave is turned into sound wave. Figure 7.1 shows the idealized pressure time curve for a released blast wave in air.

Equation (7.1) conveys the modified Friedlander equation which is used to measure the vibration of blast pressure [For hemispherical condition].

\[
P(t) = P_0 + P_{\text{max}} \left(1 - \left(t/t_d\right)\right) - (bt/u) \quad [\text{Here, } u = t_d] \tag{7.1}
\]

If laminated glass is used in glass curtain wall or façade, this will save the structure from air blast pressure in case of detonation.

Laminated glass consists of two or more panels of annealed or tempered glass with PVB interlayer. The elasto-plastic property of PVB can delay the glass failure and breaks into large pieces. So, laminated glass is called the safety glass. Figure 7.2 denotes the typical failure mechanism of laminated glass under static or dynamic loading.

![Figure 7.1. The idealized pressure time curve for a released blast wave in air.](image-url)
The PVB interlayer of laminated glass removes possibility of scattering splinters of glass and ensures the life safety. The popular FEM code for blast loading simulation is EUROPLEXUS. Generally high computational power with 3D solid model predicts better numerical simulation for laminated glass under blast load. The laminated glass in blast loading, failure does not occur in positive phase because of having the binding capability of the PVB interlayer between the glass panes but failure occurs in negative phase.

Figure 7.2. The typical failure mechanism of laminated glass under static or dynamic loading.

Weggel and Zapata (2008) [89] inspected on the effect of low level blast load on the simply supported curtain wall which was consisted of laminated glass lites. They used silicon sealant in the four corners of the glazing fenestration of this wall. After the analysis of the post cracking behavior, such type of curtain wall showed better performance under blast load. Glass lites mean of the pieces of glass whose are used to make glass doors or windows.

A blast loading experiment in the field is very expansive. So, conducting research in this field is very limited. Zhang (2013) [90] et al. conducted several blast loading tests on the laminated float glass window. Considering the major parameters of their investigations were glass thickness, interlayer thickness, boundary condition and window dimension. They found that the blast loading resistance capacity was directly proportional to PVB thickness and number of glass ply because of having a quasi-static behavior of PVB. After the analyzed of pressure-impulse diagram, pinned boundary condition showed flexible character than fixed boundary condition. They also used LS-DYNA software for numerical simulation and compared with field blast test.

Zhang and Hao (2015) [91] used LVDT behind the steel window frame to determine the central displacement of laminated glass window under blast loading criterion. They also adopted trinitrotoluene explosive, two high speed camera and data acquisition system for their tests set up. Pressure transducer was also installed to record the blast pressure.

Zhang et al. (2014) [92] investigated the effect of blast load on tempered glass windows and found tempered glass created less debris than annealed glass. They adopted (1.5 m × 1.2 m) tempered monolithic pane (t = 6 mm and 10 mm), 5-10 kg TNT explosive at 4.5-12.3 m distance
and high speed camera for measuring splinter velocity. Figure 7.3 shows the typical ejected velocities versus time of tempered glass fragments under blast load.

Figure 7.3. Typical ejected velocities versus time of tempered glass fragments under blast load.

Figure 7.4. Typical launching velocity versus time diagram of debris after blast loading.
Figure 7.5. Typical test-setup for dynamic loading test on glass window.

Zhang et al. (2014) [92] proposed a model for predicting size, shape and emitting velocity of annealed glass fragments. Actually the studies of numerical simulation of different types of glass fragmentation are very restricted or limited. So, this is considered the main potential research gap in this glass structure related research. They used smooth soft dishrag so that the glass splinter
could not penetrate into the ground. They also installed a pressure gauge at the front of the partition wall which was situated between two glass windows.

They measured the glass fragment launching velocities at the center and corner of the window were 22 m/s and 12 m/s by the post-mortem of the high-speed camera image. They concluded that if the glass window was failed in planner pattern then the launching velocity of debris from corner might travel at a great speed.

**Table 7.2.** Recent studies on the dynamic responses of glass window.

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Specimen details</th>
<th>Targeted observations</th>
<th>Variations of parameters consideration</th>
<th>Outputs</th>
<th>Name of the conducted tests</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Laminated glass window under field blast loading condition</td>
<td>Flexural bending and failure behaviour</td>
<td>Boundary condition, anchorage effect, frame bite depth and connection type.</td>
<td>Interlayer anchorage increased the serviceability of glass window and pinned boundary condition increased the flexibility but reduced the joint failure</td>
<td>Field blast load</td>
<td>[96]</td>
</tr>
<tr>
<td>2</td>
<td>Tempered glass window under field blast loading condition</td>
<td>Way of window fracture and character of tempered glass fragment</td>
<td>Distance of charged TNT explosive</td>
<td>Negative pressure phase was responsible to splatter distribution and ejecting velocity of sharp fragment</td>
<td>Field blast load</td>
<td>[92]</td>
</tr>
<tr>
<td>3</td>
<td>Laminated glass window</td>
<td>Deflection and blast resistance capacity</td>
<td>Pane thickness, PVB interlayer thickness</td>
<td>Thicker window pane had higher rupture resistance, flexure stiffness, but lower residual displacement</td>
<td>Field blast load and pendulum impact tests in laboratory condition</td>
<td>[93]</td>
</tr>
<tr>
<td>4</td>
<td>Laminated window glass made of two layer thick float glass</td>
<td>Failure pattern, mid-plane strain and deflection</td>
<td>Size and thickness of glass pane and PVB interlayer, boundary condition and wooden block launching velocity</td>
<td>Thicker glass panel decreased its strain and deflection. Higher timber launching velocity increased the debris mass and amount of the fragments. The thicker PVB interlayer also increased the higher debris hindrance capacity.</td>
<td>Wooden block impact test</td>
<td>[95]</td>
</tr>
</tbody>
</table>

Generally, the pedestrians are not safe from the outside position of glass structure under blast loading condition. At the time of the blast load, more than 60% chunks of window glass may be
scattered on the outside of glass window or curtain wall. From the analysis of pressure-time wave of blast load, negative pressure phase sustains longer time than a positive pressure phase. This negative pressure creates one kind of the pulling out pressure which increases more glass fragment ejection rate. So, proper researches should be needed on the proper mechanism of negative pressure phase of blast load.

Hooper et al. (2012) [94] used silicon sealant in laminated glass window pane at field blast loading tests and observed that this delayed the progressive failure process.

Among all blast loading related numerical simulations, Jameson-Cook model [95] is considered the most standard and relevant for laminated glass window.

At the moment of the storm/cyclone/tornadoes/hurricanes, a tree trunk or any solid particles may penetrate into the glass window or glass façade and create fatal injury. And this is called “wind born debris”. Several investigations have conducted on the effect of wind born debris on the glass window. “Timber missile test” is considered the standard impact test for such kind of investigations. More inspections should be needed on this special type of field for providing proper guidelines on wind born debris protective glass window or glass façade.

Tympanum damage, lung breakdown, skull cracking or laceration attack are the major fatal injuries whose could be occurred by the scattering of glass splinter. Many techniques have been invented to create blast load protective window glass. One kind of coating is used in the interior surface of the window to restrain the glass fragments after blast load and this is called polyester coating. This is one of the cheapest materials and can be easily installed. The daylight film also uses in the visible portion of the window but not frames or mullion. The rapid and easy installation processes of daylight film reduce the initial labor cost. Wet glazed film is adopted edge to edge portion between glass and frame but skilled people are needed to apply this. Another type of film is adopted in mullions or frame to attach the window glass is called mechanically attached film [97]. It gives better protection from daylight. Cable catch system, catch anchorage system or secondary window system etc. are considered the effective solution for the protection of window glass from blast load.

![Figure 7.6 Pictorial view of the popular blast load protective techniques.](image)

Amadio and Bendon (2012) [98] installed a special type of energy dissipation device between the connection of the main structure and curtain wall in order to release the higher blast load. In this device, steel was supported by a special type of cable in the glazing façade and four hole spider features of the connector were used to make the special kind of joint. This type of
elasto-plastic device is also used in modern days for absorbing or dissipating any kind of energy or resisting the earthquake load and reducing this mid-span deflection. Effect of blast load on glass column, beam or slab must be inspected because there have extreme research gaps. Figure 7.6 defines the pictorial view of the popular blast load protective techniques.

Seismic performance of any structure is considered the lateral load resisting capability of this structure. Such kind of analysis is very important for any kind of structure. At this point of view very limited researches have been conducted on glass beams or columns or glass related any kind of structures.

R.A. Behr et al. (1995) [101] also studied the seismic performance of the storefront wall system of architectural glass. They also tried to find out the performance of serviceability limit state and ultimate limit state.

R.A. Bher (1998) [100] investigated on the seismic performance of the curtain wall of architectural glass. He conducted crescendo tests with annealed, heat-strengthened, fully tempered laminated glass. He also tried to observe the prestressing techniques of glass surface or lamination, wall system types and silicon glazing systems.

El-Dakhakhni et al. (2004) [99] inspected on the seismic behavior of the concrete masonry steel frame with infilled GFRP laminates under displacement control cyclic loading test. They found that such kind of frame can resist the lateral load and out of plane deflection but increase the load carrying capacity. Epoxy resin was used on the outer surface of this specimen. Shear slip, diagonal crack and corner concrete crushing were also observed.

![Test setup for storefront wall system with architectural glass under cyclic load](image)

**Figure 7.7.** Test setup for storefront wall system with architectural glass under cyclic load [101].

More experimented investigations should be needed on the seismic performance of glass structures (all types) in order to fill up the huge information gaps in such area.
7.3. Effect of Fire on Glass Structure

Many researches were conducted on the effect of fire in the window glass. But very few researches were run on the fire performance of glass column, beam or floor. More and more research will be conducted on such kind of components of glass structure.

In general, crack is initiated at 150 °C to 200 °C in the edge of the glass. Then the crack is spread over the whole pane of glass and broken into large pieces.

Mowrer (1998) conducted the large scale fire test on tempered and laminated glass. He found that 16 kWm$^{-2}$ heat flux can create first crack of laminated glass (single unit).

Sheild et al. (2002) [102] tested 6 mm thick float glass in room fire condition and found the initial crack propagation temperature (110 °C).

Russian scientist Roytman (1975) concluded that the overall glass breakage temperature was 300 °C. Actual glass breakage temperature is not predicted in real life because it depends on the glazing unit, thickness and property of glasses.

Manzello et al. (2007) [103] experimented the fire test on tempered glass having 6.3 mm thickness and found that initial fire resistance was 45 min. They also found that the initial fire resistance of 3 mm window glass was 360 °C, 4-6 mm was 450 °C and double glazing unit of 6 mm (each) was 600 °C. On the other hand, dynamic loading tests on glass column or beam have not also conducted ever. Dynamic and fire loading related tests will be conducted in future so that clear estimation could be possible on the seismic and fire behavior of different components of glass structure.

Lancker et al. (2018) [104] used structural silicon (rubber type) adhesive between glass-cold formed steel (C-shaped and tubular shaped) connection to investigate the behavior under static (monolithic) and dynamic (cyclic) loading condition. They inspected overall cyclic response due to mullins effect. But C-shaped steel showed more stiffness under cyclic loading condition. In Belgium (2005), structural silicon glazing façade was used in Covent Garden. And it showed better performance in case of hurricane and high temperature.

7.4. Conclusions

Laminated glass may be a good solution for fire and dynamic issues because its performance is satisfactory to hold glass splinter. It is called safety glass for its safe failure mode. Various special devices are installed in the laminated glass to create more safety factor. So, more investigations should be needed in each and every glass structure related components to sustain more blast, fire, wind-borne debris and cyclic loads. Proper measures should also be taken on this issue.
Chapter VIII

CODE PREDICTED GUIDELINES OF GLASS STRUCTURE

8.1. General

To design any kind of structure, code predicted guidelines must be needed. Safe structural design could be possible with the help of this design guideline. But there is a very limited empirical formula in the design guidelines for the structural use of glass. Two design code related books are followed in Europe. One is “Guidance for European Structural Design of glass components” (Eurocode 2014) and another is “Code of Practice for Structural Use of Glass 2018” (Building department of Hong Kong). So, more detailed design guidelines should be needed to implement glass structure all over the world. Paucity of sufficient research is the main factor for this. So, handsome investments should be needed to conduct good and quality research on glass structure.

8.2. Design Guidelines of Glass Structure

The equation of the basic compressive strength of glass,

\[ f_{ck} = K_{mod} \cdot k_{sp} \cdot f_{kg} \]  (1)

where,

- \( K_{mod} \) is one kind of factor which depends on the load characteristics and varies from 0.29 to 1
- \( k_{sp} \) depends on glass surface characteristics and varies from 0.32 to 0.56
- \( f_{kg} \) depends on the raw materials of glass and varies from 70 MPa to 120 MPa

If the glass pane is simply supported by four side condition then,

the thickness, \( t = 4.87 a^{0.965} b^{0.22} (R/C)^{0.545} \) when \( (b/a) \leq 5 \)  (2)

but when \( (b/a) > 5 \) then

the thickness, \( t = 6.2 a^{1.15} (R/C)^{0.5} \)  (3)

where,

- \( a \) = Small distance of glass pane (m)
- \( b \) = Long distance of glass pane (m)
- \( R \) = Pressure factor which designed for individual glass pane (kPa)
- \( C \) = Strength coefficient varies from 1.0 to 4.0

So, the equation of the deflection of glass pane,

simply supported for four side condition: \( \delta = te^{(r + sx + t(x-x))} \)  (4)

where,

\[ x = \ln \left[ \ln \left( \frac{(Ra^2 b^2)}{(Et^4)} \right) \right] \]  (5)
and simply supported for two-side condition:

\[ \delta = \frac{(5Ra^4)}{(32Et^3)} \]  

where,

\[ \delta = \text{Deflection at centre position (mm)} \]
\[ a = \text{Small distance of glass pane (mm)} \]
\[ b = \text{Long distance of glass pane (mm)} \]
\[ t = \text{Minimum glass pane thickness (mm)} \]
\[ R = \text{Pressure factor which is designed for individual glass pane (kPa)} \]
\[ E = \text{Glass panes modulus of elasticity} \]
\[ r = 0.553 - 3.83(b/a) + 1.11(b/a)^2 - 0.0969(b/a)^3 \]
\[ s = -2.29 + 5.83(b/a) - 2.17(b/a)^2 + 0.2067(b/a)^3 \]
\[ t = 1.485 - 1.908(b/a) + 0.815(b/a)^2 - 0.0822(b/a)^3 \]

Local buckling of glass column can be checked by this equation,

\[ \frac{(Et^3)}{6(1 + \nu)} > M_w \]  

where,

\[ M_w = \text{Glass fins working moment} \]
\[ \nu = \text{poisson’s ratio} \]

The limit of deflection for glass beam or fin might be less than \((L/180)\), where,

\[ L = \text{Span of glass beam or fin} \]

8.3. Conclusions

To find an accurate empirical formula, more and more investigations should be needed. Accurate regression analysis is the first step to obtain good empirical formulas. And if the property changing parameter of any material is chosen correctly which is found from experimental results then the accurate empirical formula will be found through perfect regression analysis. So, it is cleared more expert researchers should be needed in this field to conduct good research on glass structure so that structural engineers could implement this practically without any kind of hesitation.
Chapter IX

PRACTICAL APPLICATIONS OF GLASS STRUCTURES

9.1. General

Glass structure is being very popular day by day due to the aesthetic architectural aspects. It also increases the attractiveness in many tourism places. Proper guidelines and awareness should be needed to apply this practically. At first glass is used structurally or commercially in Europe. Except European zone, this is used occasionally all over the world. So, the practical application of glass structure is described below.

9.2. Practical Applications of Glass Structures

R.O.M. glass house was built in Holland by a reputed structural designing company and having the transparent capability of both sides. 8 feet 3 inch square glass wall was supported by concrete foundation and slab. Steel beam and wood framed roof were used in this structure. 3.5 inch thick toughened glass was used all over the structure.

Figure 9.1. R.O.M glass house in Holland
[Google image].

12.5 feet long glass bridge was constructed between two buildings in the Arnhem town of Netherland in order to exhibit birds. The interesting fact that no steel was used in this bridge and silicon joint is applied as a connection without drilling any kind of hole. 0.75 inch laminated glass wall and roof were used in this bridge. The shape of the roof was created as a circular to prevent rain water logging condition.
A beautiful staircase was installed in the New York branch of Apple. The laminated glass thread was connected to the glass wall. The length of glass thread is 6 feet and the thickness is less than two inch.

Waterloo station in London, a large peripheral building with high glazing walls was installed to give extra compressive sustainability facilities from wind load. A steel truss with ties and struts were also attached to increase the extra rigidity of this structure.
A special type of glass which is called acrylic (polymethylmethacrylate) glass was used in the fish aquarium in the shopping center at Dubai Mall. Small weight and resistance to any kind of fracture are the main advantages of such kind of glass.

In the Ostrava City of Czech Republic, an attractive bus station is situated with two layers of laminated glass roofing. In glass slab of this station, four pin supports with steel ropes were installed. Such type of bus station was also installed in the Hamburg city in Germany. To increase the transparent aesthetic beauty and to protect from wind load, a transparent rib is installed.
perpendicularly to act as a supporting bar in glass wall. Such kind of arrangement is called glass fin. A large transparent glass wall with glass fin is noticed in the Burj Al Arab hotel in Dubai. Figure 9.6 (a) defines the glass roof of the bus station in Ostrava City of Czech Republic. And Figure 9.6 (b) shows the glass fin in the Burj Al Arab hotel in Dubai.

![Figure 9.6](image)

(a)

(b)

**Figure 9.6.** Glass roof and glass fin
[Google image].

Rob Nijsse is the professor of the building construction department in TU Delft University. He was the main pioneer to install the 14 m long glass arch pedestrian bridge in TU Delft campus at Netherland. There interlocking glass cast brick was in the upper portion of the steel girder and the truss type glass column was used under the steel girder which could take excellent compression and transfer the load from grass mat slab to two supports. Many students were marched through this bridge but it took only 50% load of its capacity. The main concept of this bridge was taken from the glass bridge destruction screen from the Thor (2011) movie by hammer. A beautiful
aesthetic two storey concrete-timber framed structure with gorgeous and artful glass wall was built in 2014 near the Lake Biel at Western Switzerland.

In this structure, concrete was used in roof, floor and foundation but timber and glass were used as an outward frame and glazing façade.

Figure 9.7. Glass arch pedestrian bridge in TU Delft campus at Netherlands [105].
Lancker et al. (2018) [106] used structural silicon (rubber type) adhesive between glass-cold formed steel (C-shaped and tubular shaped) connection to investigate the behavior under static (monolithic) and dynamic (cyclic) loading condition. They inspected overall cyclic response due to mullins effect. But C-shaped steel showed more stiffness under cyclic loading condition. In Belgium (2005), structural silicon glazing façade was used in Covent Garden. And it showed better performance in case of hurricane and high temperature. The Iconic Torre Europe Building (120 m) was constructed in Madrid (center capital in Spain) in 1980. Its first renovation work has just finished in 2018. Two structural glass façade was situated at 100° angle to each other and steel canopy was constructed in the upper portion of this building. Vertical glass fin with the laminated glass panel was fixed at the entrance hall of this building where bolted connection was used. The top end of the vertical glass fin was connected to the glass beam where glass façade was adjusted. This laminated safety glass panel (heat strengthened and fully tempered) sustained moderate wind load and snow load. Such kind of mechanism was used in this building. Laminated glass with sentry plus interlayer was used as stiffen glass façade in Montpellier Medical School in France. There titanium plate was used in glass fin to create a bolted connection so that better post breakage behavior could achieve. This is used in seismic zone whose having the ability to resist cyclic load. Prestressing cable rod was also used to stiffen the glass façade.
(a) Virtual view of The Iconic Torre Europe Building

(b) Components of glass façade

(c) Cladding panel installation

(d) Finished glass façade.

**Figure 9.9.** Construction mechanism of The Iconic Torre Europe Building [107].
**Figure 9.10.** Typical glass fin test setup.

**Figure 9.11.** Glass fin installation in Montpellier Medical School in France [108].
Van Gogh Museum (2015) was constructed in Amsterdam. The main architectural design was conducted by Kish Kurokawa and Hans Van Heeswijk. A spheroidal glass-steel composite roof was stiffened by glass fin. Glass fins were constructed of laminated glass with sentry glass plus interlayer and largest one is 9.4 m. The radius of the elliptical shaped glass façade is 11.5 m.

Figure 9.12. Van Gogh Museum in Amsterdam [109].
Figure 9.13. Architectural aspects of “La Maison Des Fondateurs” museum [110].

Figure 9.14. Construction steps of “La Maison Des Fondateurs” museum [106].
Figure 9.15. Climbing in vertical glass according to the Gecko’s mechanism [111].

Spiral glass was used in front and as an important building element in “La Maison Des Fondateurs” museum which was installed in Le Brassus in Switzerland (2013). Actually steel construction was adopted at the center of this glass spiral and a tower crane was used to install this glass.

Gecko is one kind of lizard which length varies from 1.6 to 60 cm but having special abilities in its toes to climb in horizontal and vertical surface of glass. Special types of adhesives were emitted by its toes at the time of climbing. A joint research program was held between Stanford university and Massachusetts institute of technology about the mechanism for climbing vertical glass of gecko [112]. Their aim was to apply this to mankind where humans could climb easily in vertical glass. After many researches a special type of glove was invented to climb vertical glass surface from the analysis of gecko’s climbing mechanism. More investigations should be needed to modify the mechanism of climbing vertical surface of the glass easily. This mechanism is mainly applicable in smooth glass surface but for undulatory surface this type of mechanism should be studied (Figure 9.15).
9.3. Conclusions

The practical application of glass structure has been increased rapidly all over the world. Awareness should be needed in this sector. Cost is the main hindrance for the application of the glass structure. If the proper practice of glass structure is increased then the cost will be decreased.
Chapter X

CONCLUSIONS AND RECOMMENDATIONS

10.1. General Conclusions

Architectural aspects and transparency are considered the main positive sign of the glass structure. But the production of glass is very costly which hampers its large practical implementation. If the demand for the practical application of the glass is increased then the cost will be decreased. Improper practicing of the glass structure may be caused due to the fear, unconsciousness, lower tensile strength, improper ductility, lakes of expert people or research fundings and brittleness behavior. Careful design of the glass structure should be needed. Glass composites (reinforced with other material) are the best solution to increase its compressive strength and ductility. Various glass related industries and different agencies should provide proper funding for conducting glass related research so that glass structure implementation related all problems would be solved. The following conclusions can be drawn within the limited scope of this study:

1. Fully toughened glass retains its strength after 20 years aging effect than other glasses.
2. Laminated glass shows better ductility and safe failure behavior under cyclic, blast or monolithic loading condition.
3. Rectangular cross sectional laminated glass column bears more compressive loads and sustains more flexural buckling
4. Glass bundle column with pre-stressed borosilicate rod increases the ductility, load-carrying capacity, deformability and safe failure behavior.
5. Laminated glass beam with pre-stressed GFRP (Glass fiber reinforced polymer) rod increases its load-carrying capacity and ductility.
6. Glued connection is effective than point supported connection in glass-steel composite structure and having sufficient ductility.
7. Glass-concrete composite beam shows more load-carrying capability, energy dissipation capacity and deformability.

10.2. Recommendations

1. Details investigations should be needed on the effect of seismic, blast and fire on the laminated glass member (column, beam, panel wall, slab etc.)
2. Effective pre-stressing techniques of glass-bundle column and laminated glass beam should be studied.
3. Effect of different types of loading (fire, cyclic, blast, monolithic etc.) must be studied on restrained glass beam or column.
4. More experimental inspections should be needed on glass-concrete, glass-steel and glass-timber composite members.
5. A special type of research proposal on concrete-filled glass tubular column is attached in the appendix portion of this monograph.
References


Zhang, X. and Hao, H., 2015. Experimental and numerical study of boundary and anchorage effect on laminated glass windows under blast loading. Engineering Structures, 90, pp. 96-116


APPENDIX

PROPOSED MODEL FOR CONCRETE FILLED GLASS TUBULAR COLUMN (CFGT)

Figure 10.1. Proposed elevation and cross-section of CFGT column.
Figure 10.2. Proposed experimental setup for concentrically loaded CFGT column.
In this Figure 10.2, strain gauges are proposed to determine the load-strain responses or ductility of CFGT column and LVDTs are proposed to determine axial shortening and out of plane deflection. For determining the eccentric behavior of CFGT column, a knife edge setup could be used. At least having the 5000 kN capacity of the UTM machine of 1mm/min displacement control rate should be maintained. Fire or dynamic responses could be investigated.