# DESIGN OF GLASS STRUCTURES: EFFECTS OF INTERLAYER TYPES ON HEAT-TREATED LAMINATED GLASS

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# ABSTRACT

DESIGN OF GLASS STRUCTURES:
EFFECTS OF INTERLAYER TYPES ON HEAT-TREATED LAMINATED GLASS



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Glass is an inherrently strong and elastic building material that allows the enclosure of spaces to provide both comfort and æsthetic appeal. It is evidently due recognition of these properties that has resulted in the current propensity to use it in ever larger sizes; and then with minimum–if not total absence–of visible supporting structure. It is, however, its lack of plastic behavior under stress–leading to catastrophic failure without warning–that has been the main drawback preventing its use as a structural material on its own. Ergo, the development of composite configurations with plastic interlayers, commonly known as structural glass. Contemporary working methods for glass have also been able to provide better structural characteristics–particularly after heat treatments, which reduce its vulnerability to cracking and brittle failure. In combination, these methods offer designers the possibility of using glass panels capable of acting as load-carrying structural elements.

The aim of this study was to investigate the performance of glass -adhesive-glass composite, or laminated, elements and the use of glass as a structural material in light of their inherent strength properties. Here, an attempt was made to define the be - havior of interlayers in structural glass and to then prepare a selection guide. To this end, it was necessary to first gather information about the materials and design methods used to create glass structures. As the literature notes that such stresses are particularly important to structural glass design due to the inability of the material to flow plastically and to thus relieve high stresses, pertinent simulation techniques (*e.g.*, finite element analysis) were then used to investigate shear transfer between glass panes and interlayers. These simulations allowed determination of stiffness with different types of interlayer for panes of different dimensions and orien - tation in respect to loading conditions. It was the results of these analyses that were finally compiled into the selection guide already noted. It is expected that these results will make a worthwhile contribution to developing glass structure design and its application in practice.

Keywords: structural glass, laminated glass, SentryGlas®Plus, SJ Mepla, selection guide

# ÖZ

CAM YAPILARIN TASARIMI:
ARAKATMAN ÇEŞİTLERİNİN ISISAL İŞLEM GÖRMÜŞ LAMİNE CAMLAR ÜZERİNDEKİ ETKİSİ

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Cam konfor ve estetik sağlamak amacıyla büyük hacimlerin kaplanmasına izin veren önemli bir yapı malzemesidir. Son zamanlarda camın yaygın kullanımı alışılmış taşıyıcı yapıları en aza indirgeme hatta tamamıyla kullanımdan kaldırma eğiliminin bir belirtisi olarak yorumlanabilir. Ancak, diğer yapısal elemanlardan farklı olarak cam aşırı kırılgan bir yapıya sahiptir.

Bu çalışma camın doğal mukavemet özellikleri ışığında cam-ara katman-cam kompozit elemanının performansını ve camın yapısal eleman olarak kullanımını açıklamıştır. Modern yöntemler, özellikle bazı ısısal işlemler cama gelişmiş yapısal özellikler kazandırmakta ve camın çatlamaya karşı hassasiyetini ve kırılganlık özelliğini azaltmaktadır. Bu işlemlere ek olarak cama noktasal delikler açılabilmekte ve cama laminasyon işlemi uygulanabilmektedir. Sözü geçen bu metotlar tasarımcılara cam panelleri yapısal taşıyıcı eleman olarak kullanmasına olanak sağlamaktadır.

Bu çalışma modelleme teknikleri kullanarak yapısal cam elemanlarda kullanılan değişik ara katman çeşitlerinin davranışını açıklamayı ve seçim rehberi hazırlamayı amaçlamıştır. Bu çalışma kapsamında cam yapıları oluşturmak için gereken malzemeler ve tasarım yöntemleri ile ilgili bilgiler bir araya getirilmiştir. Modelleme teknikleri, cam paneller ve ara katmanlar arasındaki kesme kuvveti aktarımını araştırmak için kullanılmıştır. Yazım bölümünde belirtildiği camın yüksek gerilimleri azaltmak için plastik akma yapamaması nedeniyle yapısal cam tasarımında kesme gerilimi önem kazanmakta ve bu nedenle genelde stresin yeniden dağılımının sağlanması amacıyla cam panellerin arasına yapışkan ara katmanlar konulmaktadır. Yapılan modellemeler değişik ölçü ve konumdaki camların farklı ara katman çeşitleri kullanılarak yükleme problemlerinin tahlil edilmesini ve bu çerçevede seçim rehberi hazırlanmasını sağlamıştır. Sonuçların yapısal cam tasarımının gelişimine ve onların uygulamalarına katkıda bulunması beklenmektedir.

Anahtar Sözcükler: yapısal cam elemanlar, lamine cam, SentryGlas®Plus, SJ Mepla, seçim rehberi

To

my parents,

Ayşe and Mükremin Akdeniz,

for their

unwavering support and love.

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# LIST OF ABBREVIATIONS

ABBREVIATIONS

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| CEN | European Committee for Standardization |
| CSI | Construction Specifiers' Institute |
| ENs | European Norms |
| FEM | Finite Element Method |
| GANA | Glass Association of North America |
| ISO | International Organization for Standardization |
| LAG | Laminated architectural glass |
| LSG | Laminated Safety Glass |
| OSCO | Osaka Sheet Glass Company |
| PPG | Pittsburg Plate Glass Company |
| PVB | Polyvinyl Butyral |
| SGP | SentryGlas® Plus |
| TSE | Türk Standartları Enstitüsü (Turkish Standards Institute) |
| UV | Ultraviolet |

# LIST OF NOTATIONS

NOTATIONS

| | |
|---|---|
| $\boldsymbol{\lambda}$ | Coefficient of thermal conduction |
| H | Height |
| v | In-plane displacement |
| L | Length |
| P | Load |
| E | Modulus of Elasticity |
| I | Moment of Inertia |
| $\nu$ | Poissons ratio |
| $\boldsymbol{\lambda_c}$ | Safety ratio |
| G | Shear Modulus |
| $\boldsymbol{\varepsilon}$ | Strains |
| $\boldsymbol{\sigma}$ | Stress |
| $\boldsymbol{\sigma_{allowable}}$ | Maximum allowable surface stress |
| $\boldsymbol{\sigma_{max}}$ | Maximum surface stress |
| $\Delta T$ | Temperature difference |
| $\varphi$ | Torsion angle |

## LIST OF UNITS

UNITS

| | |
|---|---|
| $^{o}C$ | Centigrade Degree Celcius |
| kg | Kilogram |
| $kg/m^2$ | Kilogram per meter square |
| $kg/m^3$ | Kilogram per cubic meter |
| g | Gram |
| $g/cm^3$ | Gram per cubic centimeter |
| m | Meter |
| cm | Centimeter |
| mm | Millimeter |
| min | minute |
| mm/min | millimeter per minute |
| N | Newton |
| kN | Kilo Newton |
| $N/mm^2$ | Newton per square millimeter |
| $N/m^2$ | Newton per square meter |
| $kN/m^2$ | Kilo Newton per square meter |
| $kN/mm^2$ | Kilo Newton per square millimeter |
| $kN/m^3$ | Kilo Newton per cubic meter |
| W/mK | Watt per meter Kelvin |
| Mpa | Mega Pascal |
| µm | Micrometer |

# CHAPTER 1

# INTRODUCTION

In this chapter is first presented the argument for and the objectives of the study, under Sections 1.1 and 1.2, respectively. It continues with Section 1.3, 'Procedure', where a succinct account of the basic steps followed in its conduct is outlined and concludes with a preview of what is embodied in subsequent chapters, under the last section, 1.4, titled, 'Disposition'.

## 1.1 ARGUMENT

Traditionally, the main use of sheet glass has been as infill where, basically, it was only required to resist out-of-pane wind loads, provided these loads –as well as its own weight–were duly carried into the building structure proper by some kind of framing. That is to say, its brittle nature and variable strength were not considered to be significant, the main interest being transparency.

On the other hand, contemporary architects today use more glass than in all previous times combined. While their superficial stand was increasing the level and penetration of natural light in their buildings –particularly with the advent of the open office environment, they were, in fact, simply fascinated by the idea of a transparent building. Ergo, the fully glazed skyscrapers that adorn the skyline of major cities all over the world. In time, not only have the sizes of glass sheet available increased many times over, but the methods of their support have become more and more complex.

In recent years, improvements in production and refining technologies have made the structural use of glass possible and have led to new, innovative and architecturally unique structures and building envelopes. Perhaps more than in the mere practical interest of achieving higher levels of illumination, but simply to enable even more daring designs, much effort has gone into eliminating non-transparent elements from the envelope altogether, so that glass is now being used in self-supporting configurations, again with structural members of glass. In view of the ever-increasing demand for such glass applications, the safety of their design has become a major concern, as glass must now be capable of withstanding long-term in-plane loading. This arises from the fact that glass behaves quite differently when the loading is long-term rather than short-term and transient; also, glass appears to become weaker as the duration of loading increases.

One might ask why glass is used in these new applications if it is a material so un-suitable in structural terms. The simple answer is cost. Glass is mass-produced with ubiquitous raw materials and is therefore one of the cheapest fully-transparent materials available. It is seen that glass is a crucial material if the new transparent architecture is to be welcomed by way of its price.

In materials science, the term "glass" is often used to designate any substance which does not exhibit long-range molecular order. For purposes of this study, however, it has been taken in its ordinary sense, as the commonplace substance used for glazing windows. Soda-lime-silica glass is a solid, non-crystalline, brittle material. Its elasticity is perfectly linear until failure, with a Young's modulus of 70MPa, similar to that of aluminum. Its failure is governed by fracture, which occurs at cracks on its surface. In most cases these cracks are too small to be seen by the naked eye. Owing to variation in the size of the cracks, there is a variation in actual failure stress.

Values for short-term strength range from 20 to 200MPa. Glass also undergoes a loss in strength with duration of loading, commonly referred to as "static fatigue". Its long-term strength depends on a myriad of factors. While it is predominantly affected by surface finish, it is also influenced by glass type, by environmental conditions (especially loading), by production defects and by several other factors of lesser importance. Essentially, the performance of glass is highly predictable under normal operation, but the point at which failure occurs can appear to be a quite random one.

Until recently there was little information publicly available on the structural design of commercial glass. The variability in glass failure strength was demonstrated by Fair (1996), who loaded a series of annealed and heat-toughened beams in bending. Strength variability was also encountered by Wren (1998), who tested cylindrical glass columns. In the traditional uses of glass, the compressive loads encountered are modest and generally similar in magnitude to the tensile stresses likely to be generated. Since glass failure arises at zones of tension, it is therefore tensile stresses, rather than compressive ones, which are critical in design. In the new structural glass applications, greater concentrations of loads are found in compressive members, such as columns.

An M.Sc. thesis by Crompton (1997) reports on a number of design theories and their applicability to glass. Accordingly, existing design methods for steel, concrete or timber structures cannot be applied directly to structural glass elements owing to properties particular to the material itself. Also investigating the matter of alternative load paths this author found that use of more than one member/ply for each structural element had become common practice in glass construction, the underlying reason being to thus provide just such alternative load paths in the event any one single member/ply became subject to brittle failure. The consequences of such failure are other reasons for this added redundancy: Apart from any material loss caused by the failure itself, serious injury could be sustained by occupants from falling or flying shards of glass.

Studied in the investigation by Crompton (1997) was the case of a multi-ply beam with a constant overall width. The same statistically probabilistic strength parameters were applied to each layer in the glass member. It was shown that, as the number of plies increased, the probability of failure under a given load decreased. It was thus concluded that having alternative load paths–as resulting from the discrete plies, provided greater safety in design and was more economical, as the total volume of glass required for any particular stress was actually reduced.

The issue of shear stress is particularly important in structural glass design due to the inability of the glass itself to flow plastically and to thus relieve high stresses; ergo, the benefit of laminated glass–glass with polymer interlayers–in facilitating such stress redistributions. Norville (1997) points out on the basis of published experimental data that the strength of laminated glass under certain conditions equals or exceeds that of monolithic glass having comparable dimensions. Studying interlayer thicknesses, the author asserts that the strength of laminated glass panes increases dramatically with increasing interlayer thickness.

In an experiment on treatment time, Amos (2005) studied temperature defects for different types of interlayer for computing stress development and deflection behavior in laminated glass. In result, it was argued that strength and deflection for bending-dominated cases were dependent on the modulus properties of the polymer interlayer.

Strength performance, characterized by stress development and deformation behavior under specified loading and support conditions was used as a primary design consideration that dictated the final constructional configuration of many laminated glass applications. ASTM has also developed design tables for standard types of interlayer. By the same token, growing demand for laminated glass in building facades has itself spawned research into developing new interlayer compositions that can extend even further the physical performance of such laminates.

It was thus with the foregoing aspects in mind that the scope of the study reported on here was delimited to investigating the overall effect of two interlayer types–one with high yield stress and stiffness properties and the other, with lower values in these respects–on acceptable limits of loading for different orientation of stock float glass sheet. In this, focus was therefore on stress development and deformation behavior in the composite laminate itself, as an integral element. It was also considered worthwhile to formulate dedicated analyses for wall, floor, roof and dome applications in anticipation of potential variation that might arise from such.

## 1.2 OBJECTIVES

While glass demonstrates a certain degree of elasticity under ideal conditions, its inherent brittleness does remain as the crucial problem in structural applications. We must therefore always remind ourselves that glass structures are a step into unknown territory at such time as they are so designed.

The responsibility of designers in regard to user safety is of great concern. Glass, all by itself and as an integral component of the façade system, must be able to perform safely and durably as the sole intermediary between continuously changing outdoor and indoor climatic conditions being kept suitable for the occupants.

In the light of these concerns, the specific objectives of the study were:

1- To compile a precise of existing knowledge on structural glass in general and on interlayer materials in particular.

2- To understand the function and performance of interlayers–structural and otherwise–as used in composing structural glass members within safety limits.

3- To evaluate and classify interlayers and thereby introduce possible design criteria for different structural glass members and/or applications.

4- To establish probabilistic load and resistance models adapted to the material-specific needs for the design of glass structures.

5- To construct design charts for specified laminate combinations considering the probability of glass breakage.

6- To point out, if possible, potential structure-versus-form relationships from both architectural and constructional points of view.

It was finally deemed that results emanating from this study could be put to good use by all parties concerned–from designers and fabricators to contractors, as those done so far appear lacking in the specifics needed for practical application.

## 1.3 PROCEDURE

The study was designed to evaluate two different types of interlayer depending on maximum allowable glass dimensions and parameters by using finite element model analyses. Apart from a literature survey conducted on library databases, several related websites were visited to obtain required background information. Contact with professional firms through interviews and e-mail were other sources for this as well as for the interpretation of results. Descriptive booklets, technical brochures and photos depicting the structural use of glass were gleaned from a variety of professional companies.

Information on structural glass systems and the interlayers used between them was obtained from manufacturing and construction companies and from existing projects using structural glass. While most was downloaded from websites, some were received by post, direct from the manufacturing companies themselves.

After gathering all related documents, whole information was analyzed to explore differences and similarities between stiff interlayer with a high yield stress and less stiffer interlayer with a low yield stress. Both interlayers were analyzed in same predetermined parameters to compare them easily and then possible maximum design options were investigated by the use of both interlayer. Thereafter, whole analyze results were combined in comparison charts.

## 1.4 DISPOSITION

The study is comprised of five chapters. Apart from this, Chapter 1, where its argument, its objectives, its procedure and the disposition of the text following is put forth, presented in Chapter 2 is a summary of the comprehensive literature survey conducted on the subject. This latter includes discussions on treatments, load principles, standards, structural properties and behavior of structural glass and concludes with an overview of design principles.

In Chapter 3 are described the study material and the methodology applied thereto. That is international standards were investigated and they were delimited such as glass thickness, interlayer types, load and support conditions. These data were used as input in the finite element analyses.

The chapter following, Chapter 4, then summarizes the results obtained from the analyses, accompanied by brief discussions on their significance in light of studies and analyses reported in the literature. These included comparisons between soft and rigid interlayers and between different support conditions. Finally, in Chapter 5, are stated the conclusions drawn from the study together with questions considered to be germane for further and future research.

# CHAPTER 2

# SURVEY OF LITERATURE

In this chapter are presented the literature survey about structural glass, its material properties, treatments, adhesives, standards, element types and their des ign methods. This is studied basically under three main topics; glass as a material, structural analysis methods and structural glass elements. General properties and different types of glass used in structural glass production are presented. Its weak and brittle nature is explained. Structural adhesives used for structural application are studied; interlayer properties are examined. Secondly, structural use of glass is investigated; structural glass design methods are described. At the final part structural glass elements are studied regarding their structural properties.

## 2.1 GLASS AS A MATERIAL

Behling & Behling (1999) says that one obvious advantage of glass is its simple constituents, such as sand, soda and potash, which are formed into crystal -clear industrial substances with the application of heat and energy. Since its initial production glass has been transformed into a high -tech product. By making changes to the surface, it can be given many different appearances and technical properties.

### 2.1.1 Glass Substrate

The Osaka Sheet Glass Company (2006) describes glass as a non -crystalline solid subjected to Transformation Phenomenon, called as a super cooled liquid as shown in Figure 2.1.

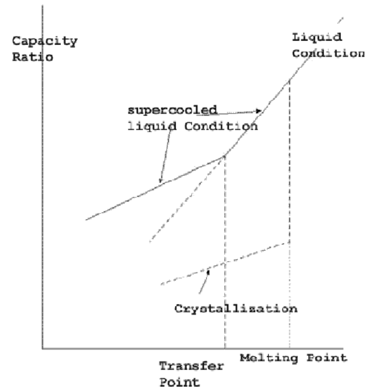



Figure 2.1. Transformation Phenomenon.

*Source: www.osgco.com, 2006*

Likewise, Leitch (2005) claims that glass is a uniform amorphous solid material in which there is not long-range order to the positions of the atoms. This type of atomic structure occurs when a viscous molten material cools to a rigid form without allowing crystallization to form a regular network. Although liquids are characterized by a disordered structure, glass is different from a liquid because its inherent rigidity prevents it from flowing. It is this disordered crystal structure lacking a periodic geometry that makes glass behavior so difficult to study. It is a biologically inactive material that can be formed into smooth and impervious surfaces. It is brittle and will break into sharp ends. These properties can be modified or changed with the addition of other compounds or by heat treatment.

According to Glass-on-web (2006), float glass does not resist to high temperatures, to sudden thermal changes and to corrosive chemicals. Osaka Sheet Glass Company (2006) further emphasizes that *g*lass break without forewarning due to microscopic cracks on its surface. If a cracking force is concentrated to one of those cracks, it grows to break force against the glass. Glass cannot prevent cracks growing since it does not have any boundary like solid structures. Table 2.1 shows mechanical properties of float glass.

Table 2.1. Properties of float glass.

*Source: Renckens, 1998*

| **Properties of Float Glass** | **Values** | **Unit** |
|---|---|---|
| Specific weight | 2,5 | $g/m^3$ |
| Elasticity module at 20 $^0$C | 7,3* $10^4$ | $N/mm^2$ |
| Coefficient of elongation | 6-11* $10^{-6}$ | per $^0$C |
| Coefficient of thermal conduction λ | 0,8 | W/mK |
| Poisson Ratio | 0,22-0,25 | |

### 2.1.2 Strength of Glass

According to Renckens (1998), mechanically, glass is an especially strong material. The high share of silicon oxide is decisive for its hardness and strength; also the brittleness of glass is determined by it. Glass is not subjected to plastic deformation. If the plastic deformation limit is minimally exceeded, the glass breaks spontaneously. There is no alarm mechanism as in metals indicating an excessive strain as shown in Figure 2.2.

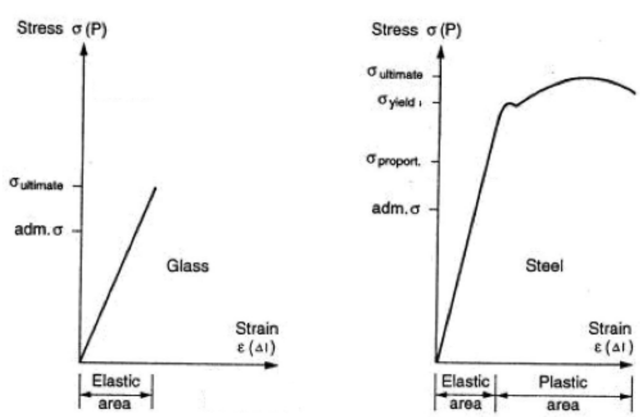



Figure 2.2. Comparison of stress-strain curves of glass and steel.

*Source: Kallioniemi, 1999*

Leitch (2005) points out that on paper; however, glass seems fairly strong, failure usually occurs long before the theoretical value is achieved. Similarly, compressive strength of glass should fall around same value; however, any attempt to measure compressive stress generates tensile stresses, so an accurate representation of actual allowable compressive stress is difficult to obtain. In theory, given it's commonly accepted chemical bonds and the energy it would take to break them, the values for the tensile strength of manufactured glass is much lower than expected.

Renckens (1998) claims that some solid inclusions and bubbles may be found in float glass. The formations of these are important because faults may form in glass plate at bubble and inclusion boundaries.

Leitch (2005) also explains a theory that if glass inherently flawed by minuscule defects and any force is applied, that lead breaking of the inter-atomic bonds, then generating cracks lead to failure. According to A.A. Griffith, these minute defects result from particles of dust and moisture contaminating the surface, the more Griffith flaws, and the more failure of glass. The variability of Griffith flaws in each sheet of glass makes it nearly impossible to determine the exact strength of single pieces. By performing stress and breakage tests on an established size of glass, the results produced by the samples set the value, which can be used as measurement level for the failure point. However, this is nor foolproof, since it is impossible to achieve 100% survival rate for every piece of glass. At best, one can achieve a level of low risk and a high percent of confidence in the survival rate.

Leitch (2005) further says that glass is also subjected to static fatigue. Glass may be strong enough to endure stress for a brief period; however, failure will definitely occur if the stress is applied for a long period of time. This pressure would build up around any of the glass's defects, perhaps a single crack or multiple Griffith flaws that weakened the inter-atomic bond, until the strain causes the glass to fail. It is interesting to note that glass can actually withstand applied loads, at twice the rate of long-term loads it would take to cause failure.

In this regard, Renckens (1998) further claims that , although glass appears “fragile”, its resistance may withstand loads such as gusty winds, and pedestrian traffic. Historically, the inherent flaws governed its limited use as a structural element. Today, however, several processes compensate for the negative impacts of surface integrity, and produce glass that is as strong as conventional building material.

### 2.1.3 Strengthening of Glass

According to the Glass web site (2006), the rate of cooling directly affects the strength of glass. The regular process of cooling or annealing float glass results in a slow rate. Stronger glass can be produced by changing the rate of cooling.

Renckens (1998) also states that if a glas s panel is bent, tensile stress occurs at the “elongated” side, and compressive strain on the “shortened” side. In the case of too high tensile stress, glass breaks. A possibility to increase stress capacity of a glass pane is the application of a pressure area on both exterior sides of the glass pane. In case of deformation, tensile stress up to the degree of pre -stressing will then be compensated for by the already present compressive strength. The strains become stronger on the compressed side. This proc ess of applying compressive strains is called pre-stressing of glass. Stress distribution in a float glass after thermal pre - stressing is shown in Figure 2.3.

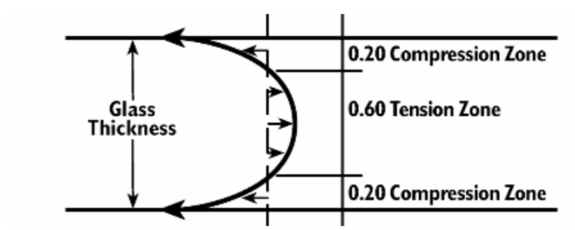



Figure 2.3. Stress distributions in a float glass pane after thermal pre -stressing.

*Source: Guardian Glass Company, 2007*

Moreover, Leitch (2005) states that to improve the safety and strength performance of structural glass, there are four primary processes that can be conducted following basic manufacturing: annealing, tempering, heat-strengthening, and laminating. Although each of these processes has contributed to the advancement of structural glass, lamination is the most significant. According to Glass Association of Nort h America, characteristics of glass can be compared in the table follows:

Table 2.2. Comparison of glass characteristics.

*Source: Specifiers Guide to Architectural Glass, 2005*

| Performance Characteristic | Monolithic Annealed | Heat-Strengthened | Fully Tempered | Laminated Annealed | Laminated Heat-Strenthened | Laminated Fully Tempered |
|---|---|---|---|---|---|---|
| **Wind-loading strength** | Basic Glass Strength (1x) | Two times basic glass strength of the same thickness (2x) | Two times basic glass strength of the same thickness (4x) | %75- %100 as strong as monolithic annealed of the same thickness | Almost twice strong as laminated annealed of the same thickness (1.5x-1.8x) | Almost four times strong as laminated annealed of the same thickness (3x-3.6x) |
| **Thermal stress breakage resistance (edge-strength)** | Low resistance to high thermal stresses | Resists high thermal stresses | Resists high thermal stresses | Low resistance to high thermal stresses | Resists high thermal stresses | Resists high thermal stresses |
| **Break pattern upon impact** | Many Cracks forming large, long and narrow shards | Simple, few cracks and larger pieces | Entire lite breaks into small, irregular shaped fragments. | Starburst pattern from impact point, one or both lites may break | Simple, few cracks and larger pieces, one or both lites my break | One or two lites may break into small, irregular shaped fragments. |
| **Penetration resistance (after breakage)** | Limited after breakage | Limited after breakage | None after breakage | Good resistance (proportional to interlayer thickness) | Good resistance (proportional to interlayer thickness) | Good resistance (proportional to interlayer thickness) |

### 2.1.3.1 Annealed Glass

The Wikipedia Encyclopedia (2006) defines annealed glass as glass without internal stresses caused by heat treatment (*i.e.* toughening or heat strengthening). Glass becomes annealed if it becomes heated above a transition point and then allowed to cool slowly. Thus glass made using the float glass process is annealed by the process of manufacture.

In this regard, Leitch (2005) claims that annealed glass behaves perfect elastically until brittle fracture. Fracture can result from impact, bending stress, thermal stress, and imposed strains. When and where it fractures also depend on the flaws in the glass that could be inherent, or resulted from cutting, grinding or drilling.

#### 2.1.3.2 Heat-Toughened Glass

The Wikipedia Encyclopedia (2006) states that tempered glass, heat-toughened glass, is a type of safety glass that has increased strength and will usually shatter in small, square pieces when broken. It is used when strength, thermal resistance and safety are important considerations. Although toughened glass is most susceptible to breakage via edge damage, breakage can also occur from impacts at th e centre of the glass pane.

According to Renckens (1998), the maximum admissible bending/ tensile stress of this type of glass is approximately 200 $N/mm^2$. In practical, a permissible bending/ tensile stress of 50 $N/mm^2$ is accepted which globally correspo nds to one quarter of the mean tension at the collapse of glass.

#### 2.1.3.3 Heat-Strengthened Glass

Renckens (1998) also argues that if glass must be pre-stressed only in order to intercept thermal tensions resulting from partial shading and heat built -up from solar loading, it is heat strengthening, semi-pre-stressing. The glass is cooled less quickly than during full thermal pre-stressing. The maximum admissible bending/ tensile stress thus are 2 to 2.5 times higher than annealed glass, sufficient to avoi d thermal fracture, and amounts to approximately 100 N/mm2. Practical work is done with a permissible bending/ tensile stress of 30 N/mm2

Moreover, The Wikipedia Encyclopedia (2006) claims that heat-strengthened glass, is glass that has been heat treated to induce surface compression, but not to the extent of causing it to "dice" on breaking in the manner of tempered glass. On breaking, heat-strengthened glass breaks into sharp pieces that are typically somewhat smaller than those found on breaking annealed glass, and is intermediate in strength between annealed and toughened glass.

Renckens (1998) further states that by semi-pre-stressing the glass, the maximum admissible bending/tensile stress of glass is greatly determined by the quality of the glass edges. Thermal tensions are higher there, and small damages, by inaccurate cutting or unprofessional storage, may induce thermal fracture. Pre-stressed glass must have been submitted to all kinds of mechanical processing beforehand (drilling, grinding). After the process this is no longer possible since glass pane would break into fragments at contact with the interior area which is subject to tensile stress.

#### 2.1.3.4 Laminated Glass

The Glass web-site (2006) points out that being a type of safety glass, laminated glass is held in place by an interlayer, typically of PVB (Polyvinyl Butyral) between two or more layers of glass, in the event of breakage. The interlayer's high strength prevents the glass from breaking up into large sharp pieces. This produces a characteristic "spider web" cracking pattern when the impact is not enough to pierce the glass completely. Laminated glass is normally used when there is a possibility of human impact or where the glass could fall if shattered.

**Laminated Glass Standards**

Savineau (1999) claims that laminated glass test methods and performance requirements are relatively well known in Europe and USA. It is manufactured according to standards.

According to Mortelmans (2002), the level and durability of adhesion between PVB interlayer and glass determine largely the performance of the laminate. CEN-TC129 National Building Codes are in place but the determination of laminated glass thickness varies strongly from one country to another. This is the result of the different glass strength factors used to calculate the so called “equivalent thickness”. However the forthcoming European Standards will clarify and standardize the approach. Three essential documents -Design of glass panes – are circulating for enquiry: draft prEN 13474-1 gives a general basis for the design of glass panes, draft prEN 13474-2 specifies a method to calculate the thickness of flat glass panes required to resist uniformly distributed actions (*e.g.* self-weight, wind and snow loads) acting normal to the glass pane, draft prEN 13474-3 design for line and concentrated loads.

**Interlayer Types**

According to Bennison (2006), architectural laminated glass is dominated by the use of PVB interlayers. This ascendancy can be traced to the over 60 years, successful history of PVB use in the automotive industry for laminated safety glass windshields. Although many requirements for automotive laminates and architectural laminates are the same, there are notable differences. The demands of performance longevity for architectural applications generally exceed those needed for automotive applications. If we relax the need for post-glass breakage compliance (softness) and scrutinize the performance needs for architectural applications, we quickly realize that polymers with enhanced structural, temperature and durability performance are attractive for architectural applications.

**a) *Polyvinyl Butyral (PVB)***

Leitch (2005) claims that with a perfect cohesion of the glass layers, PVB laminated glass achieve the transparency, durability, and scratch resistance of standard float glass. Currently, Germany is one nation that does not permit design using the composite behavior of laminated glass, meaning that a member composed of separate panes bonded by PVB should not be considered to have the same behavior as a single member of glass of equivalent dimensions. This is primarily due to the lack of understanding of shear transfer between glass panes. However, it is responsible for the shear transfer and the intrinsic adhesion level of it can vary depending on type. PVB producers offer it with low/medium/high adhesion level. Moisture content of it is a key element for adhesion and impact performance of the laminate.

Leitch (2005) asserts that the behavior of PVB depends on the load duration and the temperature, with secondary effects stemming from thickness of the foil and buckling length of the member as shown in Figure 2.4. Thus, the shear modulus becomes the critical factor when determining the design strength of a composite laminated member. Research by Albrecht *et al* discovered that the aging process aided by UV light and humidity also produces an effect on the shear modulus of PVB. This study showed the current importance of investigating laminated members using a finite element analysis that links the deformation of individual panes, using the properties of PVB.

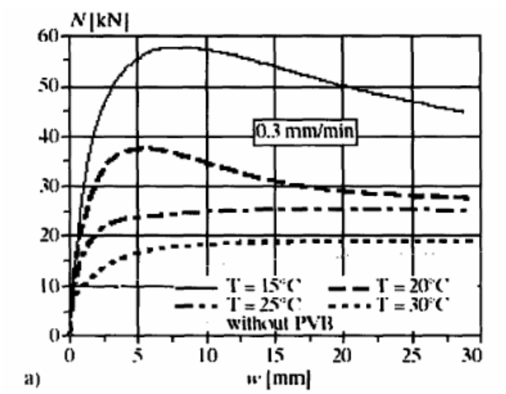



Figure 2.4. Load carrying behavior of Laminated Safety Glass.

(L=800mm, 8mm/, 1,52mm/8mm) under different tempe ratures.

*Source: Leitch, 2005*

Accordingly, monolithic behavior can be described as a member acting with the dimensions corresponding to the thickness of the glass panes and the thickness of the PVB interlayer. A laminated glass assembly behaves more like a monolithic glass member when experiencing short duration loading at low temperatures. Figure 2.5 illustrates the shear modulus of PVB depending on temperature and time.

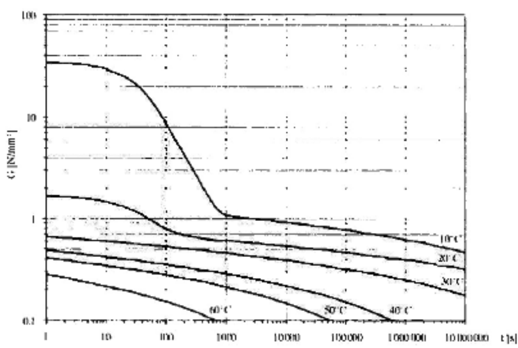
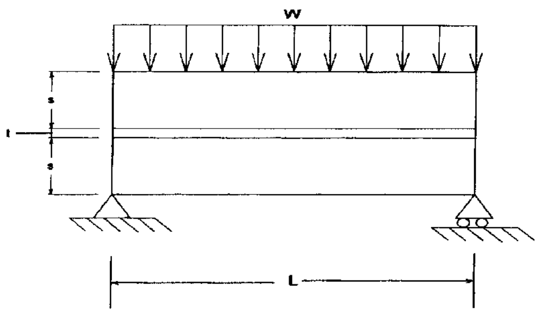



Figure 2.5.Shear modulus, G, of PVB depending on temperature and time.

*Source: Leitch, 2005*

According to Norville (1997), the thicker interlayer accounts for the increase in strength. He advanced a theoretical beam model based on engineering mechanics. His model explains the role of PVB interlayer in laminated glass bending under uniform loading. The laminated glass beam in Figure 2.6 is made from two glass panes each having thickness s, and a PVB interlayer having thickness t. In a laminated glass beam, the flexural behavior of the PVB near the middle surface of the beam becomes insignificant. The PVB serves only two functions. It maintains the spacing and transfers some portion of the horizontal shear force between the glass plies. The percentage of horizontal shear force that the PVB transfers varies principally as a function of temperature. Figure 2.7 shows the flexural stress distribution at a section of the laminated glass beam in Figure 2.6.



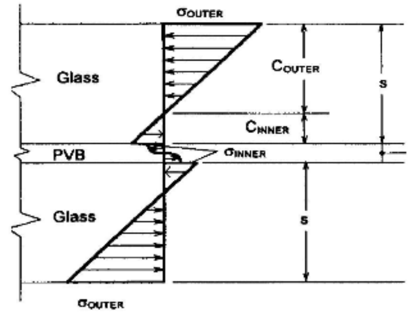




Figure 2.6. Laminated glass beam.

Figure 2.7. Flexural stress distributions in laminated glass panes.

*Source: Norville, 1997*

Norville (1997) concluded the results of experiments as the effective section modulus provides a measure of the strength of a laminated glass beam. As the effective section modulus increases, the strength of the laminated glass beam also increases. Two factors affect the strength of laminated glass beam: the ability to transfer horizontal shear force and the thickness of the interlayer.

In addition to Norville (1999), Amos (2005) also asserts that key to the accurate structural analysis of laminates is adequate characterization of the time -temperature nature of polymer interlayers. Particular emphasis is placed on how to treat time and temperature effects on strength and how different types of interlayer affect the performance of the laminated glass. He displays stiffness properties of the type of PVB (Butacite) interlayer in Table 2.2. These values represent the end point states after relaxation at the temperature and load duration.

Amos (2005) further explains that strength and deflection for a bending -dominated case are dependent on the modulus properties of the polymer interlayer. Enhanced structural performance can be achieved with the use of stiffer and stronger interlayer like SentryGlas® Plus interlayer.

Table 2.3. Stiffness properties of PVB (Butacite®).

*Source: Amos, 2005*

| Property | Temperature | Load Duration | Shear Modulus | Poisson Ratio |
|---|---|---|---|---|
| **Butacite** | 30 C | 3 second | 0,971 | 0,4998 |
| | 30 C | 1 month | 0,069 | 0,5 |
| | 30 C | > 1 year | 0,052 | 0,5 |
| | 50 C | 3 second | 0,44 | 0,4999 |
| | 50 C | 1 month | 0,052 | 0,5 |
| | 50 C | > 1 year | 0,052 | 0,5 |

**b)** ***Structural non-PVB interlayer/ SentryGlas® Plus***

In his assay Bennison (2006) introduces SGP (SentryGlas® Plus) as follows;

It is based on a different chemistry to PVB and has been developed from a class of DuPont proprietary polymers. The performance limits for PVB-based laminated glass are generally well known and in some cases they are defined clearly in national standards. For example, ASTM E1300-04 uses design charts to map the strength of laminates under wind load. The charts show that for short-duration loading up to 50ºC in four-side supports. However, where support is less than four sides, PVB laminates are weaker than equivalent monoliths. High temperatures and long duration loads challenge the load transfer of the PVB interlayer resulting on sub-monolithic performance. Invariably, design solutions require the use of thick glass to compensate for the lack of load transfer across the PVB interlayer .

According to the brochures of the DuPont:

SGP is 100 times stiffer and 5 times stronger than traditional interlayers, helping thinner laminates meet specified wind loads or structural requirements. It has low mechanical strain under loads, and outstanding post-breakage resistance to creep and collapse. Glass constructions can be designed with thinner glass when using it.

Accordingly, upon impact, the glass may break, but dangerous fragments will adhere to the SGP interlayer, reducing the risk of injury and fallout by use of its post -glass breakage performance. Moreover, curvature in panes of glass can be detrimental in many constructions. SGP laminates show less deflection for many different types of supported glass configurations. In addition to them, laminated glass made with SGP tolerates high stress loads. The interlayer becomes a higher performing structural layer in the multilayer composite. The physical properties of the SGP are shown in Table 2.4 and 2.5 respectively.

Table 2.4. Properties of SGP.

*Source: SentryGlas® Plus Introduction Brochure, 2005*

| **Property** | **Units Metric** | **Value** | **ASTM Test** |
|---|---|---|---|
| Young's Modulus | Mpa | 300 | D5026 |
| Tensile Strenght | Mpa | 34.5 | D638 |
| Elongation | % | 400 | D638 |
| Density | $g/cm^3$ | 0.95 | D792 |
| Flex Modulus 23 $^0$C (78$^0$F) | Mpa | 345 | D790 |
| Heat Deflection Temperature at 0.46 Mpa | $^0$C | 43 | D648 |
| Coefficient of Thermal Expansion (-20 $^0$C to 32 $^0$C) | - | 10-15 x $10^{-5}$ /C$^0$ | D696 |

Table 2.5. Stiffness properties of SGP.

*Source: Amos, 2005*

| **Property** | **Temperature** | **Load Duration** | **Shear Modulus** | **Poisson Ratio** |
|---|---|---|---|---|
| **SentryGlas® Plus** | 30 C | 3 second | 65,7 | 0,484 |
| | 30 C | 1 month | 3,1 | 0,499 |
| | 30 C | > 1 year | 2,9 | 0,499 |
| | 50 C | 3 second | 7,1 | 0,498 |
| | 50 C | 1 month | 2 | 0,5 |
| | 50 C | > 1 year | 2 | 0,5 |

Laminating procedures for SGP are similar to those for more conventional materials. Differences in handling and processing of SGP relate mainly to its supplied form cut sheets instead of wound rolls and it does not need refrigerated sto rage. SGP can be laminated using existing manufacturing lines and equipment. Available maximum sizes are 2540mm x 4724mm and thicknesses are 1.52mm, 2,28mm and 2.54mm.

## 2.2 SRUCTURAL ANALYSIS METHODS

Under this title, was a brief literature survey given on structural analyses methods of glass through references from selected sources. Due to the fact that simulation methods provide better capabilities to professionals, documentation on simulation methods was also presented.

### 2.2.1 Structural Design Methods

Heyder (2006) says that structural glass defines not only modernity, but also value, richness and "future technology". However, the knowledge about technological properties and proven construction details are less than for any other modern building material.

The author asserts his studies as “Glass can always break, even if designed properly. Glass structures must be designed redundantly, so if one glass part breaks, the rest of the structure either steel or glass parts will still be safe, with reduced level of safety. Redundancy is assessed by means of analysis, but mostly by experiments. Since glass is typically used as plates with linear or punctual supports, bending moments and support reactions are obtained by using simple FEA programs with plate elements or by literature with tabulated values for plates. The approach with the linear-elastic theory, Kirchhoff-theory, is used because it’s at safe side. Deflections more than plate thickness indicate the limit of that theory. Thus the nonlinear calculation is yield lower stresses shown in Figure 2.8.”

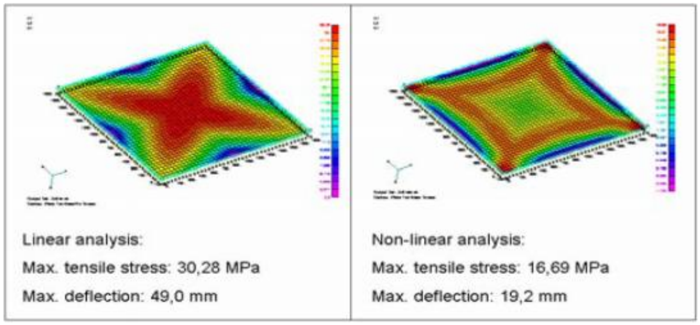



Figure 2.8. Difference for the results in case linear and nonlinear calculation for an example of a glass pane a/b=2000/2000mm, t=2x6mm, p=2,0 kN/m $^2$.

*Source: Siebert, 2005*

Heyder (2006) further writes that for the allowable stress approach the forces and bending moments need no load factors included. FEM programs give the stresses in both direction and the principal stresses. Due to glass crack mechanism, the principal tension stress will lead to the crack, so this maximum value ought to be compared with the allowable stress. Although there is currently no code of practice for structural glass, the following values for maximum allowable stresses include global safety factor of 2.4 against 5%-quantil value for breaking are shown in table 2.6.

Table 2.6. Maximum allowable stresses.

*Source: Heyder, 2006*

| **Glass** | **Allowable Stress** | **Comment** |
|---|---|---|
| Tempered Glass/ ESG | 50 N/mm2 | also in laminated glass |
| Tempered Glass/ ESG | 30 N/mm2 | if imprinted at tension side |
| Heat-Strength Glass/ TVG | 37 N/mm2 | also in laminated glass |
| Heat Strength Glass/ TVG | 18 N/mm2 | if imprinted at tension side |
| Float Vertical | 18 N/mm2 | slope up to 10 to the vertical |
| Float Horizontal | 0 N/mm2 | in overhead glazing forbidden |
| Float Horizontal in Insulating Glass | 12 N/mm2 | only applicable for upper glass, the lower glass must be a laminated glass |

The author further asserts as follows:

"Experiments have shown that in-plane stresses lead earlier to failure than plate stresses due to bending, so for the maximum allowable stress for in-plane loads, shear panel loads, 90% of the values above should be taken. Punctual fittings consider much more detailing knowledge. The common way is to test the actual fitting type with the glass type and find experimentally the maximum break load.

Deflection of glass is limited to 1/100 ... 1/200 of span. Actually, in terms of breaking the deflection does not matter at all, due to the low Young's modulus of glass that lets to bend astonishingly wide before breaking. More important is the deflection of the steel substructure of the glass. The allowable substructure movement can be checked by FEM analysis as well.

### 2.2.2 Use of Finite Element Method for Glass

Finite element method is used for design and static of glass panes with various support conditions and under various types of loading in the engineering practice. Low tensile strength with high variability and decreasing strength with increasing size, duration of load and age of the glass characterize the inherent nature of glass strength. Many researchers have explained this inherent nature by the existence of microscopic flaws in the surface of the glass. It is difficult to predict the strength of glass panels, not only due to the nature of the glass itself, but also due to the fact that when glass panels are subjected to high loads, the relationship between the applied loads and the resulting stresses becomes non-linear.

Sophisticated computer programs are enabling a solution of the problem to be obtained. These programs are used to calculate the stresses over the surface of the glass panels and then a Weibull probability distribution is used, to approximate the variability of glass breakage data and to predict the probability of breakage of the glass panels at a given load. SJ MEPLA is a program for design and static of multi layered sandwich plates.

Bohmann & Bohmann describes SJ MEPLA program as folows:

"All inputs, like the geometry, the boundary conditions, the kind of loading, the calculation approach or the requested output, are guided and displayed by input masks. The control and output of the results occurs visually on a graphics surface and a calculation protocol which can be used for the static assessment.

Finite element methods allow the simple input and quick calculation of sandwich plates, *e.g.* laminated glass. Thus the program is suited for dimensioning as well as for assessment purposes, by use of various calculation possibilities; automated mesh generation for the general basic forms. All subsequent calculations can be made linear or non-linear. Any sandwich structure, e.g. laminated safety glass, can be calculated considering the stiffness of the compound material only by defining the thickness and the order of layers. Support conditions are springs in any direction, pre-defined edge supports, elastic edge and line supports, elastic base, reinforcing edge beams, spacers within insulation glass units and point fixings.

Load conditions are face loads, dead weight in any direction, concentrated loads, line loads, point loads, climatic loads, temperature loads within the panes, and all these loads can be combined. The program gives pressure hits, wind -and detonation blasts, calculation protocol of all input and outputs, curve diagram of force, displacement and stress distribution during impact for each pre-defined positions.

Manifold evaluation possibilities within the graphics surface are: stresses across the plate thickness and layer order at any point, output of all stress components, display of the spring forces, vector-plot of the principal stresses and colored displacements"

## 2.3 STRUCURAL GLASS ELEMENTS

Behling & Behling (1999) explain that a number of glazing systems are suitable for use in façade construction. Nowadays, glass buildings that are as transparent as possible are once again in vogue. Therefore, modern façade systems reflect this desire to achieve maximum transparency by reducing the non-transparent bearing structure. Further dematerialization is possible when glass itself assumes bearing functions and is even used in supporting mullions or beams. In this section are presented basic structural glass elements under five titles in the light of their definitions, strength and stability considerations and examples. Further experiments are presented to express their specific design considerations.

### 2.3.1 Glass Beams and Fins

**Definition**

Glass beam members are usually simply supported or cantilevered and the span of glass beams are limited to the length that a single piece of glass can be manufactured, In some cases, glass beams can be assembled from shorter members to extend past these lengths.

Leitch (2005) claims that glass fins like glass beams are thin load bearing members made of glass. They are vertical or sloping beams used to support facades and to help resist wind and other lateral loads. Fins are assumed to be loaded in bending. The primary difference between fins and beams is the inherent difficulty forming joints with fins that carry sustained bending moments, particularly in laminated glass. Fins are not generally limited by the length of glass that can be produced, and are often spliced together using friction-grip connections to achieve the desired height. The material “gripping” the glass fins must be enough not to cause stress concentrations on the glass, and must be elastic enough to accommodate possible differential thermal behavior between the glass and the splice plates.

**Beam Strength**

Leitch (2005) further claims that glass beams and fins should be designed to sustain minimal tensile stress. Tensile stress promotes the gradual propagation of cracks due to microscopic flaws. Most glass beams are designed with substantial redundancy, or are designed so that steel cables carry the tensile loads putting the glass in compression. Tensile loads imposed on the structure usually result from short-duration wind gusts, vibration, or deflection. Any material imperfection dramatically reduces the beam's capacity to endure tensile loads. Thus, glass beams must be designed for low levels of stress, deflection is rarely problematic.

**Elastic Stability**

Accordingly, all thin structural members can become unstable if not adequately braced. For example, a glass façade provides some rigidity and rotational restraint for the glass fins affixed to it. This relationship makes instability failure less probable. Rotational restraint is essential to prevent buckling of many columns, fins and beams. A finite element analysis is preferable for the design of a glass wall supported by glass fins. Local buckling should be investigated in addition to the buckling of the free edge.

Belis & Impe (2006) also explains that the failure mechanism that is usually described is brittle fracture due to exaggerated tensile stresses. These stresses are induced by simple bending along the strong axis, so the beam is supposed to deform only in its own plane. Due to the slenderness of the rectangular cross-section, however, the potential risk of a more critical second failure mechanism increases. This mechanism is based on instability, in particular on lateral torsional buckling.

In favor of general comprehensibility, lateral torsional buckling is briefly illustrated in Figure 2.9, in which the combined action of out-of-plane displacement u, in-plane displacement v and torsion angle φ due to a post-critical in-plane load P is indicated.

Lateral torsional buckling can be the factor that limits the load-bearing capacity instead of fracture due to in-plane bending. Precautions in order to prevent lateral torsional buckling are lateral supports provided along the length of the beam, excluding any out-of- plane movement.

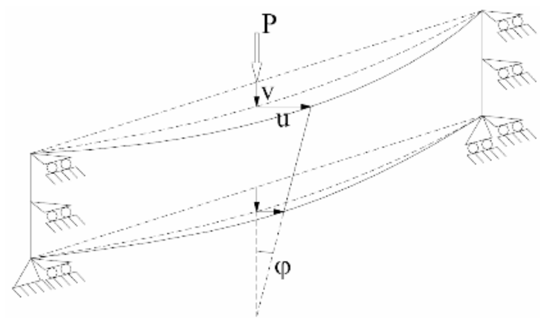



Figure 2.9. Principle of lateral torsional buckling.

*Source: Belis & Impe, 2006*

Belis & Impe (2006) further explains that in the numerical analysis, the amplitude of the half sinusoidal wave is L/400, where L represents the length of the beam. For simple float glass, the initial shape imperfections should be considered of Span/333, according to the value of overall bow found in EN 572-2.

The author further asserts that the parameter that influences the buckling load most is the visco-elastic behavior of the interlayer. For short-term loadings, the PVB is able to increase the overall buckling resistance considerably. At long-term loadings or higher temperatures, however, the gain in torsional stiffness and moment of inertia around the weak axis, which could be expected from the application of the adhesive interlayer, disappears. The study of the initial shape imperfection showed that overall bow will cause out-of-plane displacements very quickly, which penalties the overall load-bearing capacity of the glass beam. Lateral torsional buckling instead of strength seems to be the failure mechanism for beams with a slender cross-sections and a long span in case they are composed of thermally treated glass. Depending on the beam's geometry, even float glass beams can fail due to buckling.

**Examples**

The elongated Sainsbury Centre for Visual Arts building in Norwich, Engla nd, constructed by Foster and Partners in 1974 -1978, is enclosed by two 30 m x 7, 5 m glazing. They consist of 2.4 m x 7.5 m toughened panes that are stiffened by glass fins with a width of 60cm as illustrated in Figure 2.1 0.

Figure 2.10. Sainsbury Centre for Visual Arts, Norwich, 1978.
*Source: www.fosterandpartners.com , 2007*

The successful usage of glass fins for wind bracing resulted in the idea of also using them as supports or beams. In 1993, arc hitects J. Brunet and E. Saunier constructed a roof glazing with glass beams for the shops in the Musee du Louvre, Paris. For the 4 m x 16 meter roof glazing, laminated panes supported by laminated beams were used as shown in Figure 2.11. The material beha vior was examined in comprehensive elements. The elements showed that the glass beams can be loaded with 12.2 to 14 tons instead of the previously estimated 5 tons.

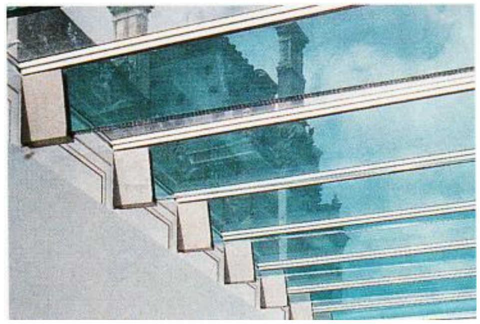


Figure 2.11. Shops in the Musee du Louvre, Paris, 1993.
*Source: Behling & Behling, 1999*

### 2.3.2 Glass Columns

Architects and clients do not like columns; they stand in the way and they block the view. Architects ask the columns to be made as small as possible. On the contrary, structural engineers reduce the span of beams and floors, and mak e structures less complicated. Another way to make columns more attractive and less repulsive to architects would be to make them out of glass.

#### Column Strength

Leitch (2005) claims that although glass performs well under compression; there is a danger of buckling, which makes it hard to conceive a safe glass column. Buckling will result in tensile stresses and the miniature cracks will play their spoilsport role. If one part fails for whatever reason, the remaining parts must still be able to carry the load so that the damaged element can be replaced.

The author further claims that the general design principles for glass columns are similar to those for other not reinforced piers or walls. The applied load, however, must be carefully distributed into the glass column in a way that localized areas of concentrated stress do not develop a brittle failure. The edges of the glass panels have to be ground with chamfers to avoid stress concentrations at the edges that cause premature failure of the glass column. Structural elements have to be doubled, tripled or more. Similar caution must be exercised when introducing load into laminated glass columns. It is common for the panes of glass to line up somewhat unevenly at the edges, creating non-homogenous load transfer into the layers of the glass. To ensure structural participation from all layers of glass, steel shoes should be used to support the glass.

Accordingly, when a load is applied, a column resists and responds by deforming and developing internal and edge stresses. Glass under increasing axial compression will deform elastically until experiencing sudden failure by elastic instability. It is important to minimize exposure of a column to endue impact or abrasion by locating it in sheltered location. It is advisable to make a column using toughened, pre-compressed glass, even though it may seem counterintuitive to add additional axial force to a compressive member. The pre-compression serves to reduce the "out-of-straightness" effects of unanticipated lateral load by keeping the glass surface in compression. There are instances where annealed glass is used in lieu of toughened glass, but in such cases, protective laminations must be adhered to either side of the glass compression member. Not only will the additional laminations protect the internal layer, but they also increase the bending stiffness and increase the degree of redundancy.

**Elastic Stability**

Leitch (2005) further claims that there are three ways in which columns can collapse. The first one is by crumbling, slowly yielding under too big a compression load. The second is by buckling, by sudden breaking in the middle. This case is most of the times the critical one. The third is by breaking due to shear force; sliding along each other. Like glass fins, glass columns are most likely to fail due to lack of stability, which includes column buckling and lateral torsional buckling. Buckling tests performed on laminated glass compression members show visco-elastic buckling behavior. Concepts of Eular buckling are applicable for pinned, axially loaded members in compression; however, a safety factor must be applied.

The author further explains that columns be designed to withstand shear and bending forces in addition to axial loads. Under these conditions, the columns act like a beam or fin and consequently are designed as such. Despite the column dimensions, the column should not be subjected to excessive compressive stress, since it will fall first along a shear plane instead of a crushing mechanism. The critical load that would induce loss of stability, or bifurcation, splitting into two parts, buckling, can never be attained in practical applications due to inherent material flaws that reduce the member capacity. The most significant factors influencing load capacity include, glass thickness, initial geometric deformation, visco-elastic PVB, and the breakage stress of glass.

**Deflection**

According to Institute of Structural Engineers (1999), the high modulus of elasticity, the lack of creep and shrinkage, and the low working stresses that indicate axial shortening should not be an issue. Glass has a modulus of elasticity comparable to that aluminum, and greater than those of timber and concrete. The Institute goes on to say that lateral deflection of columns is not usually a major consideration unless the sway of an entire building storey is being considered.

**Examples**

A spectacular application of glass supports is presented in the glass roof of the central courtyard of the community administration building in Saint-German-en-Laye, Figure 2.12, constructed by architects J. Brunet and E. Saunier in 1994. The 24 m x 24 m roof glazing consists of supporting steel work made of steel profiles holding the roof glazing on spacers. This glass roof is carried by cross-shaped 22 cm x 22 cm glass supports consisting of laminated fins with three toughened panes. The cross-shaped supports, approved for a load of 6 tons, but calculated for 50 tons; represent a world's first in glass construction.

Figure 2.12. Administration building in Saint-German-en-Laye, Paris, 1994.
*Source: www.brunet-saunier.com , 2007*

**Further Experiments**

Veer (1999) claims that, although transparent columns exist, these are either made of flat glass resulting in architecturally undesirable and mechanically inefficient shapes. The most efficient shape for a column is a tubular member. During the development of a transparent column; the concentric tubes are put in a special holder that keeps them equidistant along their whole axis. The space between the tubes is filled with a specially developed UV curing resin.

The author further asserts that, columns which are sufficiently short, or rigidly clamped, to avoid buckling, fail by gradual fragmentation from the base. The columns deform spreading out like a mushroom while still carrying the full maximum load as shown in Figure 2.13 Tested prototypes of length 550 mm, diameter 40 mm and with a wall thickness of 4 mm loaded to 35 kN before failure started.

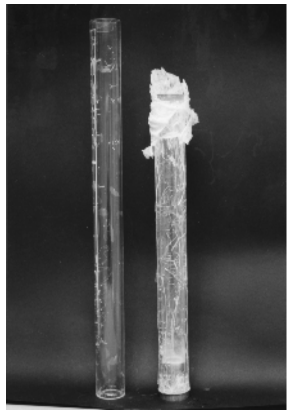


Figure 2.13. Rigidly clamped column specimen next to untested specimen.

*Source: Veer, 1999*

The author further explains that, on the contrary, columns that have a high ratio of length to width and with the bases that can rotate fail by bucklin g as shown in Figure 2.14. Specimens of similar dimensions as used before showed elastic behavior up to loads of 110 kN after which buckling started. The columns started to show considerable deflection while still carrying the maximum loads. Failure starte d in the compression zone where the outer glass layer disintegrated.

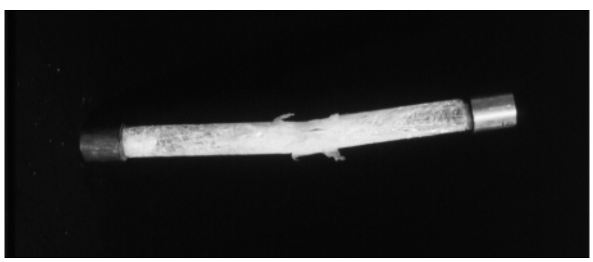


Figure 2.14. Buckled column specimen.

*Source: Veer, 1999*

### 2.3.3 Glass Walls and Point Supported Glass

**Glass Walls**

Leitch (2005) claims that walls have evolved to allow building o ccupants to visually connect with the environment and also it protect us from the environment. Glass walls essentially behave like very wide glass columns. To sustain loads, walls must have substantial thickness and, consequently, multiple plies. Like colu mns, designer must be careful that load transfer does not generate undue concentrated stresses. To minimize this possibility, the support should be as centralized as possible. Also, the most likely mode of collapse is via buckling or plying.

Accordingly, glass walls present a safety risk in two ways. Glass could fracture and fall out of the pane causing harm to people and property below, or it could allow someone to fall out of the building itself. The development of safety glass intended to prevent such injuries. In these situations, it is necessary that the wall continue to protect its occupants even after breaking.

**Point Supported Glass**

Most engineers almost immediately associate glass curtain walls with spider connections. The metallic fingers that a re supported today's curtain walls allow the designer to increase transparency and translucency by minimizing the structural framing.

The maximum span for bolted clamp plates of toughened glass is given in the following table from the Institute of Structu ral Engineers. Smaller spans correlate with Planar and Spider type bolted fittings. Manufacturer product information is integral in making responsible engineering decisions. It is only after extensive product testing and quality control that manufacturer's offer design resources for the application of their products.

Table 2.7. Maximum spans for toughened glass panels using bolted clamp plates.
*Source: Institute of Structural Engineers, 1999*

| Loading | | Maximum Span (mm) for toughend glass | | | |
|---|---|---|---|---|---|
| UDL in kN/m2 | Point Load in kN | 6 mm | 8 mm | 10 mm | 12 mm |
| 0,50 kN | 0,25 kN | 1.400 mm | 1.800 mm | 2.150 mm | 2.450 mm |
| 1,00 kN | 0,50 kN | 900 mm | 1.500 mm | 1.800 mm | 2.050 mm |
| 1,50 kN | 1,50 kN | - | - | 1.200 mm | 1.650 mm |

Behling & Behling (1999) explains that glass plates deform and develop stresses when coping with uniformly distributed surface pressure, like wind pressure. Deformations are elastic until they exacerbate inherent surface flaws in the material and minute cracks reach a critical length. If the flaw occurs near a concentration of stresses, around a bolt for example, than the tensile stress the panel can withstand is diminished. This relationship between stress and flaws indicates the influence of additional factors including area, loading history, surface compressive stress, and quality of the installation.

The author further claims that deflection is not a significant design criterion unless on the macro scale where the sway of the entire structure is being considered. Glass walls can be designed to have low stiffness and tolerate large deflections. The limit of the deflections is then determined according psychological response - human perception of safety. Companies and employees will not occupy a building if they find deflections alarming, despite whether the building is structurally sound. Rule of thumb, limits glass wall flexibility to roughly span/175

**Examples**

Point-fixing systems with articulated fittings are used in order to reduce the concentration of high bending forces and torsional forces around the bore-hole. The first fastening system with articulated fixings was developed by Adrien Fainsilber and the glass structure specialists Rice-Francis-Ritchie for the greenhouses of the Museum of Science and Technology in Paris 1986 as shown in Figure 2.15. The glazing consists of toughened 2 x 2 meter panes, 12 mm thick, which form square fields with 8 meter long sides.

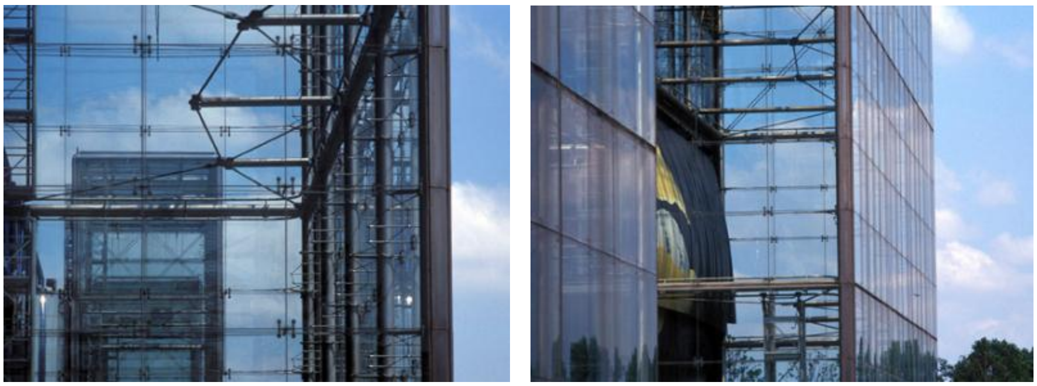


Figure 2.15. Museum of Science and Technology, Paris, 1986.
*Source a-b: www.rfr.fr, 2007*

The other step in the dematerialization of bearing structures is the reduction of the linear elements to a point-fixing systems without perforation, the glass panes are fixed in position by fittings attached on both sides, which are either locate d at the joints or at their corners. An example of this is the central courtyard glazing of the Kempinski Hotel at the Munich airport, completed by architects Murphy/Jahn in 1994 illustrated in Figure 2.16. The load bearing structure consists of crosswise arranged cables that form a flat cabling mesh. At the nodal points the laminated panes (1,5 x 1,5 meter) are fastened by clamping plates that have been specifically developed for this purpose.

Figure 2.16. Kempinski Hotel in Munich, 1994.

*Source: www.kempinski-airport.de , 2007*

### 2.3.4 Glass Roofs and Floors

#### Glass Roofs

Leitch (2005) explains that the roof can be most distinctive part of a structure. In urban areas where buildings continue to push up toward the sky, they look down upon the "fifth façade". Glass roofs seem to be conventional for horticultural purposes, but they remain elegant nonetheless. The benefit of the glass roof is that it transmits natural daylight, but this feature also leads to undesirable thermal gain. The development of PVB technology and glass tinting allows designers to control the amount of light transmitted and refracted in to a structure, an ability that makes glass roofs, once again, highly desirable.

#### Floors

Humans are fascinated by the prospect of walking through the air, or on water. Although it may make the hearth race, glass floors are desirable because they capture the imagination. It is always a very conscious feature of any structure utilizing this design feature.

Behling & Behling (1999) emphasize that because of its perfect smooth appearance, it may seem to compromise safety using glass as a floor. Designers attempt to protect glass from excessive contact and tend to situate it in protected locations, because surface starches tend to increase tensile forces, ultimately resulting in failure of the member. A floor contradicts this off-limits concept, so the degree of robustness must be adjusted according to the traffic and abuse the floor will see. In addition to surface abrasion from traffic, floors are potentially subjected to longer load duration.

**Examples**

In 1993, Glass Bridge by Architects Krajvanger and Urbis in Rotterdam, Netherlands, connected the second floor of two adjacent buildings. The 3.2 m long bridge structure consists of laminated panes that are connected to one another by stainless-steel point fasteners. The base plate is a laminated pane resting on two glass beams made of laminated panes.

Figure 2.17. Glass Bridge, Rotterdam, 1993.

*Source: Behling & Behling, 1999*

In 1996, the glass canopy of the Yurakucho underground station in Tokyo, Japan, designed by Rafael Vinoly Architects. The projecting glass structure is 10.6 m long, 4.8 m wide and 4.8 m high at its top. The load bearing structure consists of three parallel, cantilevering beams that are composed of several triangular, interlocked laminated panes and plexiglass panes which are used because they are earthquake - safe. The roof glazing made of laminated panes i s point-fastened to these cantilevers.

Figure 2.18. Glass Canopy of the Yurakucho Underground Station, Tokyo, 1996.

*Source a: Behling & Behling, 1999*

*Source b: www.lusas.com, 2007*

### 2.3.5 Glass Domes

Leitch (2005) claims that the synthesis of metal and glass structures immediately incubated the generation of domed structures. Domes proliferated over markets and train stations in the 19th century. The glass panels were not structural and were fixed onto a lightweight metal frame. Single panes o f glass were used in early examples of glass domes, which would not provide adequate safety by today's standards.

Innovation came in 1863 when Schwendler included stiffening diagonals to the ribbed dome. Years later, geodesic domes using strut -and-tie geometry was developed. Then, the evolution of free-formed glass domes came later, around 1989, with the invention of the grid shell. A steel net of rods and nodes are erected in a infinite number of configurations, or spatial geometries. Grid shells are vul nerable to unbalanced loads, like snow. This system provides flexibility to accommodate the double curvature structures.

**Examples**

Osaka Maritime Museum is designed by Architect Paul Andreu, in 2000. 70m diameter, fully- glazed steel dome is a hemispheri cal single layer grid shell fixed at its 'equator' level to a circular reinforced concrete wall. The spherical surface is approximated by a series of squarish planes with maximum repetition. The glazing system uses laminated flat glass, without panel bendi ng or warping or any noticeable steps between panels. The rods are pre-stressed so that none goes slack under any design load combination. Seismic and wave loads were considered in addition to dead and wind loads.

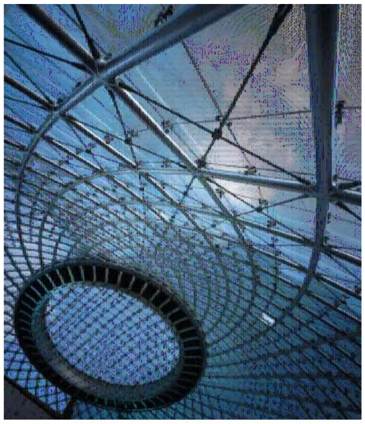


Figure 2.19. Osaka Maritime Museum, the diagrid shell and the ring beam.

*Source: Dallart & Facer, 2001*

# CHAPTER 3

# MATERIAL AND METHOD

Here are presented the materials and methods of the study. The former describes pertinent physical characteristics of the glass type and of the two interlayer substances taken into consideration for the investigation. The latter then presents a detailed account of the various input parameters assumed for the analysis proper –as derived from the literature, such as structural elements, support conditions, load and temperature conditions; and so on. A brief overview on specifics of the SJ Mepla simulation program as applied for the structural analyses is also included here.

This study did not analyze any form of wired, patterned, etched, sandblasted, drilled, notched or grooved glass with surface edge treatments that alter the mechanical properties of glass. This study was addressed only the laminated glass with heat-treated panes and their deformation and resistance to uniformly distributed loads.

## 3.1 STUDY MATERIAL

The analyses were carried out on a range of interlayer types and on glass elements having rectangular geometry covering aspect ratio (long dimension/ short dimension) from 1/3 to 5. Heat-treated laminated glass panes with different types, thicknesses and dimension were used. Here is presented glass types and interlayers as study material under two main topics.

### 3.1.1 Glass Types, Thickness and Stock Dimensions

Here is a presented glass types, glass thickness and glass stock dimension that is used as material in the study.

#### Glass Types

Laminated glass was the main material that was used for the study. Nevertheless only the lamination was not enough to compose structural glass elements. As mentioned in the second chapter, heat-treated glass, tempered or heat-strengthened, was used for this purpose. In order to achieve the required glass types table for each structural element, they were classified under two main topics; first they were grouped according to their direction vector of gravity respectively vertical elements *i.e* glass walls and the horizontal elements, *e.g.* glass floors, roofs and domes, which are also called as over-head glazing. Then the second group was organized depending on their thermal tension possibility. That was one of the main parameters to choose heat-strength glass for over-head glazing. Consequently, Table 3.1 was prepared.

Table 3.1. Glass types.

| **Glass Type** | Laminated Glass with Tempered Panes | Laminated Glass with Heat-Strengthened Panes |
|---|---|---|
| **Element Type** | Glass Floor | Glass Walls, Roofs and Domes |

#### Glass Thicknesses

Engineers and architects use standard laminated glass combinations depending on load carrying capacity and their availability from manufacturer's standard production tables. In this study Trakya Cam product profile was used as a main resource for glass thickness. Glass types were tempered or heat-strengthened type to compose laminated glass, thus available thicknesses were between 4 mm and 19 mm.

General production and preference range for thickness selection were 6 mm, 8 mm, 10 mm and almost 12 mm depending on structural elements that is in usage. As studied in “Strengthening of Glass” section, in order to combine laminated glass two glass panes was required to the outer sides of the interlayer. Moreover in “Structural Design Methods” section usage of glass panes that have equal thicknesses were advised. According to this information Table 3.2 was prepared to show selected thickness as input for the analyses. As interlayer thickness was identified as IT in the table. Whereas for glass floor 3 layer laminated glass usage is general, for glass walls, roofs and domes two layered laminated glass was preferable.

Table 3.2 Glass thickness.

| **Element Type** | Glass Floor | Glass Walls, Roofs and Domes |
|---|---|---|
| **Glass Thickness** | 10 mm+ IT+ 10 mm+ IT+10mm<br>12 mm+ IT+ 12 mm+ IT+12 mm | 6 mm+ IT+6mm,<br>8 mm+ IT+8mm,<br>10 mm+ IT+10mm |

**Stock Dimension**

Glass pane dimension was the other parameter affecting the structural performance of a laminated glass, whereas as noted previously glass pane dimension was also depended on available dimension of heat-treated glass. Thus available sizes of tempered and heat-strengthened glass were gathered in the Table 3. 3, obtained from the Turkey’s biggest glass producer Trakya Cam Sanayii A.Ş., so as to achieve base dimension selection.

Table 3.3. Trakya Cam Sanayii A.Ş. product dimension schedule.
*Source: Trakya Cam Sanayii web-site, 2007*

| **Glass Type** | **Dimension (mm)** | |
|---|---|---|
| | **Minimum** | **Maximum** |
| Tempered (grinding in ) | 350mm x 105mm | 4500mm x 2400mm |
| Heat-Strenght (grinding in ) | 350mm x 105mm | 4500mm x 2400mm |
| Laminated | - | 6000mm x 3210mm |

**Dimensional tolerances are excluded from this table*

### 3.1.2 Interlayer Types and Thickness

Here is a presented interlayer types and thickness that is used as material in the study.

#### Interlayer Types

In this study explained in the Literature Survey, two different types of interlayers were investigated. The first and the traditional one was PBV layer, which is widely used around the world to make laminated glass. It has some advantages such as; it achieves transparency, durability, and shear resistance. In addition, it provides impact resistance, better acoustic insulation, and enhanced regulation of solar impact. And also it is more economical than the other interlayer types. On the other hand, pointed out the structural design method part, the static behavior of the laminate glass the shear composite effect ought to be neglected, since it is not sure.

The second interlayer type, described as DuPont SentryGlas® Plus, has some more advantages than standard PVB layer. It is more durable against delamination when exposed to outside weather. In addition to them, it is stiffer and stronger. It has stronger post-breakage performance. It shows less deflection relative to standard PVB interlayers.

**Interlayer Thickness**

The interlayer thickness that was used in analysis depends on interlayers types standard production table and their availability. Commonly used PVB interlayer thickness were 0.38mm, 0.76mm, 1.14mm, 1.52mm, 2.28mm, and 2.54mm.

On the other hand SentryGlas® Plus interlayer thickness were 1.52mm, 2. 28mm and 2.54mm. The conversation with the SentryGlas® Plus showed that the common usage is mainly 1,52mm regarding standard façade. As the main purpose of this material was to make safe windows against hurricane effects, 2.28mm and 2.54mm thickness was mostly preferable in hurricane zones. Regarding the information, this study was delimited to use 1.52mm thickness interlayer.

## 3.2 METHODOLOGY

In this study, an optimization approach was proposed where the evaluation criteria was related to the structural performance of the glass interlayer, in terms of strength. For this purpose, the study was conducted as parametric study to be able to identify the contributions of interlayers to laminated structural glass. In this part, the method and process of the parametric study is explained.

The study was carried on different types of interlayers, as a main component of laminated glass, and their effects on variable structural glass elements. In this regard, the parameters that affect the structural glass analysis were described briefly. Support conditions, load types and duration, maximum allowable stress and deflection consideration were taken into account according to EN, German and ASTM standards. To determine glass parameter selection strategy, all inputs were gathered and grouped according to their relation to the structural glass elements. Finally, a glass parameter selection table was prepared as shown in Table 3. 4. The parameters that were determined as input for each analyses were demonstrated with dots.

Selected parameters and their selection reasons were summarized in the following sections.

Table 3.4. Glass parameters.

| STRUCTURAL ELEMENTS | PARAMETER TYPE | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***BASE PARAMETERS*** | | | | | | ***DEPENDENT PARAMETERS*** | | | | | | | | | | | | | |
| | INTERLAYER | | | SUPPORT | | | GLASS | | | | | | | LOAD | | | | | TEMPERATURE | |
| | *Interlayer Type* | | *Interlayer Thickness (mm)* | *Support Condition* | | *Support Type* | *Laminated Glass Type* | | *Glass Thickness (mm)* | | | | | *Load Type* | | | *Load Duration* | | *Temperature Differance* | |
| | PVB | SGP | 1,52 | Two Sided | Four Sided | Simple Support | Tempered | Heat-Strength | 6+6 | 8+8 | 10+10 | 10+10+10 | 12+12+12 | Wind | Snow | Live | Short | Long | Outside/ $\Delta T:50^0C$ | Inside/ $\Delta T:0^0C$ |
| **Glass Wall** | • | • | • | • | • | • | | • | • | • | • | | | • | | | • | | • | |
| **Glass Floor** | • | • | • | • | • | • | • | | | | | • | • | | | • | | • | | • |
| **Glass Roof** | • | • | • | • | • | • | | • | • | • | • | | | | • | | | • | • | |
| **Glass Dome** | • | • | • | • | • | • | | • | • | • | • | | | • | • | | • | • | • | |

### 3.2.1 Structural Elements

Structural glass element types were one of the main information for the study . All analyses were conducted according to structural glass elements. However, as mentioned in the literature survey section, every structural element has its own characteristic structural behavior and they need special application individually. Thus, in this study glass walls, glass floors, glass roofs and glass domes were analyzed according to pre-defined parameters. On the other hand, glass column, glass beam, glass fin and point supported glass were excluded from analysis study, as they need very complex calculation process by using Finite Element Method and special knowledge about application of this simulation type.

### 3.2.2 Support Conditions

Support conditions were accepted according to ASTM -E1300 standard test methods. For every structural element co ntinuous simply supported panes along two and four edges were used. All elements were simply supported and free to slip in plane, acts as simply supported beam.

### 3.2.3 Load Conditions

The third prerequisite for the structural analysis was to determine t ype and duration of loads with regard to international and national codes. Under this section, types of loads were classified as wind loads, snow loads, dead weight and the live loads, and also their effects on load duration were explained. As sited in "st rengthening of glass" section they affect the strength of the glass.

**Type of Loads**

In this study for the determination of the Loads TS498 Standard was taken as a main resource. All load types were assumed to be uniformly distributed load.

***Wind Load***

In the TS 498-T1/1997, wind load was accepted to effect in horizontal direction and wind load value was mainly depended on the geometry of the building. Pressure, suction and friction impacts were calculated together. Wind velocity and suction values relative to height from the ground was determined in mentioned standard. According to TS498, wind load information was given in Table 3. 5. If the wind is affected in an angular way, the formula on height of the building/ width of the building ratio has to be fall owed. If height of the building/ width of the building ratio is smaller than 5, C value had to be 1,2 and if this ratio is bigger than 5, C had to be calculated 1,6.

Table 3.5. Wind load relative to height from the ground.

*Source: TS498-T1*

| Height from ground level | C=1,2 W | C=1,6 W |
|---|---|---|
| 0 – 8 m | 600 $N/m^2$ | 800 $N/m^2$ |
| 9 – 20 m | 960 $N/m^2$ | 1280 $N/m^2$ |
| 21 – 100 m | 1320 $N/m^2$ | 1760 $N/m^2$ |
| > 100 m | 1560 $N/m^2$ | 2080 $N/m^2$ |

The study assumption was to limit height of the building between 8 meter and 20 meter, and to take the building height/width ratio minimum than 5. Then the wind load parameter of the study was accepted as 960 $N/m^2$.

***Snow Load***

Snow load was accepted depending on the structural element position that was analyzed. All structures assumed to be situated on the territory and for glass roofs that is assumed the slope of the roof is lower than 30 °. Snow load chart indicated 1250 $N/m^2$ where the altitude was 800 m and the place was in the fourth region. However, for the glass dome this method was not available.

The glass dome had its own characteristic therefore that has to be calculated separately. The section angles of Glass Dome were changing almost between 0 °– 90° in other words that was the worst case, both snow and wind load had to be calculated together. According to TS498 in order to calculate snow and wind load together the formula 1 or formula 2 had to be used. Pk was the snow load and W was the wind load. The worst condition was taken into account.

Pk= W x 0,5…………………………………… (1)

or W= Pk x 0,5……………………………..…….. (2)

According to this formula our load combination for the glass dome was;

$$W_2{:}960\ N/m^2 \ \text{and}\ P_{ko}{:}\ 1250\ N/m^2 \rightarrow P{:}\ 1730\ N/m^2$$

***Dead Weight and live loads***

Unit weight of the glass was accepted as 25kN/m $^3$. For the structural elements during the calculation process, the extra weights that have to be carried ought to be calculated *i.e.* live loads for the glass floors. Live load was accepted as 5 kN/m $^2$ according to TS498/ Section 12/ "uniformly distributed live load for general public place"

**Load Duration**

Firstly depending on the load types, load duration varies. For example wind load was a short duration load, whereas snow load and live load was long duration load. As mentioned in The Literature Survey, the strength of the laminated glass changes with the load duration. Glass and interlayer perform less structural behavior when the loading is long term rather than short term and transient, and also the laminated glass appears to become weaker as the duration of loading increase. As glass had a safety factor of 2,4 for it's maximum allowable design stress, load duration mainly affected the interlayer. Then, as noted previously in literature survey interlayer stiffness values were selected from Table 2.3 and Table 2.5, according to their load -time dependent values.

**3.2.4 Temperature Conditions**

Structural elements were grouped according to their general usage conditions. Glass wall, glass roof and glass dome were exposed to outside air condition and temperature difference between inside and outside of laminated glass pane was identified as 50$^0$C. Only the glass floor was not exposed to outside air condition, thus temperature difference was accepted 0$^0$C

### 3.2.5 Structural Analysis Program and Parameters

As mentioned in the second chapter, static analysis of glass panes with various glass types and sizes, support conditions and under various types of loading were calculated by the sophisticated finite element method, SJ Mepla. It was used to calculate the stresses over the surface of the glass panels which uses Weibull probability distribution, to approximate the variability of glass breakage data and to predict the probability of breakage of the glass panels at a given load.

All inputs, like geometry, mechanical properties of layers, boundary conditions, load conditions, the calculation approach or the requested output, were guided and displayed by input masks. The control and output of the results were given visually on a graphics surface and a calculation protocol which was used for the static assessment.

All calculations were made geometrically non-linear method which releases large deformations. Laminated glass considering the stiffness of the compound material was defined by thickness and the order of layers. Support conditions of springs in three direction and pre-defined simple supports were used. Load conditions of uniformly distributed face loads, dead weight in suitable direction, climatic loads, temperature loads and live loads within the panes were combined. The program gave calculation protocol of all input and outputs, displacement and stress distribution during impact for each pre-defined positions.

The structural analysis parameters are the evaluation criteria depend on the properties of the glass type and dimension of the glass pane applied to the case analysis. They were used to assess the relative condition created by selected parameter cases. In the framework of this study maximum allowable stress value was used to evaluate strength limit of selected glass type and maximum allowable deflection to evaluate displacement limit within the glass according to German and ASTM standards. Maximum values were selected and they were compared with the maximum allowable limits. One of the maximum limits was exceeded; it was the critical one. That is the other limit was not affecting the glass pane any more.

According to German and ASTM standards heat-strengthened glass maximum allowable stress was accepted as 37 N/mm $^2$. However, for tempered glass ASTM standards and German Standards were varying. Then to be on the safe side smaller one was accepted as critical limit. Thus, for tempered glass 50 N/mm $^2$ were accepted as maximum allowable stresses. Regarding ASTM standards maximum allowable deflection limit was accepted as Span/175.

### 3.2.6 Data Processing

At this stage of the study, the analyses were limited to combine a selection strategy. Every structural element had its own characteristic, where as they had some common parameters, explained in Material Section. For every structural glass element analyses conducted to evaluate effects of the base parameters independently. Only one base parameter was changed at a time and all other base and dependent elements kept constant. For each base parameter evaluated, a new chart was created. For example a simulation analyzing one of the base parameter, effect of interlayer stiffness on pane, was created by altering only its interlayer type without any change in other properties. The effect of each base parameter was evaluated, according to their influence on the output measures.

During the study, the base parameters were changed and then the resulting parameters were simulated regarding structural element types. In the next step, the result of the simulations was compared in the charts. This requires manually computing the dimension variables and entering the values in appropriate places in sections of SJ Mepla. New layer compositions were created to describe different interlayer choices and configurations. The evolving descriptions were PVB and SGP interlayer. This was a repetitive process including interval selection, finding possible critical dimension, adjusting the geometry, glass pane and interlayer types, load and support condition and evaluation. Then if critical limits are achieved entering data to the tables and preparing the comparison charts, *etc*.

This section explains the process used to evaluate the variables. In ad dition, the data that is used to evaluate the performance of the variables i.e. constant and output measures, are describes in this section.

**Base Measures**

In this study three distinct base parameters were evaluated; type of structural element, type of interlayer and type of support condition. Each step was represented as a different layout. The parameters were applied according to glass parameters, previously illustrated in Table 3.4. In other words structural element types, interlayer types and support conditions were kept throughout the study; they were analyzed according to their effect on strength.

**Variable measures**

The dependent measures of the parametric study were kept unchanged for one structural element cases that are analyzed throughout the st udy. They were only changed if structural element type was also changed. The analyzed dependent parameters were glazing type, glazing thickness, load condition and temperature differences within the glass pane. After detailed evaluation of each single para meter the combination of best performing ones were applied to structural elements. According the assumptions and the acceptance from the norms as detailed descriptions was given earlier; analyses were conducted following these parameters.

### 3.2.7 Determination of Variation Chart Intervals

The main problem for the dimensioning was to select intervals to prepare the glass variation chart regarding their maximum allowable stress and maximum allowable deflection consideration. In order to solve this problem th e references were searched, and it was observed that in ASTM test methods, aspect ratio of glass was taken as a parameter.

According to aspect ratio information, rectangular glass panes having diagonal geometry covering aspect ratio (long dimension/ shor t dimension) from 1 to 5 was used for plate shaped four sides simply supported structural elements. Then the ASTM standard dimension chart, Figure 3.1., was modified according to this ratio information for the study.

However this method was not only enou gh to compose variation chart. For this reason, the modulation of the glass was designed by the help of static analysis program that which intervals were more critical regarding aspect ratio information.

According to results, for the four sides simply sup ported elements 0,1 m interval created considerably great difference between maximum allowable stresses and maximum allowable deformations in long direction, when the other dimension was fixed. Therefore the sample glass dimensions were selected through 0, 1 m intervals for that direction.

The chart indicates the terminology as follows; plate length is the maximum dimension of the glass, plate width is the minimum dimension of the glass. AR is the aspect ratio, the ratio of the glass to the short dimension of the glass is always equal or greater than 1.0 for the four sides simply supported.

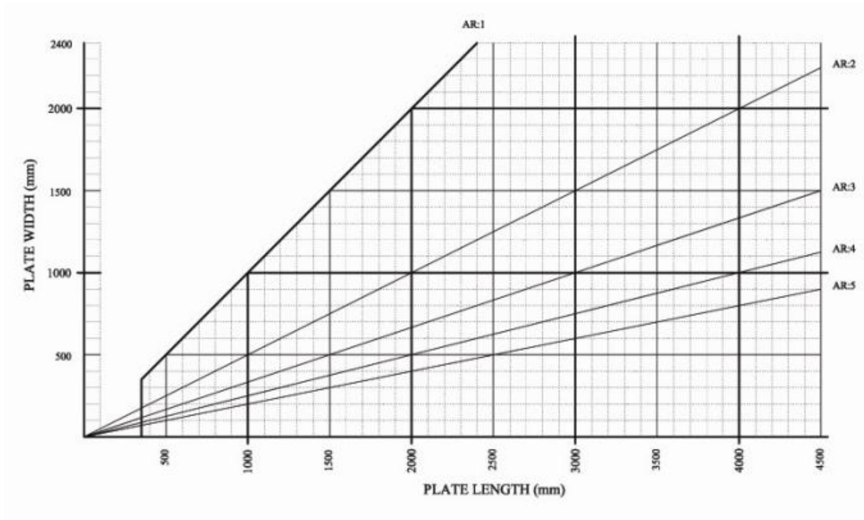



Figure 3.1. Dimension chart for glass panes simply supported on f our sides.

The chart was modified according to maximum available size of the heat -treated glass. Maximum length was 4,5 m and maximum width was 2,4 m, every 0,5 m distance and also 0,1 m variation interval distance was defined in both direction. As shown in the chart, there was not aspect ratio information smaller than 1/1. That if the maximum dimension of the glass combination was changing, maximum dimension of the plate was accepted as plate length like four sides simply supported standard plate.

At a given one fixed dimension, in order to define the exact maximum stress or deflection point for the short direction, proximity method was used. First of all, the smallest, the biggest and the intermediate dimension values were analyzed and maximum limits were checked. The intermediate dimension was the main component for this method. That is; if maximum allowable stress or deflection limit was exceeded at the intermediate dimension, then the critical limit was between intermediate and the smallest dimension. If not, the limit was at the other side. This proximity method was used until achieving 5mm interv al which is just below the maximum limits. Then the achieved limit value was maximum dimension of pane indicated as italic bolded row 4 in Table 3. 6.

Table 3.6. Determination of maximum limit for four sides simply supported glass.

| | **Width (mm)** | **Height (mm)** | **Maximum Deflection (mm)** | **Maximum Allowable Deflection (mm)** | **σ** *max* **(N/mm**2**)** | **σ** *allowable* **(N/mm**2**)** |
|---|---|---|---|---|---|---|
| Exceeds Critical Limit | 4.500 mm | 1.540 mm | -8,85 mm | -8,8000 mm | 13,09 N/mm2 | 37,00 N/mm2 |
| ***Critical Limit*** | ***4.500 mm*** | ***1.535 mm*** | ***-8,75 mm*** | ***-8,7714 mm*** | ***13,03 N/mm2*** | ***37,00 N/mm2*** |
| Below Critical Limit | 4.500 mm | 1.530 mm | -8,66 mm | -8,7429 mm | 12,96 N/mm2 | 37,00 N/mm2 |

Width refers to long dimension and height refers to short dimension of the glass in mm. Maximum deflection was shown as approximate maximum lateral deflection within the glass after loading in mm and maximum allowable deflection was Span/ 175 mm of glass according to ASTM 1300-04. $\sigma_{max}$ is maximum principle stress within the glass pane after loading in N/mm$^2$. $\sigma_{allowable}$ is the maximum allowable surface stress in N/mm$^2$ previously defined according to standards.

Then to find maximum limits for 0.1 m fixed dimension, variations were checked for linear intervals on short dimension. The variations had non-linear behavior. In order to achieve nearest maximum limit, at least two or tree 0.1 m interval was found by the help of proximity method. Then the short edge dimension was controlled for if the standard interval could be achieved. Firstly, the interval variation was depended on the plate behavior. If the aspect ratio exceeds its limit, the glass plate behaves like a one way slab, and thus the interval variations were too small and mainly linear. After exceeding aspect ratio limit, the variations were non-linear.

The variation differences between each 0,1 m intervals were studied. Depending on the distance from maximum aspect ratio limit, limit variations were differing as second or third degree function. As the aspect ratio limits were changing for each case calculated, limits for the functions were also calculated by the help of proximity method as shown in Table 3.7.

Table 3.7. Determination of maximum limit among each 0,1 m intervals.

<table>
<tr><th>width</th><th>height</th><th>Δ: 1. degree</th><th>Δ: 2. degree</th><th>Δ: 3. degree</th></tr>
<tr><td rowspan="2">3.400 mm</td><td rowspan="2">2.065 mm</td><td></td><td rowspan="2"></td><td rowspan="3"></td></tr>
<tr><td rowspan="2">45 mm</td></tr>
<tr><td rowspan="2">3.300 mm</td><td rowspan="2">2.110 mm</td><td rowspan="2">15 mm</td></tr>
<tr><td rowspan="2">60 mm</td><td rowspan="2">0 mm</td></tr>
<tr><td rowspan="2">3.200 mm</td><td rowspan="2">2.170 mm</td><td rowspan="2">15 mm</td></tr>
<tr><td rowspan="2">75 mm</td><td rowspan="2">15 mm</td></tr>
<tr><td rowspan="2">3.100 mm</td><td rowspan="2">2.245 mm</td><td rowspan="2">30 mm</td></tr>
<tr><td rowspan="2">105 mm</td><td rowspan="2">25 mm</td></tr>
<tr><td rowspan="2">3.000 mm</td><td rowspan="2">2.350 mm</td><td rowspan="2">55 mm</td></tr>
<tr><td rowspan="2">160 mm</td><td rowspan="3"></td></tr>
<tr><td rowspan="2">2.900 mm</td><td rowspan="2">2.510 mm</td><td rowspan="2"></td></tr>
<tr><td></td></tr>
</table>

First row displays the 0.1 m interval values through width of the pane and second row is variation value among them. Third, fourth and fifth rows display degree of function to find out variation relation respectively. Then the maximum limits for the each 0,1 m interval were listed for each case. Finally the points were exactly defined in the variation charts and they were connected by the help of spines as indicated in Figure 3.2

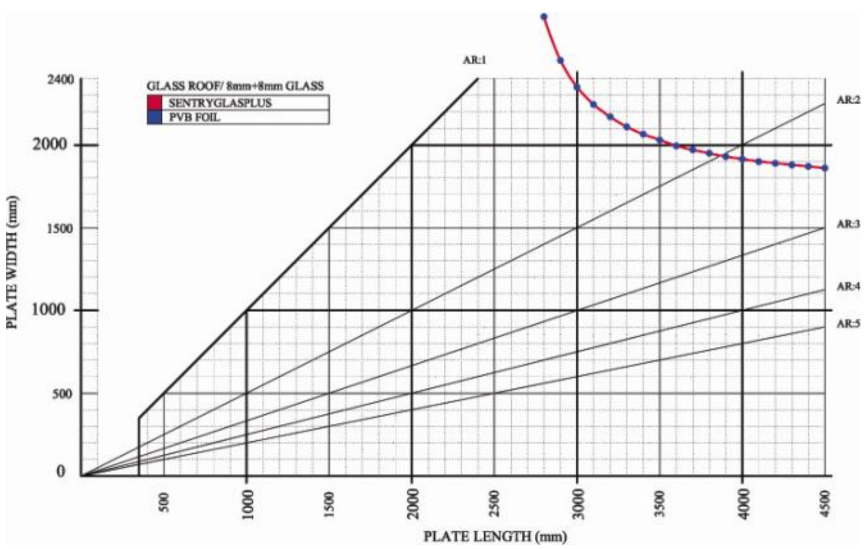



Figure 3.2. Indication of dimension intervals for glass panes simply supported on four sides.

For plate shaped two opposite sides simply supported structural element, it was accepted that the plate was behaving like one way slab throughout the all plate, different from the four sides simply supported glass plate. Then the, aspect ratio information was accepted not to have direct effect on variation determination, but it was suggested that it will help comparison the resultant charts of the cases. As a result 1/3 to 5 aspect ratio information was defined when analyzing.

For the two opposite sides simply supported elements, critical limits were investigated similarly to four side simply supported glass. That is; 0,5 m interval created slightly small difference between maximum allowable stresses and deformations at supported edge direction, thus the glass dimension were selected beginning from the minimum to maximum sizes through 0,5 m intervals. For the non-supported direction the maximum limits were also controlled for each 0,005 m interval by the help of proximity method. The maximum limits were also changing slight smaller variations that are they were almost linear. As a result two opposite sides simply supported glass variation chart, Figure 3.3, is prepared.

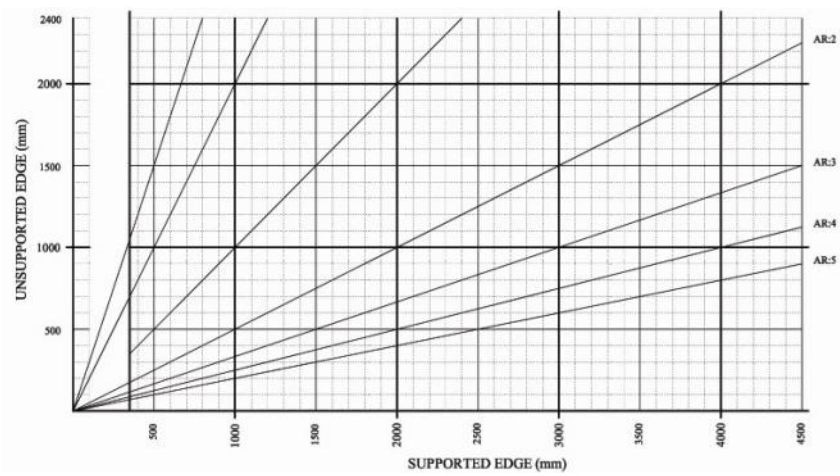



Figure 3.3. Dimension chart for glass panes simply supported on two opposite sides.

The chart was also modified according to maximum available size of the heat -treated glass. Maximum length was 4,5 m and maximum width was 2,4 m, every 0,5 m distance and also 0,5 m variation interval distance was defined in supported direction. Finally the points were exactly defined in the variation charts and they were connected by the help of spines for each case and they were indicated as circles in Figure 3.4.

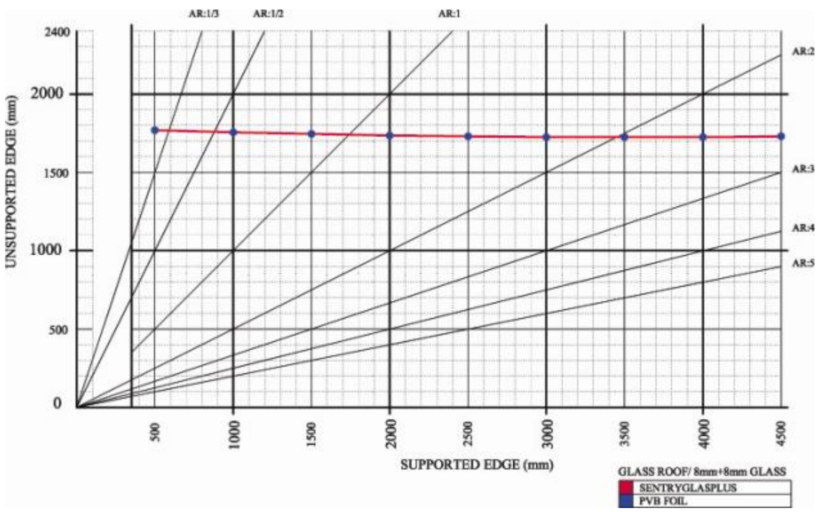



Figure 3.4. Indication of dimension intervals for glass panes simply supported on two opposite sides.

# CHAPTER 4

# RESULTS AND DISCUSSION

In this chapter the results of the analyses are presented. A number of structural element types were defined for the analyses. They were analyzed in FEM based SJ Mepla structural glass analysis program and the each parameters were applied based on glass parameters table information. In order to reach critical limits, thousands of analyses were run and the minimum interval 5mm was achieved. At the next step, the analyses results were gathered in a table shown in Appendix. They were combined according to their parameters and limitations. The first limitation was deflection consideration and the second was maximum allowable stress. Thereafter, the resultant values were analyzed comparison charts were prepared.

All parameters display same properties in terms of their affect on laminated glass, but because of interlayer properties and different support conditions , their resultant strength values were not same. In order to represent their differences following charts were created which represents reliable maximum sizes of laminated glass according to pre-defined parameters. In the following sections, detailed results of various cases are discussed and effects of the base parameters are presented.

## 4.1 Glass Walls

The parameters are represented in Table 4.1 and analyses were conducted following these parameters. The results of the simulations are presented in Figure 4.1 to 4.6 respectively depending on their glass thickness parameters and support conditions. Their limit values are also presented as Appendix A.

Table 4.1. Parameters for glass walls.

| STRUCTURAL ELEMENTS | **PARAMETER TYPE** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***BASE PARAMETERS*** | | | | | | ***DEPENDENT PARAMETERS*** | | | | | | |
| | INTERLAYER | | | SUPPORT | | | GLASS | | | | LOAD | | TEMPERATURE |
| | *Interlayer Type* | | *Interlayer Thickness (mm)* | *Support Condition* | | *Support Type* | *Laminated Glass Type* | *Glass Thickness (mm)* | | | *Load Type* | *Load Duration* | *Temperature Differance* |
| | PVB | SGP | 1,52 | Two Sided | Four Sided | Simple Support | Heat-Strength | 6+6 | 8+8 | 10+10 | Wind | Short | Outside/ $\Delta T$:50$^0$C |
| **Glass Wall** | • | • | • | • | • | • | • | • | • | • | • | • | • |

As a main component of this study glass wall structure analyses were conducted throughout this section. Base parameters were two types of interlayer, PVB and SGP and support conditions, two sided or four sided support. Interlayer thickness 1,52mm and support type, simple support, were kept unchanged. Glass type was defines as heat-strength laminated glass and thickness combinations were defined as 6 mm+ 1,52mm+ 6 mm, 8 mm+ 1,52mm+ 8 mm, 10 mm+ 1,52mm+ 10 mm respectively. As direction vector of gravity of glass wall is vertical and it was located on the outer contour of the building, it was affected by wind load value of 960 N/m $^2$ and defined as short time loading. Thus temperature difference was selected as 50 $^0$C.

***Discussions on Results***

As observed, different types of interlayers with different stiffness properties created significantly big difference in critical limits and maximum possible dimensions for different types of glass thickness and support conditions. Maximum allowable deflection limit was dominant factor when analyzing the maximum possible dimension. Maximum allowable stress limit was never achieved.

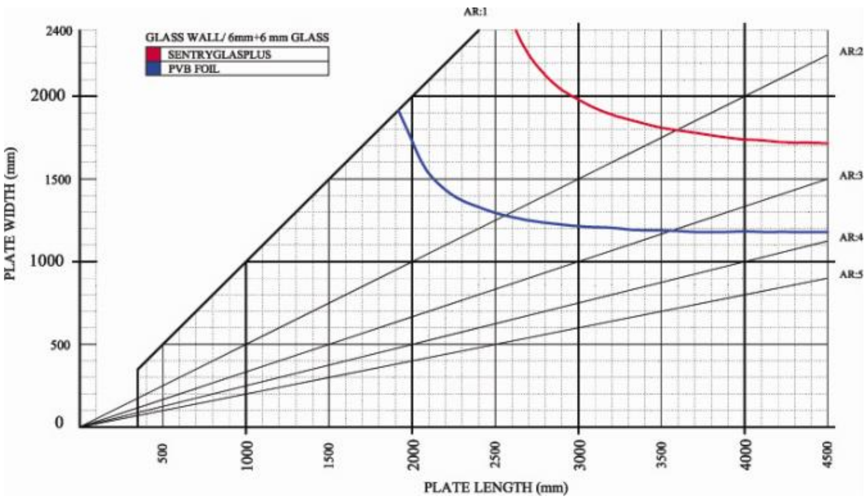



Figure 4.1. Comparison chart 1 for glass walls.

*Standard Parameters: GT: Heat-Strength, GTk: 6 mm+ 6 mm, IT: 1,52mm, WL: 960 N/m $^2$, SC: Four Side Simply Supported, LC: Short Time Loading

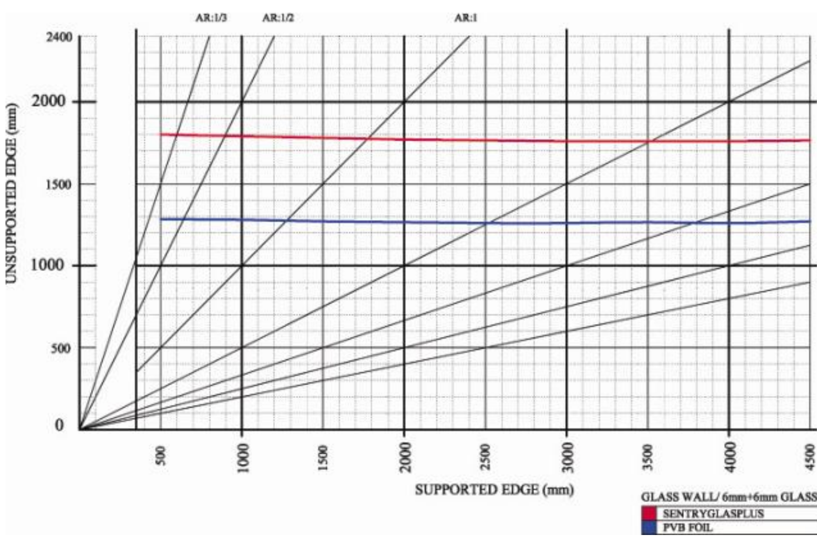



Figure 4.2. Comparison chart 2 for glass walls.

*Standard Parameters: GT: Heat-Strength, GTk: 6 mm+ 6 mm, IT: 1,52mm, WL: 960 N/m $^2$, SC: Two Opposite Sides Simply Supported, LC: Short Time Loading

The results of Figure 4.1 show that both of the interlayers were behaving as a one way slab and variations between each 0.1m distance changes slightly small till exceeding aspect ratio two. After exceeding that point, significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 6 mm+ 6 mm glass with PVB was 1,9 m to 1,955 m. By comparison, with SGP it was 2,5 m to 2,585 m which was also beyond the maximum available glass dimension. Possible maximum dimension difference between PVB and SGP were varying around 0,6m till aspect ratio two. After that point, possible dimension difference was reaching 1,2 m at 2,5m width which was almost 100% bigger than PVB dimension. Maximum deflection 14,29 mm was achieved with SGP interlayer at that dimension.

Two opposite sides simply supported condition for 6 mm+ 6 mm glass results are presented in Figure 4.2. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between each 0.5m distance changes slightly small throughout available dimensions.

Maximum dimensions for 6 mm+ 6 mm glass with PVB were 4,5 m x 1,27 m to 0,5 m x 1,285 m. By comparison, with SGP it was 4,5 m x 1,765 m to 0,5 m x 1,765 m. It was observed that all dimensions were in the limit of available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 0,5 m throughout the pane width and differing with slightly small intervals and SGP was 50% bigger than PVB interlayer. Maximum deflection 10,25 mm was achieved with SGP interlayer at 0,5 m to 1,8 m dimension.

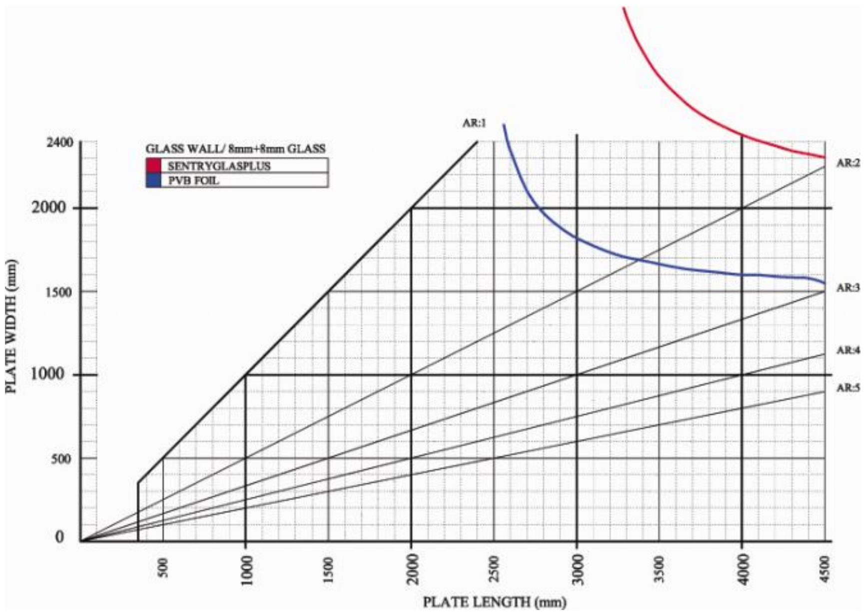



Figure 4.3. Comparison chart 3 for glass walls.

*Standard Parameters: GT: Heat-Strength, GTk: 8 mm+ 8 mm, IT: 1,52mm, WL: 960 N/m $^2$, SC: Four Side Simply Supported, LC: Short Time Loading

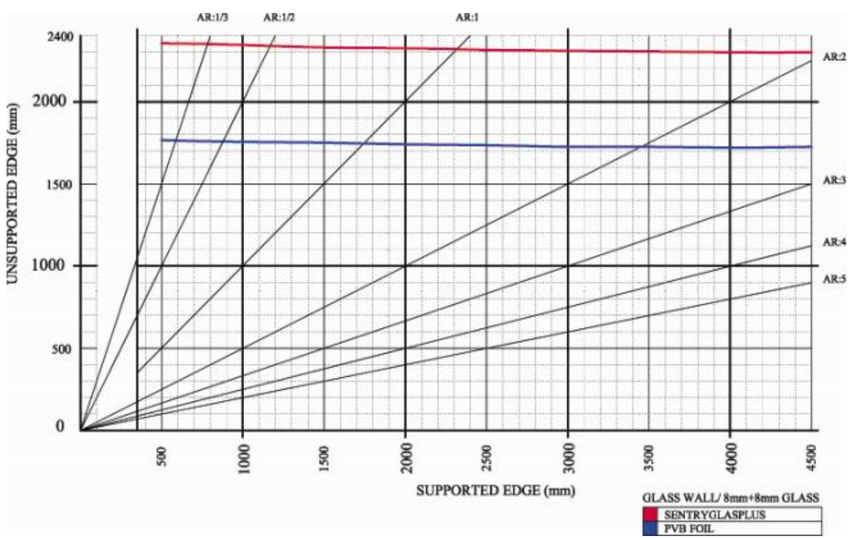



Figure 4.4. Comparison chart 4 for glass walls.

*Standard Parameters: GT: Heat-Strength, GTk: 8 mm+ 8 mm, IT: 1,52mm, WL: 960 N/m $^2$, SC: Two Opposite Sides Simply Supported, LC: Short Time Loading

The results of Figure 4.3 show that both of the interlayers were behaving as a one way slab and variations between each 0.1m distance changes slightly small till exceeding aspect ratio two. After exceeding that point, significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 8 mm+ 8 mm glass with PVB was 2,5 m to 2,56 m. By comparison, with SGP it was 3,2 m to 3,285 m, both were also beyond the maximum available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 0,7 m till aspect ratio two. After that point, possible dimension difference was reaching 1,5 m at 3,2m width which was almost 70% bigger than PVB dimension. Maximum deflection 18,28 mm was achieved with SGP interlayer at that dimension.

Two opposite sides simply supported condition for 8 mm+ 8 mm glass results are presented in Figure 4.4. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between each 0.5 m distance changes slightly small throughout available dimensions.

Maximum dimensions for 8 mm+ 8 mm glass with PVB were 4,5 m x 1,725 m to 0,5 m x 1,765 m. By comparison, with SGP it was 4,5 m x 2,300 m to 0,5 m x 2,355 m. It was observed that all dimensions were in the limit of available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 0,6 m throughout the pane width and differing with slightly small intervals and SGP was 35% bigger than PVB interlayer. Maximum deflection 13,44 mm was achieved with SGP interlayer at 0,5 m to 2,355 m dimension.

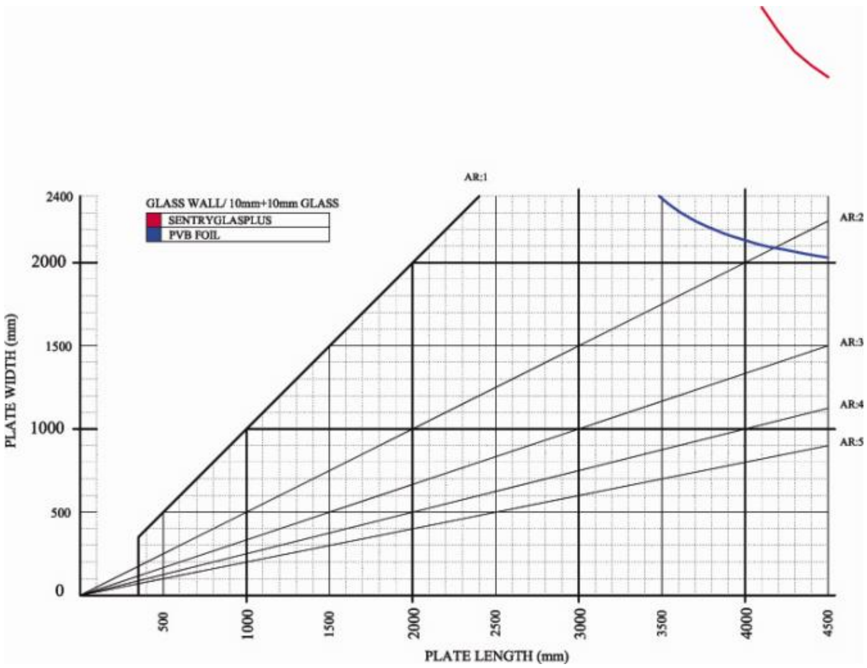



Figure 4.5. Comparison chart 5 for glass walls.

*Standard Parameters: GT: Heat-Strength, GTk: 10 mm+ 10 mm, IT: 1,52 mm, WL: 960 N/m$^2$, SC: Four Side Simply Supported, LC: Short Time Loading

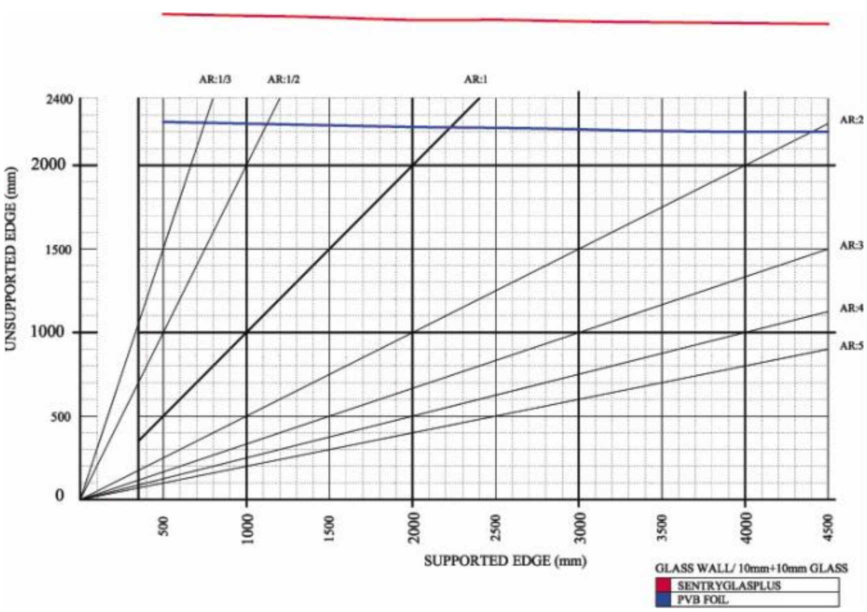



Figure 4.6. Comparison chart 6 for glass walls.

*Standard Parameters: GT: Heat-Strength, GTk: 10 mm+ 10 mm, IT: 1,52mm, WL: 960 N/m$^2$, SC: Two Opposite Sides Simply Supported, LC: Short Time Loading

The results of Figure 4.5 show that throughout the all dimensions significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 10 mm+ 10 mm glass with PVB was 3,1 m to 3,14 m. By comparison, with SGP it was 3,9 m to 3,94 m, both were also beyond the maximum available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying between 1 m to 1,8 m which w ere almost between 50% to 89%. Maximum deflection 22,26 mm was achieved with SGP interlayer at 3,9 m to 3,94 m dimension.

Two opposite sides simply supported condition for 10 mm+ 10 mm glass results are presented in Figure 4.6. Both of the interlayers we re behaving as a one way slab and dimension, deflection and stress variations between each 0.5 m distance changes slightly small throughout available dimensions.

Maximum dimensions for 10 mm+ 10 mm glass with PVB were 4,5 m x 2,2 m to 0,5 m x 2,26 m. By comparison, with SGP it was 4,5 m x 2,845 m to 0,5 m x 2,905 m. It was observed that PVB dimensions were in the limit of available glass dimensions in contrast SGP dimensions were exceeding this dimension. Possible maximum dimension difference between PVB and SGP were varying around 0,64 m throughout the pane width and differing with slightly small intervals and SGP was 30% bigger than PVB interlayer. Maximum deflection 16,60 mm was achieved with SGP interlayer at 0,5 m to 2,905 m dimension.

## 4.2 Glass Floors

The parameters are represented in Table 4.2 and analyses were conducted following these parameters. The results of the simulations are presented in Figure 4.7 to 4.10 respectively depending on their glass thickness parameters and support conditions. Their limit values are also presented as Appendix B.

Table 4.2. Parameters for glass floors.

| STRUCTURAL ELEMENT | PARAMETER TYPE | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BASE PARAMETERS | | | | | | DEPENDENT PARAMETERS | | | | | |
| | INTERLAYER | | | SUPPORT | | | GLASS | | | LOAD | | TEMPERATURE |
| | Interlayer Type | | Interlayer Thickness (mm) | Support Condition | | Support Type | Laminated Glass Type | Glass Thickness (mm) | | Load Type | Load Duration | Temperature Differance |
| | PVB | SGP | 1,52 | Two Sided | Four Sided | Simple Support | Tempered | 10+10+10 | 12+12+12 | Live | Long | Inside/ ΔT:0 $^0$C |
| Glass Floor | • | • | • | • | • | • | • | • | • | • | • | • |

Glass floor structure analyses were conducted throughout this section. Base parameters were two types of interlayer, PVB and SGP and su pport conditions, two sided or four sided support. Interlayer thickness 1,52mm and support type, simple support, were kept unchanged. Glass type was defines as tempered laminated glass and thickness combinations were defined as 10 mm+ 1,52mm+ 10 mm+ 1,52mm + 10 mm and 12 mm+ 1,52mm+ 12 mm+ 1,52 mm+12 mm respectively. As direction vector of gravity of glass floor is horizontal and it was located inside of the building, it was affected by live load value of 5000 N/m$^2$ and defined as long time loading. Thus temperature difference was selected as 0 $^0$C.

### *Discussions on Results*

As observed, different types of interlayers with different stiffness properties created significantly big difference in critical limits and maximum possible dimensions for different types of glass thickness and support conditions. Maximum allowable deflection limit was dominant factor when analyzing the maximum possible dimension. Maximum allowable stress limit was never achieved.

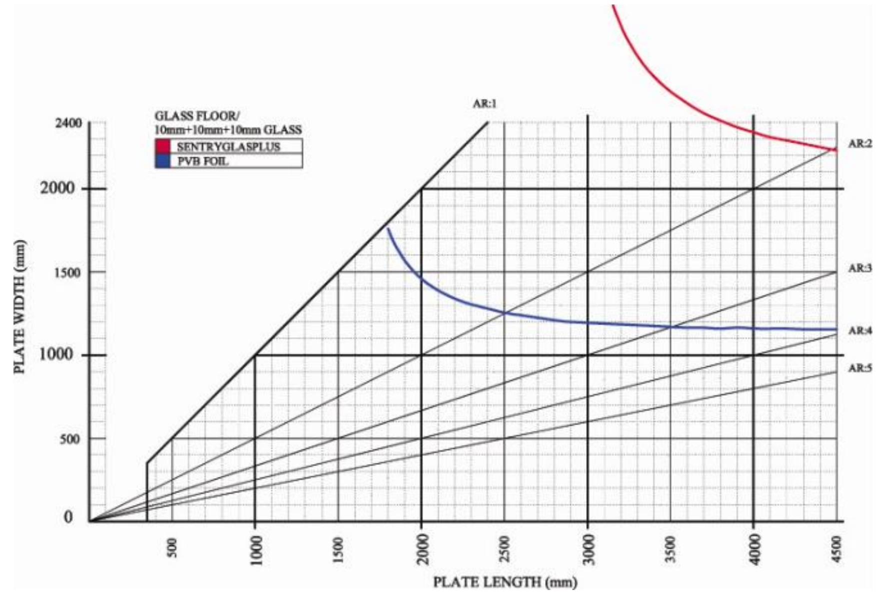



Figure 4.7. Comparison chart 1 for glass floors.

*Standard Parameters: GT: Tempered, GTk: 10 mm+ 10 mm+ 10 mm, IT: 1,52mm, LL: 5000 N/m $^2$, SC: Four Side Simply Supported, LC: Long Time Loading

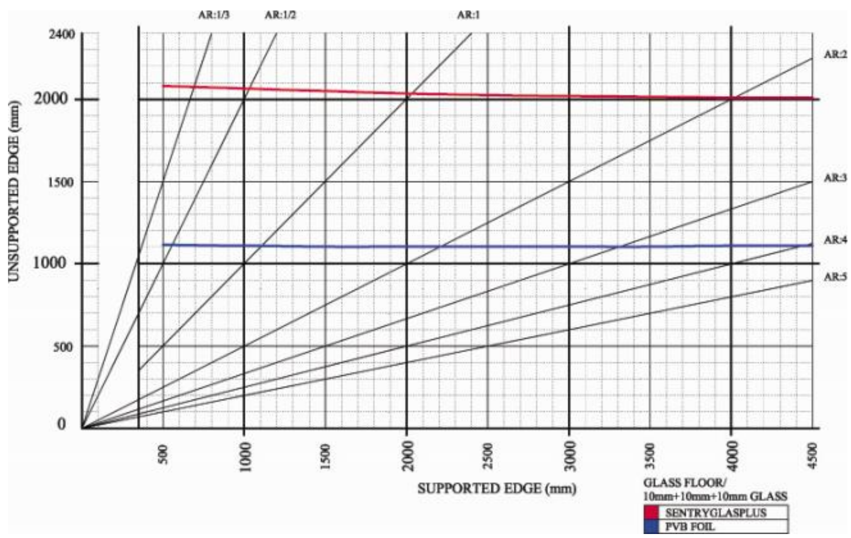



Figure 4.8. Comparison chart 2 for glass floors.

*Standard Parameters: GT: Tempered, GTk: 10 mm+ 10 mm+ 10 mm, IT: 1, 52mm, LL: 5000 N/m$^2$, SC: Two Opposite Sides Simply Supported, LC: Long Time Loading

The results of Figure 4.7 show PVB interlayer was behaving as a one way slab and variations between each 0.1m distance changes slightly small till exceeding aspect ratio two. After exceeding that point, significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 10 mm+ 10 mm+ 10 mm glass with PVB was 1,7 m to 1,825 m. By comparison, with SGP it was 3,5 m to 3,155 m which was also beyond the maximum available glass dimension. Possible maximum dimension difference between PVB and SGP were varying around 1,75m to 1,965 m. At 3,1m width difference was reaching 165%. Maxim um deflection 17,70 mm was achieved with SGP interlayer at 3,1 m x 3,155 m.

Two opposite sides simply supported condition for 10 mm+ 10 mm+ 10 mm glass results are presented in Figure 4.8. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between each 0.5m distance changes slightly small throughout available dimensions.

Maximum dimensions for 10 mm+ 10 mm+ 10 mm glass with PVB were 4,5 m x 1,11 m to 0,5 m x 1,115 m. By comparison, with SGP it was 4,5 m x 2,01 m to 0,5 m x 2,08 m. It was observed that all dimensions were in the limit of available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 0,9 m throughout the pane width and differing with slightly sm all intervals and SGP was 80% bigger than PVB interlayer. Maximum deflection 11,87 mm was achieved with SGP interlayer at 0,5 m to 2,08 m dimension.

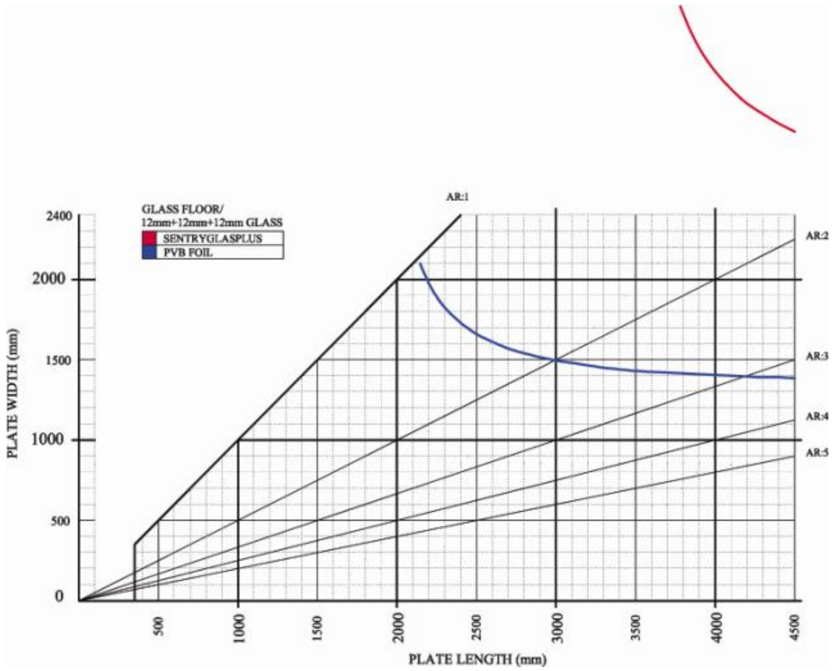



Figure 4.9. Comparison chart 3 for glass floors.

*Standard Parameters: GT: Tempered, GTk: 12 mm+ 12 mm + 12 mm, IT: 1,52mm, LL: 5000 N/m$^2$, SC: Four Side Simply Supported, LC: Long Time Loading

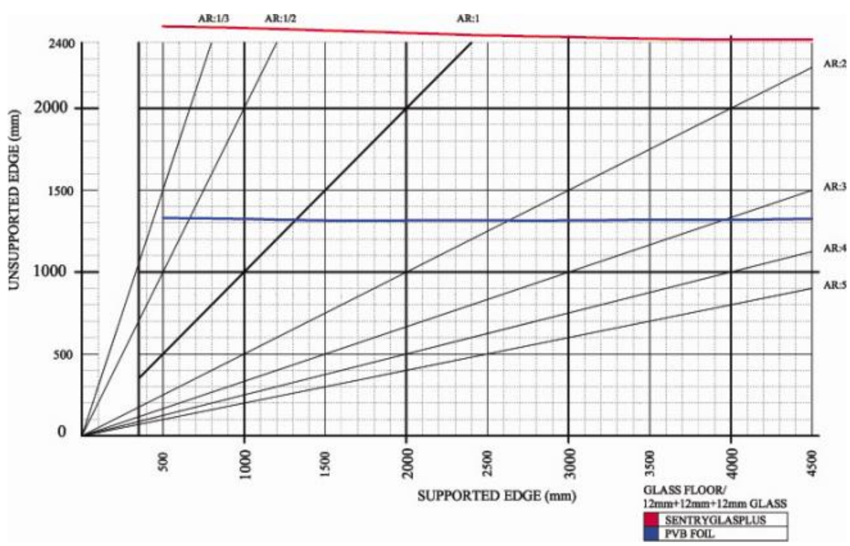



Figure 4.10. Comparison chart 4 for glass floors.

*Standard Parameters: GT: Tempered, GTk: 12 mm+ 12 mm+ 12 mm, IT: 1,52mm, LL: 5000 N/m$^2$, SC: Two Opposite Sides Simply Supported, LC: Long Time Loading

The results of Figure 4.9 show PVB interlayer was behaving as a one way slab and variations between each 0.1m distance changes slightly small till exceeding aspect ratio two. After exceeding that point, significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 12 mm+ 12 mm+ 12 mm glass with PVB was 2,1 m to 2,145 m. By comparison, with SGP it was 3,7 m to 3,7 8 m which was also beyond the maximum available glass dimension. Possible maximum dimension difference between PVB and SGP were varying around 1,75m to 2,36 m. At 3,7m width, difference was reaching 165%. Maximum deflection 21,13 mm was achieved with SGP interlayer at 3,7 m x 3,78 m.

Two opposite sides simply supported condition for 12 mm+ 12 mm+ 12 mm glass results are presented in Figure 4.10. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between each 0.5m distance changes slightly small throughout available dimensions.

Maximum dimensions for 12 mm+ 12 mm+ 12 mm glass with PVB were 4,5 m x 1,325 m to 0,5 m x 1,33 m. By comparison, with SGP it was 4,5 m x 2,42 m to 0,5 m x 2,5 m. It was observed that SGP dimensions were out of the limit of available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 1,1 m throughout the pane width and differing with slightly small intervals and SGP was 85% bigger than P VB interlayer. Maximum deflection 14,25 mm was achieved with SGP interlayer at 0,5 m to 2,5 m dimension.

### 4.3 Glass Roofs

The parameters are represented in Table 4.3 and analyses were conducted following these parameters. The results of the simulations ar e presented in Figure 4.11 to 4.16 respectively depending on their glass thickness parameters and support conditions. Their limit values are also presented as Appendix C.

Table 4.3. Parameters for glass roofs.

| STRUCTURAL ELEMENTS | PARAMETER TYPE | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *BASE PARAMETERS* | | | | | | *DEPENDENT PARAMETERS* | | | | | | |
| | INTERLAYER | | | SUPPORT | | | GLASS | | | | LOAD | | TEMPERATURE |
| | *Interlayer Type* | | *Interlayer Thickness (mm)* | *Support Condition* | | *Support Type* | *Laminated Glass Type* | *Glass Thickness (mm)* | | | *Load Type* | *Load Duration* | *Temperature Differance* |
| | PVB | SGP | 1,52 | Two Sided | Four Sided | Simple Support | Heat-Strength | 6+6 | 8+8 | 10+10 | Snow | Long | Outside/ ΔT:50$^0$C |
| **Glass Roof** | • | • | • | • | • | • | • | • | • | • | • | • | • |

Glass roof structure analyses were conducted throughout this section. Base parameters were two types of interlayer, PVB and SGP and support conditions, two sided or four sided support. Interlayer thickness 1,52mm and support type, simple support, were kept unchanged. Glass type was defines as heat-strength laminated glass and thickness combinations were defined as 6 mm+ 1,52mm+ 6 mm, 8 mm+ 1,52mm+ 8 mm, 10 mm+ 1,52mm+ 10 mm respectively. As direction vector of gravity of glass wall is horizontal and it was located on the outer contour of the building, it was affected by snow load value of 1250 N/m $^2$ and defined as long time loading. Thus temperature difference was selected as 50 $^0$C.

***Discussions on Results***

As observed, different types of interlayers with different stiffness properties created significantly big difference in critical limits and maximum possible dimensions for different types of glass thickness and support conditions. Maximum allowable deflection limit was dominant factor when analyzing the maximum possible dimension. Maximum allowable stress limit was never achieved.

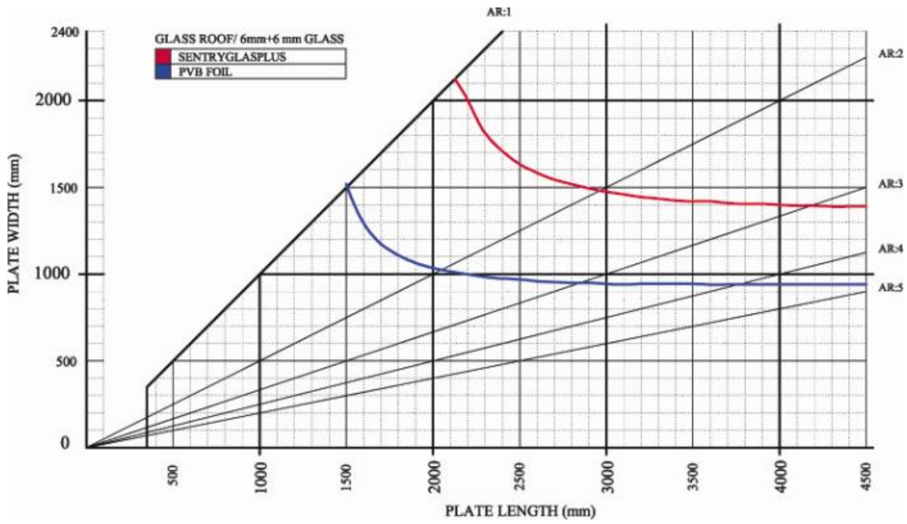



Figure 4.11. Comparison chart 1 for glass roofs.

*Standard Parameters: GT: Heat-Strength, GTk: 6 mm+ 6 mm, IT: 1,52mm, SL: 1250 N/m $^{2}$, SC: Four Side Simply Supported, LC: Long Time Loading

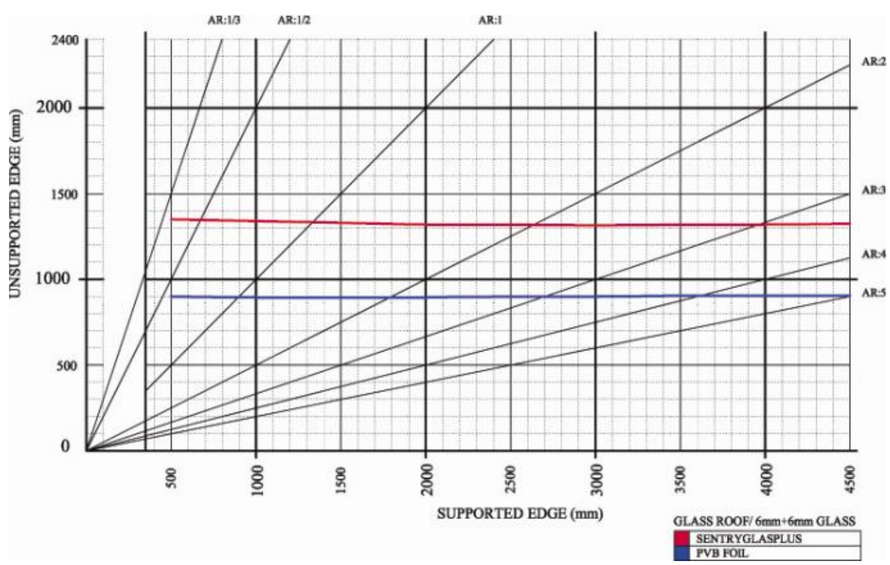



Figure 4.12. Comparison chart 2 for glass roofs.

*Standard Parameters: GT: Heat-Strength, GTk: 6 mm+ 6 mm, IT: 1,52mm, SL: 1250 N/m $^{2}$, SC: Two Opposite Sides Simply Supported, LC: Long Time Loading

The results of Figure 4.11 show that both of the interla yers were behaving as a one way slab and variations between each 0.1m distance changes slightly small till exceeding aspect ratio two. After exceeding that point, significantly great differences among variations and also maximum deflection and minimum stre ss within the glass pane were observed.

Maximum height limit dimension for 6 mm+ 6 mm glass with PVB was 1,5 m to 1,52 m. By comparison, with SGP it was 2,1 m to 2,165 m which were within the maximum available glass dimension. Possible maximum dimension d ifference between PVB and SGP were varying around 0,35 m till aspect ratio two. After that point, possible dimension difference was reaching 1,15 m at 2,5m width which was almost 110% bigger than PVB dimension. Maximum deflection 11,97 mm was achieved with SGP interlayer at 2,1 m x 2,165 m.

Two opposite sides simply supported condition for 6 mm+ 6 mm glass results are presented in Figure 4.12. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between e ach 0.5m distance changes slightly small throughout available dimensions.

Maximum dimensions for 6 mm+ 6 mm glass with PVB were 4,5 m x 0,905 m to 0,5 m x 0,9 m. By comparison, with SGP it was 4,5 m x 1,325 m to 0,5 m x 1,35 m. It was observed that all dimensions were in the limit of available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 0,4 m throughout the pane width and differing with slightly small intervals and SGP was 50% bigger than PVB interlayer. Maximum deflection 7,68 mm was achieved with SGP interlayer at 0,5 m to 1,35 m dimension.

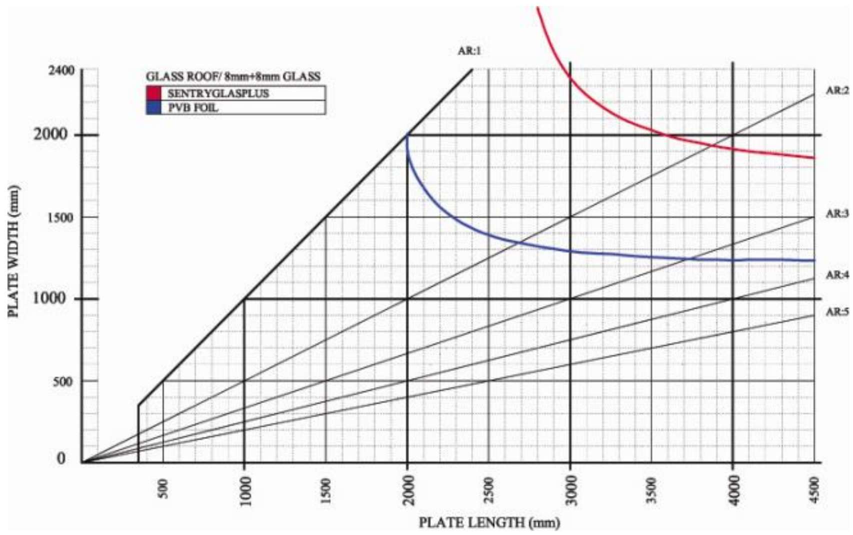



Figure 4.13. Comparison chart 3 for glass roofs.

*Standard Parameters: GT: Heat-Strength, GTk: 8 mm+ 8 mm, IT: 1,52mm, SL: 1250 N/m $^2$, SC: Four Side Simply Supported, LC: Long Time Loading

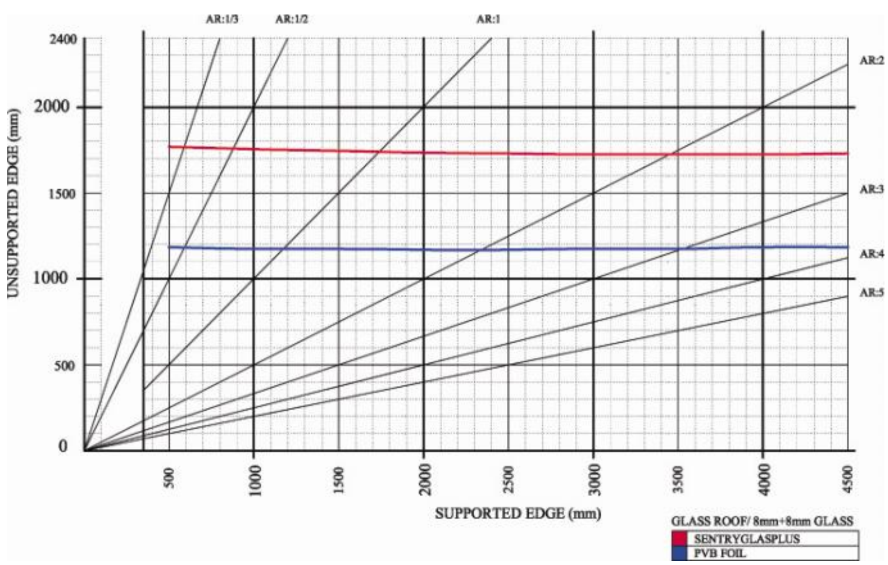



Figure 4.14. Comparison chart 4 for glass roofs.

*Standard Parameters: GT: Heat-Strength, GTk: 8 mm+ 8 mm, IT: 1,52mm, SL: 1250 N/m $^2$, SC: Two Opposite Sides Simply Supported, LC: Long Time Loading

The results of Figure 4.13 show that both of the interlayers were behaving as a one way slab and variations between each 0.1m distance changes slightly small till exceeding aspect ratio two. After exceeding that point, significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 8 mm+ 8 mm glass with PVB was 1,9 m to 2,05 m. By comparison, with SGP it was 2,7 m to 2,82 m, SGP was exceeding maximum available glass dimension. Possible maximum dimension difference between PVB and SGP were varying around 0,6 m till aspect ratio two. After that point, possible dimension difference was reaching 1,45 m at 2,7m width which was almost 110% bigger than PVB dimension. Maximum deflection 15,41 mm was achieved with SGP interlayer at 2,7 m x 2,82 m.

Two opposite sides simply supported condition for 8 mm+ 8 mm glass results are presented in Figure 4.14. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between each 0.5 m distance changes slightly small throughout available dimensions.

Maximum dimensions for 8 mm+ 8 mm glass with PVB were 4,5 m x 1,184m to 0,5 m x 1,185 m. By comparison, with SGP it was 4,5 m x 1,73 m to 0,5 m x 1,77 m. It was observed that all dimensions were in the limit of available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 0,6 m throughout the pane width and differing with slightly small intervals and SGP was 50% bigger than PVB interlayer. Maximum deflection 10,10 mm was achieved with SGP interlayer at 0,5 m to 1,77 m dimension.

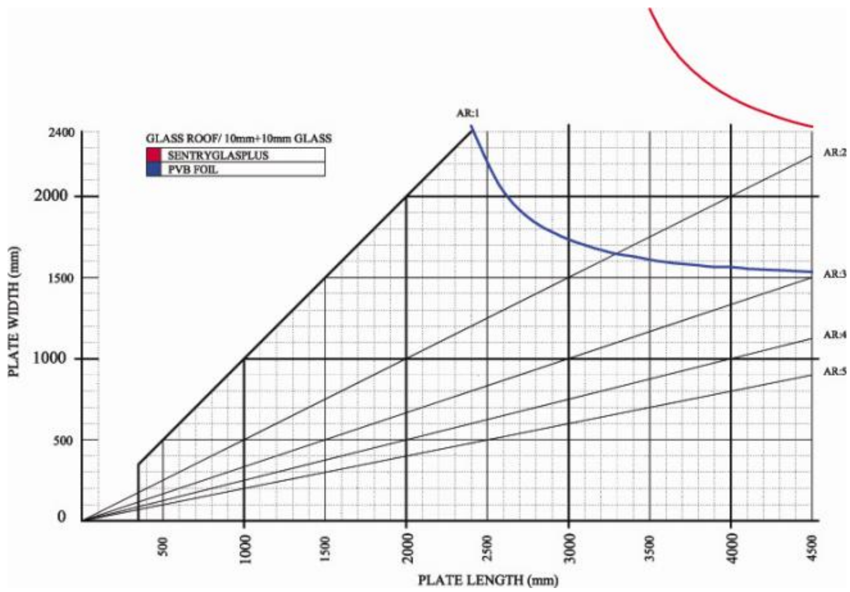



Figure 4.15. Comparison chart 5 for glass roofs.

*Standard Parameters: GT: Heat-Strength, GTk: 10 mm+ 10 mm, IT: 1,52mm, SL: 1250 N/m $^2$, SC: Four Side Simply Supported, LC: Long Time Loading

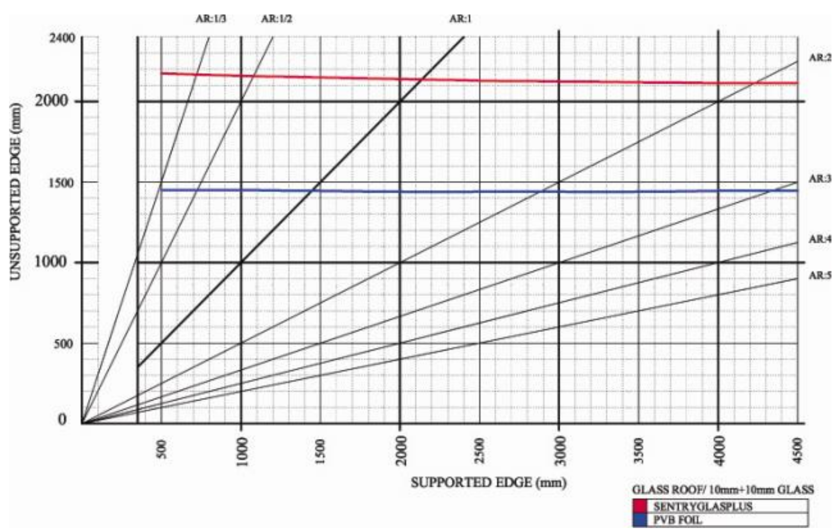



Figure 4.16. Comparison chart 6 for glass roofs.

*Standard Parameters: GT: Heat-Strength, GTk: 10 mm+ 10 mm, IT: 1,52mm, SL: 1250 N/m $^2$, SC: Two Opposite Sides Simply Supported, LC: Long Time Load ing

The results of Figure 4.15 show PVB interlayer was behaving as a one way slab and variations between each 0.1m distance changes slightly small till exceeding aspect ratio two. After exceeding that point, significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 10 mm+ 10 mm glass with PVB was 2,4 m to 2,435 m. By comparison, with SGP it was 3,4 m to 3,305 m, both were also exceeding maximum available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying between 0,9 m to 1,7 m which were almost between 58% to 100%. Maximum deflection 18,04 mm was achieved with SGP interlayer at 3,5 m to 3,16 m dimension.

Two opposite sides simply supported condition for 10 mm+ 10 mm glass results are presented in Figure 4.16. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between each 0.5 m distance changes slightly small throughout available dimensions. Maximum dimensions for 10 mm+ 10 mm glass with PVB were 4,5 m x 1,445 m to 0,5 m x 1,45 m. By comparison, with SGP it was 4,5 m x 2,115 m to 0,5 m x 2,175 m. It was observed that all dimensions were in the limit of available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 0,7 m throughout the pane width and differing with slightly small intervals and SGP was 50% bigger than PVB interlayer. Maximum deflection 12,41 mm was achieved with SGP interlayer at 0,5 m to 2,175 m dimension.

### 4.4 Glass Domes

The parameters are represented in Table 4.4 and analyses were conducted following these parameters. The results of the simulations are presented in Figure 4.17 to 4.22 respectively depending on their glass thickness parameters and support conditions. Their limit values are also presented as Appendix D.

Table 4.4. Parameters for glass domes.

| **STRUCTURAL ELEMENT** | **PARAMETER TYPE** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ***BASE PARAMETERS*** | | | | | | ***DEPENDENT PARAMETERS*** | | | | | | | | |
| | INTERLAYER | | | SUPPORT | | | GLASS | | | | LOAD | | | | TEMP. |
| | *Interlayer Type* | | *Interlayer Thickness (mm)* | *Support Condition* | | *Support Type* | *Laminated Glass Type* | *Glass Thickness (mm)* | | | *Load Type* | | *Load Duration* | | *Temperature Differance* |
| | PVB | SGP | 1,52 | Two Sided | Four Sided | Simple Support | Heat-Strength | 6+6 | 8+8 | 10+10 | Wind | Snow | Short | Long | Outside/ ΔT:$50^0$C |
| **Glass Dome** | • | • | • | • | • | • | • | • | • | • | • | • | • | • | • |

Glass dome structure analyses were conducted throughout this sectio n. Base parameters were two types of interlayer, PVB and SGP and support conditions, two sided or four sided support. Interlayer thickness 1,52mm and support type, simple support, were kept unchanged. Glass type was defines as heat -strength laminated glass and thickness combinations were defined as 6 mm+ 1,52mm+ 6 mm, 8 mm+ 1,52mm+ 8 mm, 10 mm+ 1,52mm+ 10 mm respectively. As the section angles of Glass Dome were changing almost between 0 °– 90° in other words that was the worst case, both snow and wind load had to be calculated together and it was located on the outer contour of the building, it was affected by both wind and snow load and the value is 1730 N/m$^2$ and defined as long time loading. Thus temperature difference was selected as $50^0$C.

***Discussions on Results***

As observed, different types of interlayers with different stiffness properties created significantly big difference in critical limits and maximum possible dimensions for different types of glass thickness and support conditions. Maximum allowa ble deflection limit was dominant factor when analyzing the maximum possible dimension. Maximum allowable stress limit was never achieved.

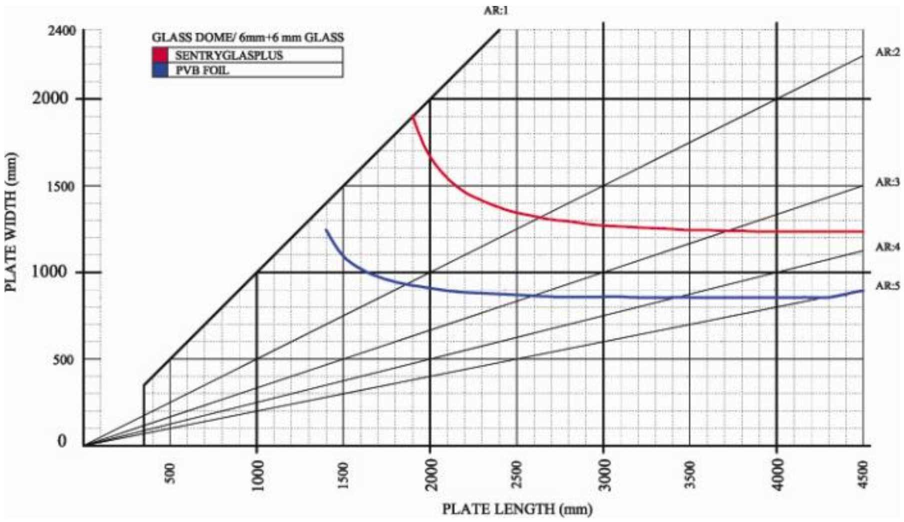



Figure 4.17. Comparison chart 1 for glass domes.

*Standard Parameters: GT: Heat-Strength, GTk: 6 mm+ 6 mm, IT: 1, 52mm, WL: 960 N/m$^2$, SL: 1250 N/m$^2$, SC: Four Side Simply Supported, LC: Long Time Loading

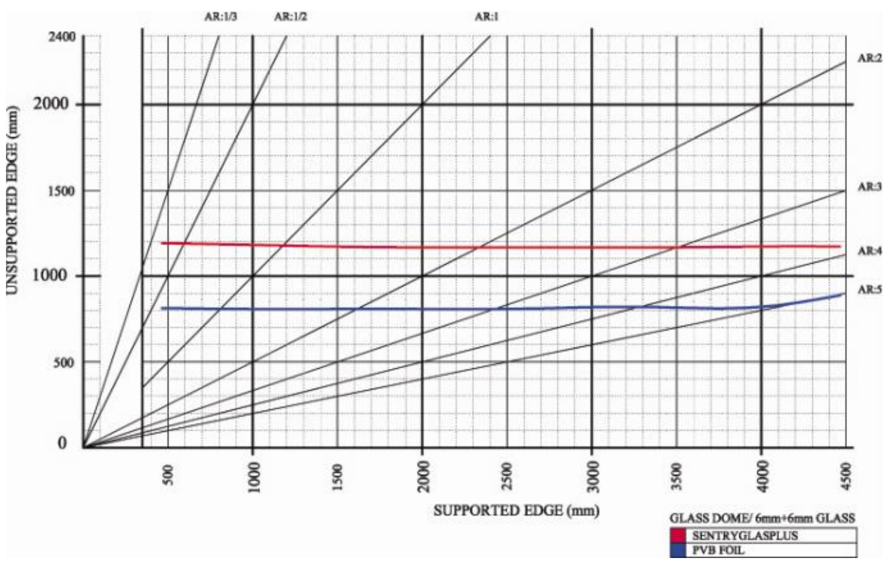



Figure 4.18. Comparison chart 2 for glass domes.

*Standard Parameters: GT: Heat-Strength, GTk: 6 mm+ 6 mm, IT: 1,52mm, WL: 960 N/m$^2$, SL: 1250 N/m$^2$, SC: Two Opposite Sides Simply Supported, LC: Long Time Loading

The results of Figure 4.17 show that both of the interlayers were behaving as a one way slab and variations between each 0.1m distance changes slightly small till exceeding aspect ratio two. After that point, significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 6 mm+ 6 mm glass with PVB was 1,3 m to 1,375 m. By comparison, with SGP it was 1,9 m to 1,905 m which was also beyond the maximum available glass dimension. Possible maximum dimension difference between PVB and SGP were varying around 0,35 m till aspect ratio two. After that point, possible dimension difference was reaching 1 m at 1,9 m wi dth which was almost 105% bigger than PVB dimension. Maximum deflection 10,82 mm was achieved with SGP interlayer at 1,9 m x 1,905 m dimension.

Two opposite sides simply supported condition for 6 mm+ 6 mm glass results are presented in Figure 4.18. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between each 0.5m distance changes slightly small throughout available dimensions.

Maximum dimensions for 6 mm+ 6 mm glass with PVB were 4,5 m x 0,895 m to 0,5 m x 0,82 m. By comparison, with SGP it was 4,5 m x 1,18 m to 0,5 m x 1,2 m. It was observed that all dimensions were in the limit of available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 0,4 m throughout the pane width and differing with slightly small intervals and SGP was 45% bigger than PVB interlayer. Maximum deflection 6,82 mm was achieved with SGP interlayer at 0,5 m x 1,2 m dimension.

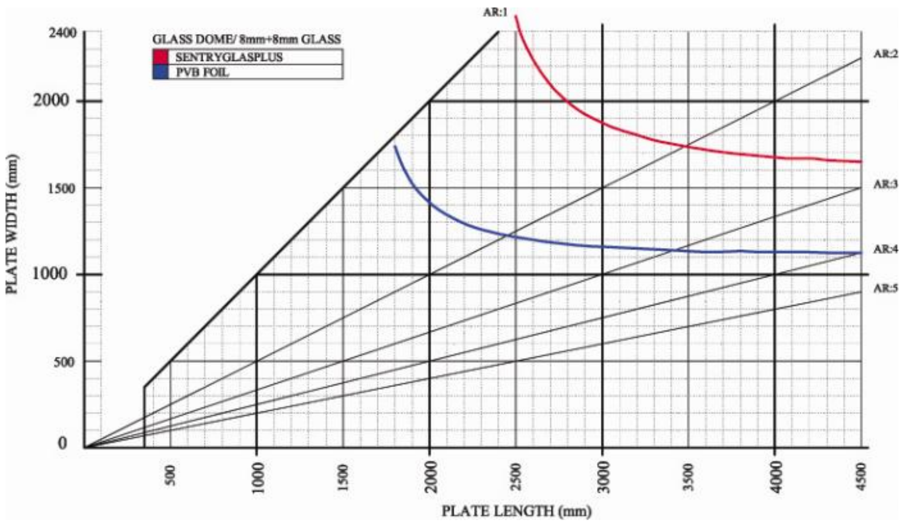



Figure 4.19. Comparison chart 3 for glass domes.

*Standard Parameters: GT: Heat-Strength, GTk: 8 mm+ 8 mm, IT: 1,52mm, WL: 960 $N/m^2$, SL: 1250 $N/m^2$, SC: Four Side Simply Supported, LC: Long Time Loading

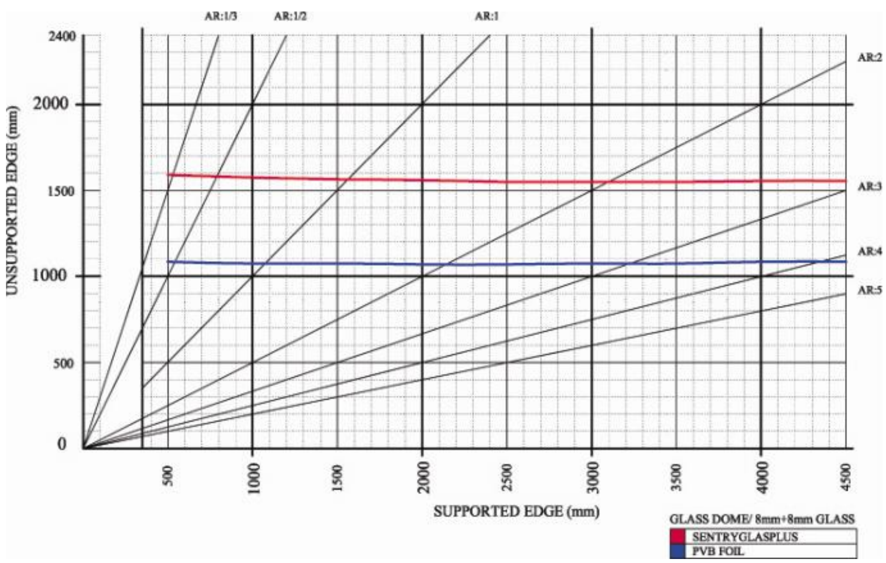



Figure 4.20. Comparison chart 4 for glass domes.

*Standard Parameters: GT: Heat-Strength, GTk: 8 mm+ 8 mm, IT: 1,52mm, WL: 960 $N/m^2$, SL: 1250 $N/m^2$, SC: Two Opposite Sides Simply Supported, LC: Long Time Loading

The results of Figure 4.18 show that both of the interlayers were behaving as a one way slab and variations between each 0.1m distance changes slight ly small till exceeding aspect ratio two. After that point, significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 6 mm+ 6 mm glass with PVB w as 1,7 m to 1,81 m. By comparison, with SGP it was 2,4 m to 2,535 m which was beyond the maximum available glass dimension. Possible maximum dimension difference between PVB and SGP were varying around 0,5 m till aspect ratio two. After that point, possible dimension difference was reaching 1,29 m at 2,4 m width which was almost 105% bigger than PVB dimension. Maximum deflection 13,68 mm was achieved with SGP interlayer at 2,4 m x 2,525 m dimension.

Two opposite sides simply supported condition for 6 mm+ 6 mm glass results are presented in Figure 4.20. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between each 0.5m distance changes slightly small throughout available dimensions.

Maximum dimensions for 6 mm+ 6 mm glass with PVB were 4,5 m x 1,085 m to 0,5 m x 1,085 m. By comparison, with SGP it was 4,5 m x 1,555 m to 0,5 m x 1,59 m. It was observed that all dimensions were in the limit of available glass dimensions. Possible maximum dimension differ ence between PVB and SGP were varying around 0,5 m throughout the pane width and differing with slightly small intervals and SGP was 45% bigger than PVB interlayer. Maximum deflection 9,06 mm was achieved with SGP interlayer at 0,5 m x 1,59 m dimension.

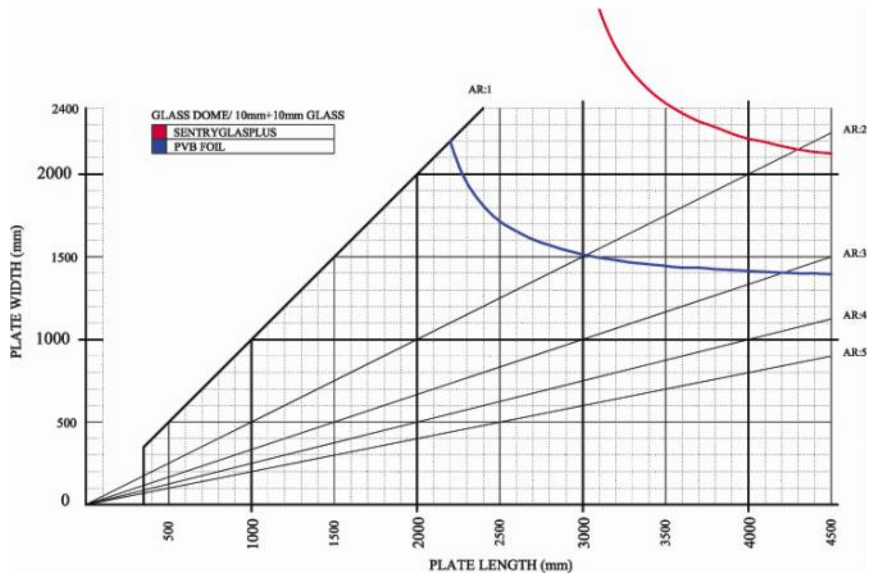



Figure 4.21. Comparison chart 5 for glass domes.

*Standard Parameters: GT: Heat-Strength, GTk: 10 mm+ 10 mm, IT: 1,52mm, WL: 960 N/m $^2$, SL: 1250 N/m$^2$, SC: Four Side Simply Supported, LC: Long Time Loading

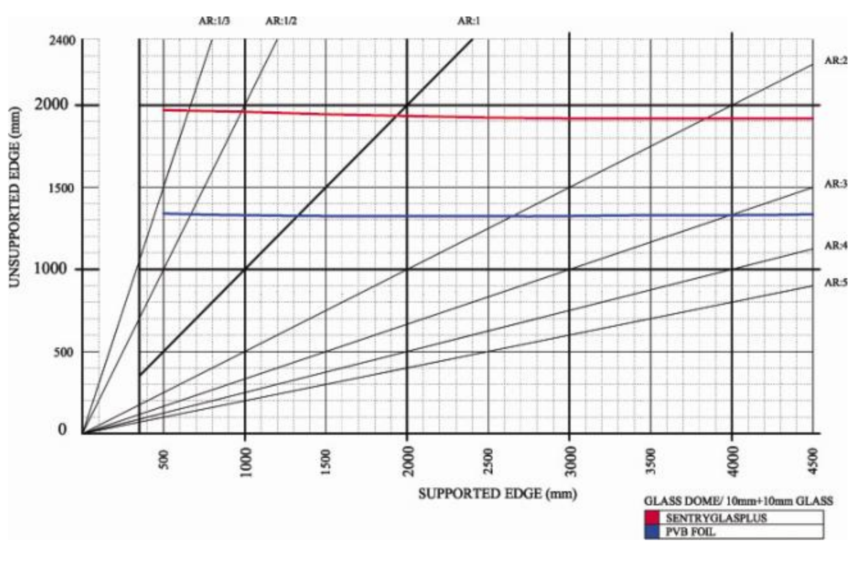



Figure 4.22. Comparison chart 6 for glass domes.

*Standard Parameters: GT: Heat-Strength, GTk: 10 mm+ 10 mm, IT: 1,52mm, WL: 960 N/m $^2$, SL: 1250 N/m$^2$, SC: Two Opposite Sides Simply Supported, LC: Long Time Loading

The results of Figure 4.21 show PVB interlayer was behaving as a one way slab and variations between each 0.1m distance changes slightly small till exceeding aspect ratio two. After exceeding that point, significantly great differences among variations and also maximum deflection and minimum stress within the glass pane were observed.

Maximum height limit dimension for 10 mm+ 10 mm glass with PVB was 2,2 m to 2,2 m. By comparison, with SGP it was 3,0 m to 3,095 m, SGP was exceeding maximum available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying between 0,7 m to 1,5 m which were almost between 52% to 100%. Maximum deflection 17,12 mm was achieved with SGP interlayer at 3,0 m to 3,095 m dimension.

Two opposite sides simply supported condition for 10 mm+ 10 mm glass results are presented in Figure 4.22. Both of the interlayers were behaving as a one way slab and dimension, deflection and stress variations between each 0.5 m distance changes slightly small throughout available dimensions. Maximum dimensions for 10 mm+ 10 mm glass with PVB were 4,5 m x 1,335 m to 0,5 m x 1,34 m. By comparison, with SGP it was 4,5 m x 1,92 m to 0,5 m x 1,97 m. It was observed that all dimensions were in the limit of available glass dimensions. Possible maximum dimension difference between PVB and SGP were varying around 0, 6 m throughout the pane width and differing with slightly small intervals and SGP was 47 % bigger than PVB interlayer. Maximum deflection 11,22 mm was achieved with SGP interlayer at 0,5 m to 1,97 m dimension.

# CHAPTER 5

# CONCLUSION

There is an increasing demand for structural glass elements, their designs become a major concern. A well known problem, glass is brittle. Laminated glass is emerging as a solution to an increasing variety of design problems. Interlayers are inserted between the glass panes to facilitate stresses to compose structural glass design as glass is unable to flow plastically to relieve high stresses.

This thesis describes the investigations conducted on interlayer's modulus properties. These investigations were based on design characteristics such as, the properties of the materials, materials thicknesses and construction standards. Possible maximum laminated glass dimensions were evaluated according to combination of parameters related to modulus properties of the interlayers and its structural performance.

Due to large number of variables considered in the analyses of several alternatives, computer assistance was essential to achieve minimum energy conservation. In this study laminated glass panes strength and deflection behavior created on pre-defined pane dimension were predicted by using the detailed finite element based simulation program SJ Mepla. The computer model was used for accurate description of the allowable limits and to create assessment of the maximum safe dimensions depending on pre-defined parameters.

During the study base and dependent parameter descriptions were composed by applying universal standards. In the next step structural element cases with different interlayer properties, support conditions, glass, loadings and temperature differences were generated with the simulation program. The results of the simulations were compared for each structural element regarding base parameters.

Interlayer modulus properties were proved to be an important facto r in structural performance. Significant dimension differences could result with proper choice of interlayer type. This research study was examined effects of two types of interlayer case; SentryGlas® Plus and Polyvinyl Butyral. Laminated glass panes stren gth and deflection for bending dominated cases are dependent on the modulus properties of the interlayer. Analyses of the research showed that a difference in maximum possible dimensions between SGP and PVB can result depending on their modulus properties. The highest dimension with allowable conditions was reached when SGP were used when compared to the corresponding element with PVB in base case.

The research study showed that the enhanced temperature performance was achieved when a combination of stiffe r interlayer was used. Overall deflections of SGP - laminates were lower than those predicted for PVB -laminates and that the deflection response is essentially stable with the time for these conditions. The stiffness of SGP versus PVB results in significant performance enhancements in deflection response over time at elevated temperatures.

The results of the simulation of this study have shown that where the type of the interlayer was the major concern, support type was the predominant effective structural factor. Four sided simple support had the highest effect on dimension, within the practical range of the glass dimension that has been established in evaluating case; increasing support edge have significant effect on reducing stress values.

This study revealed that in analyzing the impact of the aspect ratio information, four side simply supported cases always affected by aspect ratio dependent on structural element type that was analyzed. This information points out possible structure -form relation within the architectural and constructional perspectives.

With respect to maximum glass product profile, the analyses showed that this property should be improved. The results of the simulations have shown that maximum available glass dimension was exceeded. Companies involved in production must enhance current technology to achieve development in architectural and structural concept.

These results show the importance of interlayer types as the benefit were significantly high when considered that the evaluat ions were carried out on the interlayer types. These findings reveal that by expanding interlayer types to further interlayer related aspects of the construction, it is possible to create higher strength capacity or higher dimension possibilities. Such per formance attributes present architect and engineers with more design options for optimum performance glass structures. The future researchers can therefore analyze the aspects related to interlayer properties and their application on structural elements. As economical features were not analyzed throughout this study another aspect can be investigating the cost related properties of interlayer types and further structural usage of laminated glass.

***Further claims***

The increasing application of glass to enab le transparent architecture also for structural elements leads to wish of users to simple use design tables. However it is not possible to design one design table or the diagram for the design of complex structures. Further investigations and research has to be done to develop universal design tables for such a complex structural elements.

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# APPENDIX A/ GLASS WALL LIMITS

Table A.1. Glass wall limits, 1.

*Standard Parameters: GT: Heat-Strength, IT: 1,52mm, WL: 960 N/m$^2$, SC: Two Opposite Sides Simply Supported, LC: Short Time Loading, Non-Linear Calculation, Max. All. Def.:L/175

**Glass Wall/ 6+6 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.270 | -7,21 | -7,26 | 11,56 | 37,00 |
| 4.000 | 1.260 | -7,14 | -7,20 | 10,35 | 37,00 |
| 3.500 | 1.265 | -7,20 | -7,23 | 10,41 | 37,00 |
| 3.000 | 1.260 | -7,17 | -7,20 | 11,04 | 37,00 |
| 2.500 | 1.260 | -7,15 | -7,20 | 10,79 | 37,00 |
| 2.000 | 1.265 | -7,19 | -7,23 | 11,03 | 37,00 |
| 1.500 | 1.270 | -7,21 | -7,26 | 11,06 | 37,00 |
| 1.000 | 1.280 | -7,31 | -7,31 | 11,18 | 37,00 |
| 500 | 1.285 | -7,30 | -7,34 | 11,06 | 37,00 |

**Glass Wall/ 6+6 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.765 | -10,04 | -10,09 | 12,79 | 37,00 |
| 4.000 | 1.760 | -10,03 | -10,06 | 13,61 | 37,00 |
| 3.500 | 1.760 | -10,03 | -10,06 | 13,28 | 37,00 |
| 3.000 | 1.760 | -9,99 | -10,06 | 13,27 | 37,00 |
| 2.500 | 1.765 | -10,05 | -10,09 | 13,43 | 37,00 |
| 2.000 | 1.770 | -10,06 | -10,11 | 13,62 | 37,00 |
| 1.500 | 1.780 | -10,16 | -10,17 | 13,71 | 37,00 |
| 1.000 | 1.790 | -10,22 | -10,23 | 13,65 | 37,00 |
| 500 | 1.800 | -10,25 | -10,29 | 13,38 | 37,00 |

**Glass Wall/ 8+8 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.725 | -9,81 | -9,86 | 10,54 | 37,00 |
| 4.000 | 1.720 | -9,80 | -9,83 | 11,18 | 37,00 |
| 3.500 | 1.725 | -9,84 | -9,86 | 11,21 | 37,00 |
| 3.000 | 1.725 | -9,80 | -9,86 | 10,95 | 37,00 |
| 2.500 | 1.735 | -9,91 | -9,91 | 11,22 | 37,00 |
| 2.000 | 1.740 | -9,91 | -9,94 | 11,24 | 37,00 |
| 1.500 | 1.750 | -10,00 | -10,00 | 11,33 | 37,00 |
| 1.000 | 1.755 | -10,00 | -10,03 | 11,34 | 37,00 |
| 500 | 1.765 | -10,06 | -10,09 | 11,17 | 37,00 |

**Glass Wall/ 8+8 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 2.300 | -13,11 | -13,14 | 13,42 | 37,00 |
| 4.000 | 2.300 | -13,07 | -13,14 | 13,41 | 37,00 |
| 3.500 | 2.305 | -13,14 | -13,17 | 13,73 | 37,00 |
| 3.000 | 2.310 | -13,17 | -13,20 | 13,62 | 37,00 |
| 2.500 | 2.315 | -13,18 | -13,23 | 13,70 | 37,00 |
| 2.000 | 2.325 | -13,28 | -13,29 | 13,86 | 37,00 |
| 1.500 | 2.330 | -13,25 | -13,31 | 13,79 | 37,00 |
| 1.000 | 2.345 | -13,40 | -13,40 | 13,70 | 37,00 |
| 500 | 2.355 | -13,44 | -13,46 | 13,50 | 37,00 |

**Glass Wall/ 10+10 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 2.200 | -12,56 | -12,57 | 11,34 | 37,00 |
| 4.000 | 2.200 | -12,52 | -12,57 | 11,08 | 37,00 |
| 3.500 | 2.205 | -12,54 | -12,60 | 11,29 | 37,00 |
| 3.000 | 2.215 | -12,63 | -12,66 | 11,23 | 37,00 |
| 2.500 | 2.225 | -12,71 | -12,71 | 11,40 | 37,00 |
| 2.000 | 2.230 | -12,69 | -12,74 | 11,42 | 37,00 |
| 1.500 | 2.240 | -12,77 | -12,80 | 11,50 | 37,00 |
| 1.000 | 2.250 | -12,85 | -12,86 | 11,48 | 37,00 |
| 500 | 2.260 | -12,90 | -12,91 | 11,32 | 37,00 |

**Glass Wall/ 10+10 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 2.845 | -16,23 | -16,26 | 13,82 | 37,00 |
| 4.000 | 2.850 | -16,27 | -16,29 | 13,70 | 37,00 |
| 3.500 | 2.855 | -16,30 | -16,31 | 13,87 | 37,00 |
| 3.000 | 2.860 | -16,30 | -16,34 | 13,82 | 37,00 |
| 2.500 | 2.870 | -16,40 | -16,40 | 13,96 | 37,00 |
| 2.000 | 2.875 | -16,38 | -16,43 | 13,92 | 37,00 |
| 1.500 | 2.885 | -16,44 | -16,49 | 13,85 | 37,00 |
| 1.000 | 2.895 | -16,49 | -16,54 | 13,66 | 37,00 |
| 500 | 2.905 | -16,54 | -16,60 | 13,49 | 37,00 |

## Table A.2. Glass wall limits, 2.

*Standard Parameters: GT: Heat-Strength, GTk: 6 mm+ 6 mm, IT: 1,52mm, WL: 960 N/m $^2$, SC: Four Sides Simply Supported, LC: Short Time Loading, Non-Linear Calculation, Max. All. Def.:L/175

**6+6 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm²) | σ all. (N/mm²) |
|---|---|---|---|---|---|
| 4.500 | 1.180 | -6,73 | -6,74 | 13,07 | 37,00 |
| 4.400 | 1.180 | -6,73 | -6,74 | 13,06 | 37,00 |
| 4.300 | 1.180 | -6,72 | -6,74 | 13,04 | 37,00 |
| 4.200 | 1.180 | -6,71 | -6,74 | 13,02 | 37,00 |
| 4.100 | 1.180 | -6,70 | -6,74 | 13,00 | 37,00 |
| 4.000 | 1.185 | -6,77 | -6,77 | 13,05 | 37,00 |
| 3.900 | 1.180 | -6,74 | -6,74 | 11,74 | 37,00 |
| 3.800 | 1.180 | -6,73 | -6,74 | 11,70 | 37,00 |
| 3.700 | 1.180 | -6,70 | -6,74 | 11,65 | 37,00 |
| 3.600 | 1.185 | -6,75 | -6,77 | 11,66 | 37,00 |
| 3.500 | 1.190 | -6,79 | -6,80 | 11,66 | 37,00 |
| 3.400 | 1.190 | -6,75 | -6,80 | 11,59 | 37,00 |
| 3.300 | 1.195 | -6,78 | -6,83 | 11,56 | 37,00 |
| 3.200 | 1.205 | -6,87 | -6,89 | 11,58 | 37,00 |
| 3.100 | 1.210 | -6,88 | -6,91 | 11,52 | 37,00 |
| 3.000 | 1.215 | -6,93 | -6,94 | 12,16 | 37,00 |
| 2.900 | 1.225 | -6,99 | -7,00 | 12,10 | 37,00 |
| 2.800 | 1.235 | -7,02 | -7,06 | 12,01 | 37,00 |
| 2.700 | 1.250 | -7,10 | -7,14 | 11,93 | 37,00 |
| 2.600 | 1.270 | -7,23 | -7,26 | 11,84 | 37,00 |
| 2.500 | 1.295 | -7,38 | -7,40 | 11,48 | 37,00 |
| 2.400 | 1.330 | -7,60 | -7,60 | 11,36 | 37,00 |
| 2.300 | 1.370 | -7,81 | -7,83 | 11,18 | 37,00 |
| 2.200 | 1.435 | -8,19 | -8,20 | 11,09 | 37,00 |
| 2.100 | 1.535 | -8,76 | -8,77 | 10,70 | 37,00 |
| 2.000 | 1.730 | -9,87 | -9,89 | 10,24 | 37,00 |
| ***1.900*** | ***1.955*** | ***-10,83*** | ***-10,86*** | ***10,11*** | ***37,00*** |

**6+6 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm²) | σ all. (N/mm²) |
|---|---|---|---|---|---|
| 4.500 | 1.715 | -9,79 | -9,80 | 14,15 | 37,00 |
| 4.400 | 1.720 | -9,81 | -9,83 | 14,12 | 37,00 |
| 4.300 | 1.720 | -9,82 | -9,83 | 14,91 | 37,00 |
| 4.200 | 1.725 | -9,83 | -9,86 | 14,85 | 37,00 |
| 4.100 | 1.735 | -9,91 | -9,91 | 14,83 | 37,00 |
| 4.000 | 1.740 | -9,89 | -9,94 | 14,74 | 37,00 |
| 3.900 | 1.750 | -9,94 | -10,00 | 14,69 | 37,00 |
| 3.800 | 1.765 | -10,06 | -10,09 | 14,67 | 37,00 |
| 3.700 | 1.780 | -10,16 | -10,17 | 14,61 | 37,00 |
| 3.600 | 1.795 | -10,24 | -10,26 | 14,54 | 37,00 |
| 3.500 | 1.810 | -10,31 | -10,34 | 14,11 | 37,00 |
| 3.400 | 1.835 | -10,48 | -10,49 | 14,05 | 37,00 |
| 3.300 | 1.860 | -10,61 | -10,63 | 13,94 | 37,00 |
| 3.200 | 1.890 | -10,77 | -10,80 | 13,82 | 37,00 |
| 3.100 | 1.930 | -11,02 | -11,03 | 13,90 | 37,00 |
| 3.000 | 1.980 | -11,31 | -11,31 | 13,74 | 37,00 |
| 2.900 | 2.040 | -11,63 | -11,66 | 13,43 | 37,00 |
| 2.800 | 2.130 | -12,16 | -12,17 | 13,21 | 37,00 |
| 2.700 | 2.255 | -12,88 | -12,89 | 12,97 | 37,00 |
| 2.600 | 2.455 | -14,02 | -14,03 | 12,56 | 37,00 |
| ***2.500*** | ***2.585*** | ***-14,28*** | ***-14,29*** | ***12,50*** | ***37,00*** |

Table A.3. Glass wall limits, 3.

*Standard Parameters: GT: Heat-Strength, GTk: 8 mm+ 8 mm, IT: 1,52mm, WL: 960 N/m$^2$, SC: Four Sides Simply Supported, LC: Short Time Loading, Non-Linear Calculation, Max. All. Def.:L/175

**8+8 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.550 | -8,85 | -8,86 | 11,85 | 37,00 |
| 4.400 | 1.580 | -9,00 | -9,03 | 12,07 | 37,00 |
| 4.300 | 1.585 | -9,02 | -9,06 | 12,05 | 37,00 |
| 4.200 | 1.590 | -9,04 | -9,09 | 12,02 | 37,00 |
| 4.100 | 1.600 | -9,13 | -9,14 | 12,02 | 37,00 |
| 4.000 | 1.600 | -9,12 | -9,14 | 12,66 | 37,00 |
| 3.900 | 1.610 | -9,19 | -9,20 | 12,62 | 37,00 |
| 3.800 | 1.620 | -9,24 | -9,26 | 12,57 | 37,00 |
| 3.700 | 1.630 | -9,27 | -9,31 | 12,51 | 37,00 |
| 3.600 | 1.645 | -9,36 | -9,40 | 12,45 | 37,00 |
| 3.500 | 1.665 | -9,50 | -9,51 | 12,41 | 37,00 |
| 3.400 | 1.685 | -9,62 | -9,63 | 12,33 | 37,00 |
| 3.300 | 1.705 | -9,71 | -9,74 | 11,97 | 37,00 |
| 3.200 | 1.735 | -9,88 | -9,91 | 11,88 | 37,00 |
| 3.100 | 1.775 | -10,13 | -10,14 | 11,77 | 37,00 |
| 3.000 | 1.820 | -10,38 | -10,40 | 11,79 | 37,00 |
| 2.900 | 1.885 | -10,77 | -10,77 | 11,61 | 37,00 |
| 2.800 | 1.970 | -11,24 | -11,26 | 11,31 | 37,00 |
| 2.700 | 2.105 | -12,02 | -12,03 | 11,03 | 37,00 |
| 2.600 | 2.345 | -13,39 | -13,40 | 10,67 | 37,00 |
| ***2.500*** | ***2.560*** | ***-14,26*** | ***-14,29*** | ***10,58*** | ***37,00*** |

**8+8 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 2.305 | -13,66 | -13,17 | 14,64 | 37,00 |
| 4.400 | 2.325 | -13,27 | -13,29 | 13,29 | 37,00 |
| 4.300 | 2.345 | -13,35 | -13,40 | 14,45 | 37,00 |
| 4.200 | 2.375 | -13,55 | -13,57 | 14,39 | 37,00 |
| 4.100 | 2.405 | -13,71 | -13,74 | 14,29 | 37,00 |
| 4.000 | 2.440 | -13,91 | -13,94 | 14,40 | 37,00 |
| 3.900 | 2.485 | -14,18 | -14,20 | 14,28 | 37,00 |
| 3.800 | 2.535 | -14,45 | -14,49 | 14,13 | 37,00 |
| 3.700 | 2.600 | -14,84 | -14,86 | 13,87 | 37,00 |
| 3.600 | 2.685 | -15,34 | -15,34 | 13,69 | 37,00 |
| 3.500 | 2.790 | -15,93 | -15,94 | 13,47 | 37,00 |
| 3.400 | 2.940 | -16,80 | -16,80 | 13,26 | 37,00 |
| 3.300 | 3.155 | -18,02 | -18,03 | 12,91 | 37,00 |
| ***3.200*** | ***3.285*** | ***-18,28*** | ***-18,29*** | ***12,85*** | ***37,00*** |

Table A.4. Glass wall limits, 4.

*Standard Parameters: GT: Heat-Strength, GTk: 10 mm+ 10 mm, IT: 1,52mm, WL: 960 N/m$^2$, SC: Four Sides Simply Supported, LC: Short Time Loading, Non-Linear Calculation, Max. All. Def.:L/175

**10+10 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 2.030 | -11,58 | -11,60 | 12,95 | 37,00 |
| 4.400 | 2.045 | -11,66 | -11,69 | 12,90 | 37,00 |
| 4.300 | 2.065 | -11,80 | -11,80 | 12,86 | 37,00 |
| 4.200 | 2.085 | -11,91 | -11,91 | 12,80 | 37,00 |
| 4.100 | 2.105 | -12,01 | -12,03 | 12,45 | 37,00 |
| 4.000 | 2.135 | -12,20 | -12,20 | 12,39 | 37,00 |
| 3.900 | 2.165 | -12,36 | -12,37 | 12,29 | 37,00 |
| 3.800 | 2.205 | -12,60 | -12,60 | 12,20 | 37,00 |
| 3.700 | 2.250 | -12,85 | -12,86 | 12,25 | 37,00 |
| 3.600 | 2.310 | -13,19 | -13,20 | 12,11 | 37,00 |
| 3.500 | 2.385 | -13,62 | -13,63 | 11,93 | 37,00 |
| 3.400 | 2.485 | -14,18 | -14,20 | 11,67 | 37,00 |
| 3.300 | 2.635 | -15,05 | -15,06 | 11,43 | 37,00 |
| 3.200 | 2.870 | -16,39 | -16,40 | 11,13 | 37,00 |
| ***3.100*** | ***3.140*** | ***-17,69*** | ***-17,71*** | ***10,99*** | ***37,00*** |

**10+10 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 3.115 | -17,79 | -17,80 | 14,45 | 37,00 |
| 4.400 | 3.185 | -18,18 | -18,20 | 14,17 | 37,00 |
| 4.300 | 3.275 | -18,70 | -18,71 | 14,00 | 37,00 |
| 4.200 | 3.390 | -19,37 | -19,37 | 13,88 | 37,00 |
| 4.100 | 3.535 | -20,19 | -20,20 | 13,64 | 37,00 |
| 4.000 | 3.740 | -21,37 | -21,37 | 13,34 | 37,00 |
| ***3.900*** | ***3.940*** | ***-22,26*** | ***-22,29*** | ***13,15*** | ***37,00*** |

# APPENDIX B/ GLASS FLOOR LIMITS

Table B.1. Glass floor limits, 1.

*Standard Parameters: GT: Tempered Glass, IT: 1,52mm, WL: 5000 N/m $^2$, SC: Two Opposite Sides Simply Supported, LC: LongTime Loading, Non -Linear Calculation, Max. All. Def.:L/175

| 10+10+10 glass/ PVB | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 1.110 | -6,30 | -6,34 | 18,57 | 50,00 |
| 4.000 | 1.110 | -6,30 | -6,34 | 18,60 | 50,00 |
| 3.500 | 1.105 | -6,26 | -6,31 | 16,95 | 50,00 |
| 3.000 | 1.105 | -6,26 | -6,31 | 16,99 | 50,00 |
| 2.500 | 1.105 | -6,31 | -6,31 | 18,05 | 50,00 |
| 2.000 | 1.105 | -6,31 | -6,31 | 17,63 | 50,00 |
| 1.500 | 1.105 | -6,29 | -6,31 | 17,77 | 50,00 |
| 1.000 | 1.110 | -6,34 | -6,34 | 18,06 | 50,00 |
| 500 | 1.115 | -6,34 | -6,37 | 17,72 | 50,00 |

| 10+10+10 glass/ SGP | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 2.010 | -11,48 | -11,49 | 20,22 | 50,00 |
| 4.000 | 2.010 | -11,46 | -11,49 | 19,73 | 50,00 |
| 3.500 | 2.015 | -11,51 | -11,51 | 19,75 | 50,00 |
| 3.000 | 2.020 | -11,54 | -11,54 | 20,09 | 50,00 |
| 2.500 | 2.025 | -11,53 | -11,57 | 20,03 | 50,00 |
| 2.000 | 2.035 | -11,57 | -11,63 | 20,08 | 50,00 |
| 1.500 | 2.050 | -11,68 | -11,71 | 20,22 | 50,00 |
| 1.000 | 2.065 | -11,77 | -11,80 | 20,36 | 50,00 |
| 500 | 2.080 | -11,87 | -11,89 | 20,50 | 50,00 |

| 12+12+12 glass/ PVB | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 1.325 | -7,54 | -7,57 | 18,79 | 50,00 |
| 4.000 | 1.320 | -7,51 | -7,54 | 17,14 | 50,00 |
| 3.500 | 1.320 | -7,51 | -7,54 | 17,17 | 50,00 |
| 3.000 | 1.315 | -7,45 | -7,51 | 18,10 | 50,00 |
| 2.500 | 1.315 | -7,46 | -7,51 | 17,67 | 50,00 |
| 2.000 | 1.315 | -7,44 | -7,51 | 18,03 | 50,00 |
| 1.500 | 1.320 | -7,51 | -7,54 | 18,13 | 50,00 |
| 1.000 | 1.325 | -7,55 | -7,57 | 18,13 | 50,00 |
| 500 | 1.330 | -7,54 | -7,60 | 17,69 | 50,00 |

| 12+12+12 glass/ SGP | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 2.420 | -13,82 | -13,83 | 20,43 | 50,00 |
| 4.000 | 2.420 | -13,78 | -13,83 | 20,72 | 50,00 |
| 3.500 | 2.425 | -13,80 | -13,86 | 20,73 | 50,00 |
| 3.000 | 2.435 | -13,88 | -13,91 | 20,75 | 50,00 |
| 2.500 | 2.445 | -13,93 | -13,97 | 20,67 | 50,00 |
| 2.000 | 2.460 | -14,04 | -14,06 | 20,91 | 50,00 |
| 1.500 | 2.475 | -14,14 | -14,14 | 21,02 | 50,00 |
| 1.000 | 2.490 | -14,22 | -14,23 | 21,13 | 50,00 |
| 500 | 2.500 | -14,25 | -14,29 | 21,17 | 50,00 |

## Table B.2. Glass floor limits, 2.

*Standard Parameters: GT: Tempered Glass, GTk: 10 mm+ 10 mm+ 10mm, IT: 1,52mm, WL: 5000 N/m $^2$, SC: Four Sides Simply Supported, LC: Long Time Loading, Non -Linear Calculation, Max. All. Def.:L/175

| 10+10+10 glass/ PVB | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 1.155 | -6,55 | -6,60 | 18,74 | 50,00 |
| 4.400 | 1.155 | -6,54 | -6,60 | 18,71 | 50,00 |
| 4.300 | 1.155 | -6,53 | -6,60 | 18,67 | 50,00 |
| 4.200 | 1.160 | -6,61 | -6,63 | 18,76 | 50,00 |
| 4.100 | 1.160 | -6,59 | -6,63 | 18,71 | 50,00 |
| 4.000 | 1.160 | -6,57 | -6,63 | 18,66 | 50,00 |
| 3.900 | 1.165 | -6,65 | -6,66 | 18,72 | 50,00 |
| 3.800 | 1.160 | -6,57 | -6,63 | 16,94 | 50,00 |
| 3.700 | 1.165 | -6,64 | -6,66 | 16,98 | 50,00 |
| 3.600 | 1.165 | -6,60 | -6,66 | 16,89 | 50,00 |
| 3.500 | 1.170 | -6,65 | -6,69 | 16,90 | 50,00 |
| 3.400 | 1.175 | -6,69 | -6,71 | 16,89 | 50,00 |
| 3.300 | 1.180 | -6,73 | -6,74 | 16,86 | 50,00 |
| 3.200 | 1.185 | -6,75 | -6,77 | 16,82 | 50,00 |
| 3.100 | 1.190 | -6,77 | -6,80 | 16,75 | 50,00 |
| 3.000 | 1.195 | -6,77 | -6,83 | 16,65 | 50,00 |
| 2.900 | 1.200 | -6,80 | -6,86 | 17,47 | 50,00 |
| 2.800 | 1.210 | -6,86 | -6,91 | 17,39 | 50,00 |
| 2.700 | 1.225 | -6,98 | -7,00 | 17,35 | 50,00 |
| 2.600 | 1.240 | -7,07 | -7,09 | 17,25 | 50,00 |
| 2.500 | 1.255 | -7,13 | -7,17 | 16,69 | 50,00 |
| 2.400 | 1.280 | -7,31 | -7,31 | 16,58 | 50,00 |
| 2.300 | 1.305 | -7,43 | -7,46 | 16,38 | 50,00 |
| 2.200 | 1.340 | -7,62 | -7,66 | 16,41 | 50,00 |
| 2.100 | 1.390 | -7,92 | -7,94 | 16,13 | 50,00 |
| 2.000 | 1.460 | -8,33 | -8,34 | 15,65 | 50,00 |
| 1.900 | 1.570 | -8,97 | -8,97 | 15,27 | 50,00 |
| 1.800 | 1.760 | -10,05 | -10,06 | 14,58 | 50,00 |
| ***1.700*** | ***1.825*** | ***-9,71*** | ***-9,71*** | ***14,76*** | ***50,00*** |

| 10+10+10 glass/ SGP | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 2.230 | -12,68 | -12,74 | 20,88 | 50,00 |
| 4.400 | 2.250 | -12,84 | -12,86 | 20,44 | 50,00 |
| 4.300 | 2.270 | -12,97 | -12,97 | 20,40 | 50,00 |
| 4.200 | 2.290 | -13,08 | -13,09 | 20,34 | 50,00 |
| 4.100 | 2.310 | -13,16 | -13,20 | 20,23 | 50,00 |
| 4.000 | 2.340 | -13,35 | -13,37 | 20,18 | 50,00 |
| 3.900 | 2.370 | -13,51 | -13,54 | 20,35 | 50,00 |
| 3.800 | 2.410 | -13,75 | -13,77 | 20,25 | 50,00 |
| 3.700 | 2.455 | -14,00 | -14,03 | 20,11 | 50,00 |
| 3.600 | 2.515 | -14,36 | -14,37 | 19,99 | 50,00 |
| 3.500 | 2.585 | -14,76 | -14,77 | 19,68 | 50,00 |
| 3.400 | 2.675 | -15,27 | -15,29 | 19,48 | 50,00 |
| 3.300 | 2.800 | -15,99 | -16,00 | 19,33 | 50,00 |
| 3.200 | 2.985 | -17,05 | -17,06 | 18,98 | 50,00 |
| ***3.100*** | ***3.155*** | ***-17,70*** | ***-17,71*** | ***18,81*** | ***50,00*** |

Table B.3. Glass floor limits, 3.

*Standard Parameters: GT: Tempered Glass, GTk: 12 mm+ 12 mm+ 12 mm, IT: 1,52mm, WL: 5000 N/m $^2$, SC: Four Sides Simply Supported, LC: Long Time Loading, Non -Linear Calculation, Max. All. Def.:L/175

| 12+12+12 glass/ PVB | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 1.385 | -7,85 | -7,91 | 17,09 | 50,00 |
| 4.400 | 1.390 | -7,92 | -7,94 | 17,12 | 50,00 |
| 4.300 | 1.390 | -7,88 | -7,94 | 17,04 | 50,00 |
| 4.200 | 1.395 | -7,93 | -7,97 | 17,05 | 50,00 |
| 4.100 | 1.400 | -7,98 | -8,00 | 17,05 | 50,00 |
| 4.000 | 1.405 | -8,02 | -8,03 | 17,03 | 50,00 |
| 3.900 | 1.410 | -8,05 | -8,06 | 17,00 | 50,00 |
| 3.800 | 1.415 | -8,07 | -8,09 | 16,96 | 50,00 |
| 3.700 | 1.420 | -8,09 | -8,11 | 16,90 | 50,00 |
| 3.600 | 1.425 | -8,09 | -8,14 | 16,82 | 50,00 |
| 3.500 | 1.430 | -8,13 | -8,17 | 17,68 | 50,00 |
| 3.400 | 1.440 | -8,20 | -8,23 | 17,63 | 50,00 |
| 3.300 | 1.450 | -8,25 | -8,29 | 17,54 | 50,00 |
| 3.200 | 1.465 | -8,36 | -8,37 | 17,50 | 50,00 |
| 3.100 | 1.480 | -8,45 | -8,46 | 17,40 | 50,00 |
| 3.000 | 1.495 | -8,51 | -8,54 | 17,27 | 50,00 |
| 2.900 | 1.515 | -8,62 | -8,66 | 16,74 | 50,00 |
| 2.800 | 1.540 | -8,77 | -8,80 | 16,61 | 50,00 |
| 2.700 | 1.570 | -8,93 | -8,97 | 16,44 | 50,00 |
| 2.600 | 1.610 | -9,18 | -9,20 | 16,51 | 50,00 |
| 2.500 | 1.660 | -9,46 | -9,49 | 16,26 | 50,00 |
| 2.400 | 1.730 | -9,88 | -9,89 | 15,84 | 50,00 |
| 2.300 | 1.825 | -10,41 | -10,43 | 15,48 | 50,00 |
| 2.200 | 1.975 | -11,27 | -11,29 | 15,06 | 50,00 |
| ***2.100*** | ***2.145*** | ***-11,98*** | ***-12,00*** | ***14,70*** | ***50,00*** |

| 12+12+12 glass/ SGP | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 2.920 | -16,66 | -16,69 | 20,80 | 50,00 |
| 4.400 | 2.970 | -16,95 | -16,97 | 20,69 | 50,00 |
| 4.300 | 3.030 | -17,31 | -17,31 | 20,41 | 50,00 |
| 4.200 | 3.095 | -17,65 | -17,69 | 20,25 | 50,00 |
| 4.100 | 3.185 | -18,18 | -18,20 | 20,09 | 50,00 |
| 4.000 | 3.295 | -18,81 | -18,83 | 19,99 | 50,00 |
| 3.900 | 3.440 | -19,64 | -19,66 | 19,74 | 50,00 |
| 3.800 | 3.650 | -20,85 | -20,86 | 19,40 | 50,00 |
| ***3.700*** | ***3.780*** | ***-21,13*** | ***-21,14*** | ***19,32*** | ***50,00*** |

## APPENDIX C/ GLASS ROOF LIMITS

Table C.1. Glass roof limits, 1.

*Standard Parameters: GT: Heat-Strength, IT: 1,52mm, SL: 1250 N/m$^2$, SC: Two Opposite Sides Simply Supported, LC: Short Time Loading, Non-Linear Calculation, Max. All. Def.:L/175

**6+6 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 905 | -5,13 | -5,17 | 13,75 | 37,00 |
| 4.000 | 905 | -5,13 | -5,17 | 13,79 | 37,00 |
| 3.500 | 905 | -5,13 | -5,17 | 13,82 | 37,00 |
| 3.000 | 900 | -5,13 | -5,14 | 12,62 | 37,00 |
| 2.500 | 900 | -5,13 | -5,14 | 12,66 | 37,00 |
| 2.000 | 895 | -5,09 | -5,11 | 13,43 | 37,00 |
| 1.500 | 895 | -5,09 | -5,11 | 13,13 | 37,00 |
| 1.000 | 895 | -5,06 | -5,11 | 13,40 | 37,00 |
| 500 | 900 | -5,09 | -5,14 | 13,32 | 37,00 |

**6+6 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.325 | -7,52 | -7,57 | 14,91 | 37,00 |
| 4.000 | 1.320 | -7,49 | -7,54 | 13,37 | 37,00 |
| 3.500 | 1.320 | -7,49 | -7,54 | 13,38 | 37,00 |
| 3.000 | 1.315 | -7,45 | -7,51 | 14,11 | 37,00 |
| 2.500 | 1.320 | -7,54 | -7,54 | 13,86 | 37,00 |
| 2.000 | 1.320 | -7,49 | -7,54 | 14,06 | 37,00 |
| 1.500 | 1.330 | -7,59 | -7,60 | 14,14 | 37,00 |
| 1.000 | 1.340 | -7,65 | -7,66 | 14,20 | 37,00 |
| 500 | 1.350 | -7,68 | -7,71 | 14,12 | 37,00 |

**8+8 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.185 | -6,73 | -6,77 | 14,12 | 37,00 |
| 4.000 | 1.185 | -6,73 | -6,77 | 14,16 | 37,00 |
| 3.500 | 1.175 | -6,65 | -6,71 | 12,84 | 37,00 |
| 3.000 | 1.175 | -6,64 | -6,71 | 12,88 | 37,00 |
| 2.500 | 1.170 | -6,61 | -6,69 | 13,66 | 37,00 |
| 2.000 | 1.170 | -6,61 | -6,69 | 13,35 | 37,00 |
| 1.500 | 1.175 | -6,70 | -6,71 | 13,58 | 37,00 |
| 1.000 | 1.175 | -6,64 | -6,71 | 13,69 | 37,00 |
| 500 | 1.185 | -6,76 | -6,77 | 13,54 | 37,00 |

**8+8 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.730 | -9,87 | -9,89 | 14,04 | 37,00 |
| 4.000 | 1.725 | -9,85 | -9,86 | 14,84 | 37,00 |
| 3.500 | 1.725 | -9,84 | -9,86 | 14,83 | 37,00 |
| 3.000 | 1.725 | -9,82 | -9,86 | 14,47 | 37,00 |
| 2.500 | 1.730 | -9,86 | -9,89 | 14,76 | 37,00 |
| 2.000 | 1.735 | -9,87 | -9,91 | 14,75 | 37,00 |
| 1.500 | 1.745 | -9,94 | -9,97 | 14,81 | 37,00 |
| 1.000 | 1.755 | -9,98 | -10,03 | 14,79 | 37,00 |
| 500 | 1.770 | -10,10 | -10,11 | 14,73 | 37,00 |

**10+10 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.445 | -8,19 | -8,26 | 13,10 | 37,00 |
| 4.000 | 1.445 | -8,19 | -8,26 | 13,13 | 37,00 |
| 3.500 | 1.440 | -8,17 | -8,23 | 13,94 | 37,00 |
| 3.000 | 1.440 | -8,17 | -8,23 | 13,96 | 37,00 |
| 2.500 | 1.440 | -8,17 | -8,23 | 13,64 | 37,00 |
| 2.000 | 1.440 | -8,15 | -8,23 | 13,76 | 37,00 |
| 1.500 | 1.445 | -8,21 | -8,26 | 13,90 | 37,00 |
| 1.000 | 1.450 | -8,25 | -8,29 | 13,97 | 37,00 |
| 500 | 1.450 | -8,14 | -8,29 | 13,52 | 37,00 |

**10+10 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 2.115 | -12,02 | -12,09 | 15,33 | 37,00 |
| 4.000 | 2.115 | -12,02 | -12,09 | 14,97 | 37,00 |
| 3.500 | 2.120 | -12,09 | -12,11 | 15,29 | 37,00 |
| 3.000 | 2.125 | -12,13 | -12,14 | 15,15 | 37,00 |
| 2.500 | 2.130 | -12,13 | -12,17 | 15,30 | 37,00 |
| 2.000 | 2.140 | -12,21 | -12,23 | 15,36 | 37,00 |
| 1.500 | 2.150 | -12,26 | -12,29 | 15,37 | 37,00 |
| 1.000 | 2.160 | -12,29 | -12,34 | 15,30 | 37,00 |
| 500 | 2.175 | -12,41 | -12,43 | 15,24 | 37,00 |

Table C.2. Glass roof limits, 2.

*Standard Parameters: GT: Heat-Strength, GTk: 6 mm+ 6 mm, IT: 1,52mm, SL: 1250 N/m $^2$, SC: Four Sides Simply Supported, LC: Long Time Loading, Non-Linear Calculation, Max. All. Def.:L/175

**6+6 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 940 | -5,37 | -5,37 | 13,99 | 37,00 |
| 4.400 | 940 | -5,36 | -5,37 | 13,52 | 37,00 |
| 4.300 | 940 | -5,36 | -5,37 | 13,98 | 37,00 |
| 4.200 | 940 | -5,36 | -5,37 | 13,97 | 37,00 |
| 4.100 | 940 | -5,35 | -5,37 | 13,96 | 37,00 |
| 4.000 | 940 | -5,35 | -5,37 | 13,95 | 37,00 |
| 3.900 | 940 | -5,34 | -5,37 | 13,93 | 37,00 |
| 3.800 | 940 | -5,34 | -5,37 | 13,92 | 37,00 |
| 3.700 | 940 | -5,33 | -5,37 | 13,89 | 37,00 |
| 3.600 | 940 | -5,32 | -5,37 | 13,41 | 37,00 |
| 3.500 | 945 | -5,40 | -5,40 | 13,95 | 37,00 |
| 3.400 | 945 | -5,38 | -5,40 | 13,91 | 37,00 |
| 3.300 | 945 | -5,36 | -5,40 | 13,86 | 37,00 |
| 3.200 | 945 | -5,34 | -5,40 | 13,81 | 37,00 |
| 3.100 | 940 | -5,31 | -5,37 | 12,49 | 37,00 |
| 3.000 | 945 | -5,37 | -5,40 | 12,52 | 37,00 |
| 2.900 | 950 | -5,42 | -5,43 | 12,52 | 37,00 |
| 2.800 | 950 | -5,37 | -5,43 | 12,42 | 37,00 |
| 2.700 | 955 | -5,40 | -5,46 | 12,39 | 37,00 |
| 2.600 | 960 | -5,42 | -5,49 | 12,33 | 37,00 |
| 2.500 | 970 | -5,52 | -5,54 | 12,33 | 37,00 |
| 2.400 | 975 | -5,56 | -5,57 | 12,99 | 37,00 |
| 2.300 | 985 | -5,61 | -5,63 | 12,90 | 37,00 |
| 2.200 | 1.000 | -5,71 | -5,71 | 12,81 | 37,00 |
| 2.100 | 1.015 | -5,78 | -5,80 | 12,66 | 37,00 |
| 2.000 | 1.035 | -5,88 | -5,91 | 12,20 | 37,00 |
| 1.900 | 1.065 | -6,05 | -6,09 | 12,01 | 37,00 |
| 1.800 | 1.110 | -6,33 | -6,34 | 11,94 | 37,00 |
| 1.700 | 1.175 | -6,69 | -6,71 | 11,55 | 37,00 |
| 1.600 | 1.295 | -7,38 | -7,40 | 10,96 | 37,00 |
| ***1.500*** | ***1.520*** | ***-8,54*** | ***-8,57*** | ***10,33*** | ***37,00*** |

**6+6 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.390 | -7,93 | -7,94 | 13,88 | 37,00 |
| 4.400 | 1.390 | -7,92 | -7,94 | 13,85 | 37,00 |
| 4.300 | 1.390 | -7,89 | -7,94 | 13,81 | 37,00 |
| 4.200 | 1.395 | -7,96 | -7,97 | 13,84 | 37,00 |
| 4.100 | 1.395 | -7,93 | -7,97 | 13,89 | 37,00 |
| 4.000 | 1.400 | -7,98 | -8,00 | 13,81 | 37,00 |
| 3.900 | 1.405 | -8,02 | -8,03 | 13,82 | 37,00 |
| 3.800 | 1.405 | -7,98 | -8,03 | 13,74 | 37,00 |
| 3.700 | 1.410 | -8,01 | -8,06 | 13,73 | 37,00 |
| 3.600 | 1.420 | -8,11 | -8,11 | 13,76 | 37,00 |
| 3.500 | 1.420 | -8,10 | -8,11 | 14,45 | 37,00 |
| 3.400 | 1.425 | -8,10 | -8,14 | 14,37 | 37,00 |
| 3.300 | 1.435 | -8,16 | -8,20 | 14,34 | 37,00 |
| 3.200 | 1.445 | -8,21 | -8,26 | 14,28 | 37,00 |
| 3.100 | 1.460 | -8,32 | -8,34 | 14,24 | 37,00 |
| 3.000 | 1.475 | -8,40 | -8,43 | 14,17 | 37,00 |
| 2.900 | 1.495 | -8,53 | -8,54 | 13,81 | 37,00 |
| 2.800 | 1.520 | -8,68 | -8,69 | 13,73 | 37,00 |
| 2.700 | 1.545 | -8,79 | -8,83 | 13,59 | 37,00 |
| 2.600 | 1.585 | -9,04 | -9,06 | 13,65 | 37,00 |
| 2.500 | 1.635 | -9,32 | -9,34 | 13,47 | 37,00 |
| 2.400 | 1.710 | 9,77 | -9,77 | 13,17 | 37,00 |
| 2.300 | 1.815 | -10,36 | -10,37 | 12,89 | 37,00 |
| 2.200 | 2.005 | -11,45 | -11,46 | 12,54 | 37,00 |
| ***2.100*** | ***2.165*** | ***-11,97*** | ***-12,00*** | ***12,37*** | ***37,00*** |

Table C.3. Glass roof limits, 3.

*Standard Parameters: GT: Heat-Strength, GTk: 8 mm+ 8 mm, IT: 1,52mm, SL: 1250 N/m $^2$, SC: Four Sides Simply Supported, LC: Long Time Loading, Non-Linear Calculation, Max. All. Def.:L/175

| **8+8 glass/ PVB** | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 1.235 | -7,01 | -7,06 | 14,19 | 37,00 |
| 4.400 | 1.235 | -7,00 | -7,06 | 14,15 | 37,00 |
| 4.300 | 1.240 | -7,07 | -7,09 | 14,21 | 37,00 |
| 4.200 | 1.240 | -7,05 | -7,09 | 14,16 | 37,00 |
| 4.100 | 1.235 | -7,04 | -7,06 | 12,85 | 37,00 |
| 4.000 | 1.235 | -7,01 | -7,06 | 12,80 | 37,00 |
| 3.900 | 1.240 | -7,07 | -7,09 | 12,81 | 37,00 |
| 3.800 | 1.240 | -7,02 | -7,09 | 12,74 | 37,00 |
| 3.700 | 1.245 | -7,07 | -7,11 | 12,74 | 37,00 |
| 3.600 | 1.250 | -7,11 | -7,14 | 12,72 | 37,00 |
| 3.500 | 1.255 | -7,13 | -7,17 | 12,69 | 37,00 |
| 3.400 | 1.260 | -7,15 | -7,20 | 12,64 | 37,00 |
| 3.300 | 1.270 | -7,25 | -7,26 | 12,64 | 37,00 |
| 3.200 | 1.275 | -7,24 | -7,29 | 12,56 | 37,00 |
| 3.100 | 1.280 | -7,29 | -7,31 | 13,24 | 37,00 |
| 3.000 | 1.290 | -7,33 | -7,37 | 13,16 | 37,00 |
| 2.900 | 1.305 | -7,44 | -7,46 | 13,11 | 37,00 |
| 2.800 | 1.320 | -7,52 | -7,54 | 13,00 | 37,00 |
| 2.700 | 1.340 | -7,65 | -7,66 | 12,90 | 37,00 |
| 2.600 | 1.360 | -7,74 | -7,77 | 12,46 | 37,00 |
| 2.500 | 1.390 | -7,91 | -7,94 | 12,32 | 37,00 |
| 2.400 | 1.430 | -8,15 | -8,17 | 12,14 | 37,00 |
| 2.300 | 1.485 | -8,48 | -8,49 | 12,08 | 37,00 |
| 2.200 | 1.560 | -8,91 | -8,91 | 11,68 | 37,00 |
| 2.100 | 1.680 | -9,59 | -9,60 | 11,30 | 37,00 |
| 2.000 | 1.915 | -10,94 | -10,94 | 10,70 | 37,00 |
| ***1.900*** | ***2.005*** | ***-10,85*** | ***-10,86*** | ***10,73*** | ***37,00*** |

| **8+8 glass/ SGP** | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 1.860 | -10,58 | -10,63 | 15,03 | 37,00 |
| 4.400 | 1.870 | -10,65 | -10,69 | 15,02 | 37,00 |
| 4.300 | 1.880 | -10,72 | -10,74 | 14,99 | 37,00 |
| 4.200 | 1.890 | -10,77 | -10,80 | 14,94 | 37,00 |
| 4.100 | 1.900 | -10,81 | -10,86 | 14,88 | 37,00 |
| 4.000 | 1.915 | -10,90 | -10,94 | 14,83 | 37,00 |
| 3.900 | 1.930 | -10,98 | -11,03 | 14,77 | 37,00 |
| 3.800 | 1.950 | -11,12 | -11,14 | 14,41 | 37,00 |
| 3.700 | 1.970 | -11,22 | -11,26 | 14,33 | 37,00 |
| 3.600 | 1.995 | -11,36 | -11,40 | 14,25 | 37,00 |
| 3.500 | 2.030 | -11,59 | -11,60 | 14,18 | 37,00 |
| 3.400 | 2.065 | -11,78 | -11,80 | 14,25 | 37,00 |
| 3.300 | 2.110 | -12,03 | -12,06 | 14,11 | 37,00 |
| 3.200 | 2.170 | -12,38 | -12,40 | 13,96 | 37,00 |
| 3.100 | 2.245 | -12,80 | -12,83 | 13,68 | 37,00 |
| 3.000 | 2.350 | -13,41 | -13,43 | 13,45 | 37,00 |
| 2.900 | 2.510 | -14,34 | -14,34 | 13,21 | 37,00 |
| 2.800 | 2.775 | -15,85 | -15,86 | 12,83 | 37,00 |
| ***2.700*** | ***2.820*** | ***-15,41*** | ***-15,43*** | ***12,90*** | ***37,00*** |

## Table C.4. Glass roof limits, 4.

*Standard Parameters: GT: Heat-Strength, GTk: 10 mm+ 10 mm, IT: 1,52mm, SL: 1250 N/m $^2$, SC: Four Sides Simply Supported, LC: Long Time Loading, Non -Linear Calculation, Max. All. Def.:L/175

**10+10 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.535 | -8,75 | -8,77 | 13,03 | 37,00 |
| 4.400 | 1.540 | -8,79 | -8,80 | 13,01 | 37,00 |
| 4.300 | 1.545 | -8,82 | -8,83 | 12,98 | 37,00 |
| 4.200 | 1.550 | -8,84 | -8,86 | 12,94 | 37,00 |
| 4.100 | 1.555 | -8,85 | -8,89 | 12,90 | 37,00 |
| 4.000 | 1.565 | -8,94 | -8,94 | 12,89 | 37,00 |
| 3.900 | 1.565 | -8,92 | -8,94 | 13,57 | 37,00 |
| 3.800 | 1.575 | -8,98 | -9,00 | 13,53 | 37,00 |
| 3.700 | 1.585 | -9,03 | -9,06 | 13,46 | 37,00 |
| 3.600 | 1.595 | -9,06 | -9,11 | 13,37 | 37,00 |
| 3.500 | 1.610 | -9,15 | -9,20 | 13,31 | 37,00 |
| 3.400 | 1.630 | -9,30 | -9,31 | 13,25 | 37,00 |
| 3.300 | 1.645 | -9,34 | -9,40 | 13,13 | 37,00 |
| 3.200 | 1.670 | -9,51 | -9,54 | 12,74 | 37,00 |
| 3.100 | 1.700 | -9,70 | -9,71 | 12,63 | 37,00 |
| 3.000 | 1.735 | -9,90 | -9,91 | 12,50 | 37,00 |
| 2.900 | 1.780 | -10,17 | -10,17 | 12,52 | 37,00 |
| 2.800 | 1.835 | -10,47 | -10,49 | 12,30 | 37,00 |
| 2.700 | 1.915 | -10,94 | -10,94 | 11,95 | 37,00 |
| 2.600 | 2.030 | -11,60 | -11,60 | 11,63 | 37,00 |
| 2.500 | 2.210 | -12,62 | -12,63 | 11,22 | 37,00 |
| ***2.400*** | ***2.435*** | ***-13,69*** | ***-13,71*** | ***10,88*** | ***37,00*** |

**10+10 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 2.430 | -13,86 | -13,89 | 14,82 | 37,00 |
| 4.400 | 2.455 | -14,00 | -14,03 | 14,74 | 37,00 |
| 4.300 | 2.485 | -14,17 | -14,20 | 14,67 | 37,00 |
| 4.200 | 2.520 | -14,37 | -14,40 | 14,78 | 37,00 |
| 4.100 | 2.565 | -14,65 | -14,66 | 14,68 | 37,00 |
| 4.000 | 2.615 | -14,94 | -14,94 | 14,56 | 37,00 |
| 3.900 | 2.675 | -15,28 | -15,29 | 14,41 | 37,00 |
| 3.800 | 2.750 | -15,71 | -15,71 | 14,16 | 37,00 |
| 3.700 | 2.845 | -16,24 | -16,26 | 13,97 | 37,00 |
| 3.600 | 2.975 | -16,99 | -17,00 | 13,80 | 37,00 |
| 3.500 | 3.160 | -18,04 | -18,06 | 13,50 | 37,00 |
| ***3.400*** | ***3.305*** | ***NA*** | ***-18,89*** | ***NA*** | ***37,00*** |

# APPENDIX D/ GLASS DOME LIMITS

Table D.1. Glass dome limits, 1.

*Standard Parameters: GT: Heat-Strength, IT: 1,52mm, WL: 960 N/ $m^2$, SL: 1250 N/$m^2$, SC: Two Opposite Sides Simply Supported, LC: Long Time Loading, Non-Linear Calculation, Max. All. Def.:L/175

**6+6 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/$mm^2$) | σ all. (N/$mm^2$) |
|---|---|---|---|---|---|
| 4.500 | 895 | -3,33 | -5,11 | 7,50 | 37,00 |
| 4.000 | 825 | -4,71 | -4,71 | 15,12 | 37,00 |
| 3.500 | 825 | -4,71 | -4,71 | 15,16 | 37,00 |
| 3.000 | 825 | -4,71 | -4,71 | 15,20 | 37,00 |
| 2.500 | 815 | -4,58 | -4,66 | 13,71 | 37,00 |
| 2.000 | 815 | -4,63 | -4,66 | 14,65 | 37,00 |
| 1.500 | 815 | -4,63 | -4,66 | 14,33 | 37,00 |
| 1.000 | 815 | -4,61 | -4,66 | 14,61 | 37,00 |
| 500 | 820 | -4,64 | -4,69 | 14,60 | 37,00 |

**6+6 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/$mm^2$) | σ all. (N/$mm^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.180 | -6,73 | -6,74 | 16,04 | 37,00 |
| 4.000 | 1.180 | -6,73 | -6,74 | 16,06 | 37,00 |
| 3.500 | 1.175 | -6,68 | -6,71 | 14,38 | 37,00 |
| 3.000 | 1.175 | -6,68 | -6,71 | 14,38 | 37,00 |
| 2.500 | 1.175 | -6,71 | -6,71 | 15,22 | 37,00 |
| 2.000 | 1.175 | -6,69 | -6,71 | 14,83 | 37,00 |
| 1.500 | 1.180 | -6,71 | -6,74 | 14,95 | 37,00 |
| 1.000 | 1.190 | -6,78 | -6,80 | 15,18 | 37,00 |
| 500 | 1.200 | -6,82 | -6,86 | 15,15 | 37,00 |

**8+8 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/$mm^2$) | σ all. (N/$mm^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.085 | -6,19 | -6,20 | 15,41 | 37,00 |
| 4.000 | 1.085 | -6,19 | -6,20 | 15,44 | 37,00 |
| 3.500 | 1.075 | -6,08 | -6,14 | 13,98 | 37,00 |
| 3.000 | 1.075 | -6,08 | -6,14 | 14,02 | 37,00 |
| 2.500 | 1.070 | -6,04 | -6,11 | 14,83 | 37,00 |
| 2.000 | 1.070 | -6,04 | -6,11 | 14,49 | 37,00 |
| 1.500 | 1.075 | -6,13 | -6,14 | 14,75 | 37,00 |
| 1.000 | 1.075 | -6,08 | -6,14 | 14,88 | 37,00 |
| 500 | 1.085 | -6,20 | -6,20 | 14,77 | 37,00 |

**8+8 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/$mm^2$) | σ all. (N/$mm^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.555 | -8,88 | -8,89 | 15,04 | 37,00 |
| 4.000 | 1.555 | -8,88 | -8,89 | 15,04 | 37,00 |
| 3.500 | 1.550 | -8,84 | -8,86 | 15,85 | 37,00 |
| 3.000 | 1.550 | -8,83 | -8,86 | 15,47 | 37,00 |
| 2.500 | 1.550 | -8,80 | -8,86 | 15,70 | 37,00 |
| 2.000 | 1.560 | -8,91 | -8,91 | 15,64 | 37,00 |
| 1.500 | 1.565 | -8,89 | -8,94 | 15,76 | 37,00 |
| 1.000 | 1.575 | -8,94 | -9,00 | 15,79 | 37,00 |
| 500 | 1.590 | -9,06 | -9,09 | 15,78 | 37,00 |

**10+10 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/$mm^2$) | σ all. (N/$mm^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.335 | -7,57 | -7,63 | 15,62 | 37,00 |
| 4.000 | 1.330 | -7,58 | -7,60 | 14,28 | 37,00 |
| 3.500 | 1.330 | -7,58 | -7,60 | 14,31 | 37,00 |
| 3.000 | 1.325 | -7,55 | -7,57 | 15,15 | 37,00 |
| 2.500 | 1.325 | -7,55 | -7,57 | 14,80 | 37,00 |
| 2.000 | 1.325 | -7,54 | -7,57 | 15,11 | 37,00 |
| 1.500 | 1.325 | -7,50 | -7,57 | 15,09 | 37,00 |
| 1.000 | 1.330 | -7,54 | -7,60 | 15,11 | 37,00 |
| 500 | 1.340 | -7,64 | -7,66 | 14,83 | 37,00 |

**10+10 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/$mm^2$) | σ all. (N/$mm^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.920 | -10,97 | -10,97 | 16,41 | 37,00 |
| 4.000 | 1.920 | -10,96 | -10,97 | 16,40 | 37,00 |
| 3.500 | 1.920 | -10,95 | -10,97 | 16,00 | 37,00 |
| 3.000 | 1.920 | -10,91 | -10,97 | 16,25 | 37,00 |
| 2.500 | 1.925 | -10,93 | -11,00 | 16,09 | 37,00 |
| 2.000 | 1.935 | -11,01 | -11,06 | 16,22 | 37,00 |
| 1.500 | 1.945 | -11,07 | -11,11 | 16,35 | 37,00 |
| 1.000 | 1.960 | -11,20 | -11,20 | 16,39 | 37,00 |
| 500 | 1.970 | -11,22 | -11,26 | 16,26 | 37,00 |

Table D.2. Glass dome limits, 2.

*Standard Parameters: GT: Heat-Strength, GTk: 6 mm+ 6 mm, IT: 1,52mm, WL: 960 N/m $^2$, SL: 1250 N/m$^2$, SC: Four Sides Simply Supported, LC: Long Time Loading, Non -Linear Calculation, Max. All. Def.:L/175

**6+6 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 895 | -3,17 | -5,11 | 7,11 | 37,00 |
| 4.400 | 875 | -3,00 | -5,00 | 7,05 | 37,00 |
| 4.300 | 855 | -2,84 | -4,89 | 6,97 | 37,00 |
| 4.200 | 855 | -4,88 | -4,89 | 15,32 | 37,00 |
| 4.100 | 855 | -4,88 | -4,89 | 15,31 | 37,00 |
| 4.000 | 855 | -4,88 | -4,89 | 15,31 | 37,00 |
| 3.900 | 855 | -4,88 | -4,89 | 15,30 | 37,00 |
| 3.800 | 855 | -4,87 | -4,89 | 15,29 | 37,00 |
| 3.700 | 855 | -4,87 | -4,89 | 15,27 | 37,00 |
| 3.600 | 855 | -4,86 | -4,89 | 15,26 | 37,00 |
| 3.500 | 855 | -4,85 | -4,89 | 15,23 | 37,00 |
| 3.400 | 855 | -4,85 | -4,89 | 15,21 | 37,00 |
| 3.300 | 855 | -4,83 | -4,89 | 15,18 | 37,00 |
| 3.200 | 855 | -4,82 | -4,89 | 15,14 | 37,00 |
| 3.100 | 860 | -4,91 | -4,91 | 15,24 | 37,00 |
| 3.000 | 860 | -4,88 | -4,91 | 15,18 | 37,00 |
| 2.900 | 860 | -4,86 | -4,91 | 15,11 | 37,00 |
| 2.800 | 860 | -4,90 | -4,91 | 13,77 | 37,00 |
| 2.700 | 860 | -4,86 | -4,91 | 13,67 | 37,00 |
| 2.600 | 865 | -4,91 | -4,94 | 13,68 | 37,00 |
| 2.500 | 870 | -4,95 | -4,97 | 13,66 | 37,00 |
| 2.400 | 875 | -4,98 | -5,00 | 13,61 | 37,00 |
| 2.300 | 880 | -4,99 | -5,03 | 13,53 | 37,00 |
| 2.200 | 885 | -5,03 | -5,06 | 14,23 | 37,00 |
| 2.100 | 895 | -5,09 | -5,11 | 14,14 | 37,00 |
| 2.000 | 910 | -5,20 | -5,20 | 14,06 | 37,00 |
| 1.900 | 925 | -5,27 | -5,29 | 13,89 | 37,00 |
| 1.800 | 945 | -5,38 | -5,40 | 13,38 | 37,00 |
| 1.700 | 975 | -5,54 | -5,57 | 13,15 | 37,00 |
| 1.600 | 1.020 | -5,80 | -5,83 | 13,03 | 37,00 |
| 1.500 | 1.095 | -6,24 | -6,26 | 12,49 | 37,00 |
| 1.400 | 1.245 | -7,11 | -7,11 | 11,83 | 37,00 |
| ***1.300*** | ***1.375*** | ***-7,39*** | ***-7,43*** | ***11,60*** | ***37,00*** |

**6+6 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.235 | -7,04 | -7,06 | 16,58 | 37,00 |
| 4.400 | 1.235 | -7,03 | -7,06 | 16,57 | 37,00 |
| 4.300 | 1.235 | -7,03 | -7,06 | 16,56 | 37,00 |
| 4.200 | 1.235 | -7,02 | -7,06 | 16,54 | 37,00 |
| 4.100 | 1.235 | -7,05 | -7,06 | 14,93 | 37,00 |
| 4.000 | 1.235 | -7,03 | -7,06 | 14,90 | 37,00 |
| 3.900 | 1.235 | -7,01 | -7,06 | 14,86 | 37,00 |
| 3.800 | 1.240 | -7,08 | -7,09 | 14,91 | 37,00 |
| 3.700 | 1.240 | -7,05 | -7,09 | 14,86 | 37,00 |
| 3.600 | 1.245 | -7,11 | -7,11 | 14,88 | 37,00 |
| 3.500 | 1.245 | -7,07 | -7,11 | 14,81 | 37,00 |
| 3.400 | 1.250 | -7,11 | -7,14 | 14,81 | 37,00 |
| 3.300 | 1.255 | -7,14 | -7,17 | 14,79 | 37,00 |
| 3.200 | 1.260 | -7,17 | -7,20 | 14,76 | 37,00 |
| 3.100 | 1.265 | -7,22 | -7,23 | 15,53 | 37,00 |
| 3.000 | 1.270 | -7,22 | -7,26 | 15,44 | 37,00 |
| 2.900 | 1.280 | -7,28 | -7,31 | 15,40 | 37,00 |
| 2.800 | 1.295 | -7,40 | -7,40 | 15,38 | 37,00 |
| 2.700 | 1.305 | -7,42 | -7,46 | 15,25 | 37,00 |
| 2.600 | 1.325 | -7,56 | -7,57 | 14,88 | 37,00 |
| 2.500 | 1.345 | -7,65 | -7,69 | 14,76 | 37,00 |
| 2.400 | 1.375 | -7,83 | -7,86 | 14,65 | 37,00 |
| 2.300 | 1.415 | -8,08 | -8,09 | 14,70 | 37,00 |
| 2.200 | 1.465 | -8,35 | -8,37 | 14,48 | 37,00 |
| 2.100 | 1.545 | -8,82 | -8,83 | 14,13 | 37,00 |
| 2.000 | 1.670 | -9,53 | -9,54 | 13,82 | 37,00 |
| ***1.900*** | ***1.905*** | ***-10,82*** | ***-10,86*** | ***13,82*** | ***37,00*** |

Table D.3. Glass dome limits, 3.

*Standard Parameters: GT: Heat-Strength, GTk: 8 mm+ 8 mm, IT: 1,52mm, WL: 960 N/m $^2$, SL: 1250 N/m$^2$, SC: Four Sides Simply Supported, LC: Long Time Loading, Non -Linear Calculation, Max. All. Def.:L/175

**8+8 glass/ PVB**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.125 | -6,38 | -6,43 | 15,48 | 37,00 |
| 4.400 | 1.125 | -6,37 | -6,43 | 15,45 | 37,00 |
| 4.300 | 1.125 | -6,36 | -6,43 | 15,43 | 37,00 |
| 4.200 | 1.130 | -6,45 | -6,46 | 15,51 | 37,00 |
| 4.100 | 1.130 | -6,43 | -6,46 | 15,47 | 37,00 |
| 4.000 | 1.130 | -6,41 | -6,46 | 15,43 | 37,00 |
| 3.900 | 1.130 | -6,39 | -6,46 | 15,38 | 37,00 |
| 3.800 | 1.135 | -6,37 | -6,49 | 15,44 | 37,00 |
| 3.700 | 1.130 | -6,43 | -6,46 | 13,98 | 37,00 |
| 3.600 | 1.130 | -6,39 | -6,46 | 13,91 | 37,00 |
| 3.500 | 1.135 | -6,44 | -6,49 | 13,93 | 37,00 |
| 3.400 | 1.140 | -6,49 | -6,51 | 13,93 | 37,00 |
| 3.300 | 1.145 | -6,53 | -6,54 | 13,91 | 37,00 |
| 3.200 | 1.150 | -6,57 | -6,57 | 13,88 | 37,00 |
| 3.100 | 1.155 | -6,59 | -6,60 | 13,83 | 37,00 |
| 3.000 | 1.160 | -6,59 | -6,63 | 13,75 | 37,00 |
| 2.900 | 1.165 | -6,64 | -6,66 | 14,50 | 37,00 |
| 2.800 | 1.175 | -6,70 | -6,71 | 14,44 | 37,00 |
| 2.700 | 1.185 | -6,75 | -6,77 | 14,33 | 37,00 |
| 2.600 | 1.200 | -6,85 | -6,86 | 14,26 | 37,00 |
| 2.500 | 1.215 | -6,91 | -6,94 | 14,12 | 37,00 |
| 2.400 | 1.235 | -7,03 | -7,06 | 13,66 | 37,00 |
| 2.300 | 1.260 | -7,16 | -7,20 | 13,49 | 37,00 |
| 2.200 | 1.295 | -7,36 | -7,40 | 13,31 | 37,00 |
| 2.100 | 1.345 | -7,67 | -7,69 | 13,27 | 37,00 |
| 2.000 | 1.415 | -8,08 | -8,09 | 12,84 | 37,00 |
| 1.900 | 1.525 | -8,70 | -8,71 | 12,45 | 37,00 |
| 1.800 | 1.740 | -9,94 | -9,94 | 11,79 | 37,00 |
| ***1.700*** | ***1.810*** | ***-9,68*** | ***-9,71*** | ***11,87*** | ***37,00*** |

**8+8 glass/ SGP**

| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
|---|---|---|---|---|---|
| 4.500 | 1.650 | -9,37 | -9,43 | 15,41 | 37,00 |
| 4.400 | 1.655 | -9,41 | -9,46 | 15,40 | 37,00 |
| 4.300 | 1.660 | -9,44 | -9,49 | 15,38 | 37,00 |
| 4.200 | 1.670 | -9,54 | -9,54 | 15,41 | 37,00 |
| 4.100 | 1.670 | -9,53 | -9,54 | 16,17 | 37,00 |
| 4.000 | 1.675 | -9,53 | -9,57 | 16,11 | 37,00 |
| 3.900 | 1.685 | -9,60 | -9,63 | 16,09 | 37,00 |
| 3.800 | 1.695 | -9,66 | -9,69 | 16,04 | 37,00 |
| 3.700 | 1.705 | -9,70 | -9,74 | 15,98 | 37,00 |
| 3.600 | 1.720 | -9,80 | -9,83 | 15,93 | 37,00 |
| 3.500 | 1.735 | -9,88 | -9,91 | 15,86 | 37,00 |
| 3.400 | 1.755 | -10,02 | -10,03 | 15,48 | 37,00 |
| 3.300 | 1.775 | -10,11 | -10,14 | 15,38 | 37,00 |
| 3.200 | 1.805 | -10,31 | -10,31 | 15,31 | 37,00 |
| 3.100 | 1.835 | -10,46 | -10,49 | 15,19 | 37,00 |
| 3.000 | 1.875 | -10,69 | -10,71 | 15,25 | 37,00 |
| 2.900 | 1.925 | -10,97 | -11,00 | 15,07 | 37,00 |
| 2.800 | 1.995 | -11,38 | -11,40 | 14,78 | 37,00 |
| 2.700 | 2.095 | -11,97 | -11,97 | 14,55 | 37,00 |
| 2.600 | 2.240 | -12,80 | -12,80 | 14,28 | 37,00 |
| 2.500 | 2.490 | -14,22 | -14,23 | 13,83 | 37,00 |
| ***2.400*** | ***2.525*** | ***-13,68*** | ***-13,71*** | ***13,95*** | ***37,00*** |

Table D.4. Glass dome limits, 4.

*Standard Parameters: GT: Heat-Strength, GTk: 10 mm+ 10 mm, IT: 1,52mm, WL: 960 N/m $^2$, SL: 1250 N/m$^2$, SC: Four Sides Simply Supported, LC: Long Time Loading, Non -Linear Calculation, Max. All. Def.:L/175

| 10+10 glass/ PVB | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 1.395 | -7,92 | -7,97 | 14,18 | 37,00 |
| 4.400 | 1.400 | -7,98 | -8,00 | 14,20 | 37,00 |
| 4.300 | 1.400 | -7,93 | -8,00 | 14,13 | 37,00 |
| 4.200 | 1.405 | -7,98 | -8,03 | 14,13 | 37,00 |
| 4.100 | 1.410 | -8,02 | -8,06 | 14,12 | 37,00 |
| 4.000 | 1.415 | -8,06 | -8,09 | 14,10 | 37,00 |
| 3.900 | 1.420 | -8,08 | -8,11 | 14,06 | 37,00 |
| 3.800 | 1.425 | -8,10 | -8,14 | 14,02 | 37,00 |
| 3.700 | 1.435 | -8,20 | -8,20 | 14,02 | 37,00 |
| 3.600 | 1.435 | -8,10 | -8,20 | 13,88 | 37,00 |
| 3.500 | 1.445 | -8,24 | -8,26 | 14,69 | 37,00 |
| 3.400 | 1.455 | -8,29 | -8,31 | 14,62 | 37,00 |
| 3.300 | 1.465 | -8,33 | -8,37 | 14,53 | 37,00 |
| 3.200 | 1.480 | -8,43 | -8,46 | 14,46 | 37,00 |
| 3.100 | 1.495 | -8,50 | -8,54 | 14,35 | 37,00 |
| 3.000 | 1.515 | -8,62 | -8,66 | 13,93 | 37,00 |
| 2.900 | 1.540 | -8,78 | -8,80 | 13,83 | 37,00 |
| 2.800 | 1.570 | -8,96 | -8,97 | 13,69 | 37,00 |
| 2.700 | 1.605 | -9,14 | -9,17 | 13,52 | 37,00 |
| 2.600 | 1.655 | -9,45 | -9,46 | 13,53 | 37,00 |
| 2.500 | 1.715 | -9,77 | -9,80 | 13,26 | 37,00 |
| 2.400 | 1.810 | -10,34 | -10,34 | 12,85 | 37,00 |
| 2.300 | 1.950 | -11,14 | -11,14 | 12,48 | 37,00 |
| ***2.200*** | ***2.200*** | ***-12,56*** | ***-12,57*** | ***11,91*** | ***37,00*** |

| 10+10 glass/ SGP | | | | | |
|---|---|---|---|---|---|
| Width (mm) | Height (mm) | max. def. (mm) | max. all. def. (mm) | σ max. (N/mm$^2$) | σ all. (N/mm$^2$) |
| 4.500 | 2.125 | -12,14 | -12,14 | 16,50 | 37,00 |
| 4.400 | 2.135 | -12,16 | -12,20 | 16,42 | 37,00 |
| 4.300 | 2.150 | -12,24 | -12,29 | 16,01 | 37,00 |
| 4.200 | 2.170 | -12,37 | -12,40 | 15,96 | 37,00 |
| 4.100 | 2.195 | -12,54 | -12,54 | 15,92 | 37,00 |
| 4.000 | 2.215 | -12,62 | -12,66 | 15,81 | 37,00 |
| 3.900 | 2.245 | -12,80 | -12,83 | 15,74 | 37,00 |
| 3.800 | 2.280 | -13,01 | -13,03 | 15,89 | 37,00 |
| 3.700 | 2.320 | -13,24 | -13,26 | 15,74 | 37,00 |
| 3.600 | 2.370 | -13,52 | -13,54 | 15,60 | 37,00 |
| 3.500 | 2.430 | -13,86 | -13,89 | 15,43 | 37,00 |
| 3.400 | 2.510 | -14,33 | -14,34 | 15,15 | 37,00 |
| 3.300 | 2.615 | -14,93 | -14,94 | 14,93 | 37,00 |
| 3.200 | 2.765 | -15,80 | -15,80 | 14,71 | 37,00 |
| 3.100 | 2.995 | -17,11 | -17,11 | 14,34 | 37,00 |
| ***3.000*** | ***3.095*** | ***-17,12*** | ***-17,14*** | ***14,32*** | ***37,00*** |