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Passarelas de Vidro Estrutural - Um estudo comparativo entre Normas Internacionais e Método dos Elementos Finitos

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POLITÉCNICO
DO PORTO

STRUCTURAL GLASS WALKWAYS

A COMPARATIVE STUDY BETWEEN INTERNATIONAL STANDARDS AND FINITE ELEMENT METHOD

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ABSTRACT

The use of glass in construction has been increasing due to its sustainability, aesthetics, and functionality. In the last decades, glass has come to be used as a structural element, but still has little normative reference. The present dissertation aims at investigating the use of glass and its applicability in structural elements. In addition to its physical characterization, the step-by-step design of structural glass panels was detailed from the North American standards ASTM E1300 (2016), ASTM E2751 (2017), the European pre-standard prEN 16612 (2013) and the Australian standard AS 1288 (2006), since in Brazil there is no standards that approach the subject and in Europe the standard is on development phase. In addition to the normative analysis, glass elements were tested in the laboratory as glass and beams to analyze its behavior and a model of a walkway with glass structural elements were studied using the software ©DLUBAL – RFEM 5.16.

Keywords: Glass. Structural Glass. Walkway. Model.

Resumo

O uso do vidro na construção tem ganhado relevância em função de sua sustentabilidade, estética e funcionalidade. Nas últimas décadas, passou a ser utilizado como elemento estrutural, porém ainda consta com pouca referência normativa. A presente dissertação retrata uma investigação sobre a utilização e o dimensionamento de elementos de vidro com função estrutural. Além de caracterizar o vidro do ponto de vista físico, apresenta de forma pautada, o dimensionamento de painéis de vidro estrutural a partir das normas norte-americanas ASTM E1300 (2016), ASTM E2751 (2017), da pré-norma europeia prEN 16612 (2013) e da norma australiana AS 1288 (2006), uma vez que no Brasil não há normas que abordem o assunto e na Europa estão em fase de projeto de norma. Além da análise normativa, foram testados em laboratório elementos estruturais de vidro sob o ponto de vista de lajes e vigas para analisar o seu comportamento e foi estudado um modelo de uma passarela com elementos estruturais em vidro utilizando o software ©DLUBAL – RFEM 5.16.

Palavras Chave: Vidro. Vidro Estrutural. Passarela. Modelo.

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To my family who have always supported me.

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ABBREVIATIONS

AS	Australian Standard
ASTM	American Society for Testing and Materials
AR	Aspect Ratio
GTF	Glass Type Factor
LR	Load Resistance
NFL	Non-Factored Load
pREN	Pre-European Standard
PVB	Polyvinyl butyral
SGP	*SentryGlas Plus*
SLS	Serviceability Limit State
ULS	Ultimate Limit State

1 INTRODUCTION

Glass is a material widely used in civil construction and has been sought by architects due to the aesthetics and functionality that it gives to their projects. Until the early 20th century, they were used only as closing elements, such as windows and facade glazing. Today, with the advances in modern manufacturing technologies, it is possible to use glass as a structural element, so that is now being used on columns, beams and slabs, ensuring stability to the structure.

Discovered in 5000 BC, glass emerged through an accidental process in which Phoenician merchants mixed sodium nitrate and beach sand next to a fire, generating a colorless viscous liquid. Subsequently, several methods of production were developed, from the blowing to the current method called floating process.

Considered as an amorphous material, glass is mainly produced by silica sand. Its mechanical properties vary with the composition that generates different types of glass. When compressed it has high resistance. However, when tensioned, it shows around 3 to 7% of the compressive strength. One of the most used glass sheets procedure in the structural glass is laminated glass (LG), which is made by glass sheets intermingled with mixtures of high stress resistant transparent adherent thin material.

Due to the fact of being a contemporary issue, there are few specific standards for glass structural design. As observed in the studies of Torres (2015), the scarcity of national standards on the subject cause limitations in the application of glass and it is necessary to resort to international standards.

Several designs were developed and built with structural glass. Some examples of application are the Skydeck in Chicago, Skywalk in the Grand Canyon, the glass pool in the Market Square Tower in Texas, the entrance porch of the Riserva Golf in Rio de Janeiro and the famous Apple stores with stairs and glass walkways (Figure 1.1).

Figure 1.1 – Glass stair at an Apple store in Covent Garden (London).
Source: ANAVIDRO (2014).

The advantages of using glass are the use of natural light, energy saving and reliability as a structure due to its high resistance. Besides, it is a 100% recyclable material. As mentioned by Torres (2015), after being broken, glass can be recycled infinitely. Another benefit is to be prefabricated, ensuring the reduction of waste in the work sites. However, despite being a material used a long time in the construction, it can be understood as a technology recently introduced in the market regarding its structural application, which requires further studies and design standards or regulations.

This work aims to study the criteria for dimensioning glass structural elements. It is specifically intended to identify the proper glass type for structural application, review the properties and behavior of structural glass when subjected to bending and to assess the international standardizations used as guidelines for the design.

Under the scope of this work, laboratory tests were performed on laminated glass slabs and beams submitted to bending stresses for comparison of the test results with some International Standards.

Additionally, a glass walkway is modeled using the Finite Element method with specific software and discussion is made on the use of the International Standards.

1.1 ORGANIZATION OF THE DISSERTATION

The dissertation is organized into eight Chapters.

The first Chapter presents the introduction, including objectives and the justification of the research, the approaching methodology and standards applied along the work.

The second Chapter contains a bibliography revision regarding glass as material, describing its main properties.

The third Chapter presents the main guidelines for each studied standard for the design of glass structures.

In the fourth Chapter, the design of a glass slab according to each referred International Standard is presented.

The fifth Chapter is reserved for the laboratory tests of glass slabs and beams, including the predicted rupture load values calculated from each International Standard.

Along the sixth Chapter, the modeling of a walkway using the software ©DLUBAL – RFEM 5.16 is presented comparing its results with the International Standards requirements.

The seventh Chapter presents the discussion of the results obtained from the fifth and sixth Chapters.

The last Chapter provides some insight into the overall work pointing ways for further researches.

1.2 WORKING METHOD AND APPROACH

This work was developed based on theoretical and practical research.

The theoretical one refers to bibliographical research regarding the properties, manufacturing processes and dimensioning of glass structural elements. For this study, international standards were analyzed, as listed below:

a) US Standard: ASTM E2751 (2017) – "*Standard Practice for Design and Performance of Supported Laminated Glass Walkways*";
b) US Standard: ASTM E1300 (2016) – "*Standard Practice for Determining Load Resistance of Glass in Buildings*";
c) European Pre-Standard: prEN 16612 (2013) – "*Glass in building – Design of glass panes*" (created in 2013 to replace prEN 13474);
d) Australian Standard: AS 1288 (2006) – "*Glass in buildings—Selection and installation".*

The practical research was divided into two fronts: the laboratory tests and the modeling and design of a walkway for pedestrians in the software ©DLUBAL – RFEM 5.16.

The laboratory tests focused on analyzing the behavior of glass slabs and beams subjected to bending stresses. Before the test's performance, calculations were made to predict the loads of rupture of the slabs and beams and estimate the deflections. These calculations were developed based on the standards presented above. The European and Australian standards use the limit state method. Thus, the coefficients of reduction of resistances and coefficients of load increase were discarded in order to estimate the final rupture value. The American standards use the method of the allowable stresses and therefore, do not present stress reduction coefficients.

The tests set up were chosen to be four-point bending, which leads to a constant bending effort region with no shear stresses.

The laboratory test results were compared with the previous calculations of estimated values of loads, stresses and deflections from the standards. The values between standard guidelines and the influence of the load duration were also taken in account on the analysis.

A simplified walkway model was developed to analyze the safety use of glass on structural elements.

Firstly, it was developed the design of a glass slab with the dimensions intended to be used on the walkway. This design was made to determine the maximum admissible load that could be applied on the slab considering the maximum allowable stress and deflection recommended by each standard.

The conditions of support considered were continuously supported by two parallel edges and continuously supported by four edges. This consideration was made to identify the need for transverse beams on the walkway.

Later, the model was developed with the loads recommended by EN 1991-2 (2003) “Eurocode 1 – Action on structures - Part 2: Traffic loads on Bridges” for walkways and were obtained the stresses and deflections generated by these loads.

The design slab results were evaluated under different conditions of support, comparing the standard guidelines and identifying the load capacity limited by the maximum allowed stress or deflection.

2 GLASS AS A STRUCTURAL MATERIAL

Glass is an inorganic material, generated by the controlled cooling of a melting mass, that during the hardening process acquires stiffness in a way that formation of crystals is mitigated or avoided in its chemical structure, which allows to classify it as an amorphous material.

The primary raw material for the manufacture of glass is silica, found in sand, and melting oxides that contribute to the decrease of the melting temperature of silica and stabilizers that avoid the solubility of the silica compound with flux, being respectively sodium oxide and oxide of calcium. These elements make up the most used glass in civil construction: the silica-soda-lime glass. Other types of oxides may enter on the composition to give various properties to the material. The rate of raw material is illustrated in Figure 2.1.

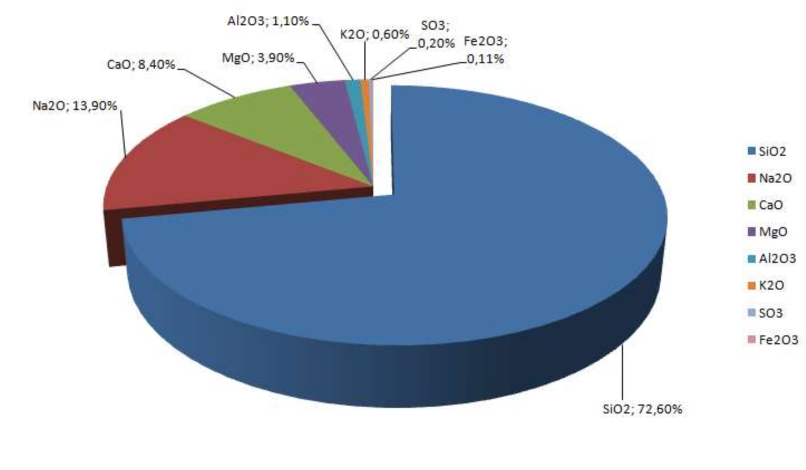


Figure 2.1 – Silica-Soda-Lime glass chemical compound.
Source: CONTINENTAL TRADE (n.d.)

Glass is a material that has perfect elastic behavior, that is, it never presents permanent strain, as steel does. Add to that, when it overcomes its load resistance, it has an abrupt breakage. Figure 2.2 compares the schematic Stress x Strain curve of glass and steel.

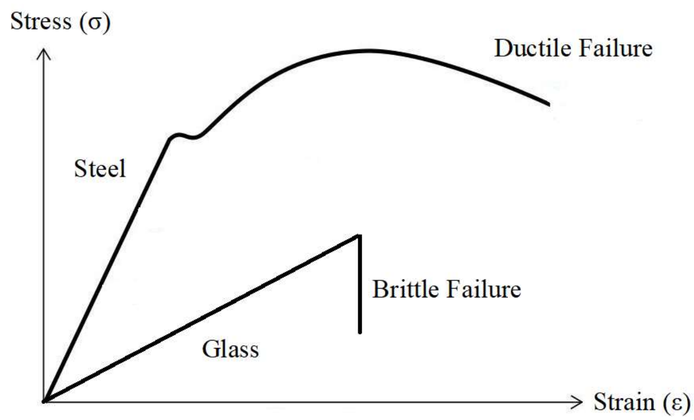


Figure 2.2 – Schematic Stress-Strain curve of glass and steel.
Source: Author (2019).

According to Haldimann et al (2008), the glass elements fail when the tensile stress on a flaw reaches its critical value. When compressed, the cracks do not increase and consequently the glass do not break. Therefore, the compressive strength of glass, as well as concrete, is much higher than its tensile strength. The glass presents a good resistance to aggressive substances and because of that, it is widely used in the chemical industry and is a durable material to be used in construction.

2.1 MANUFACTURING PROCESS OF GLASS

The float manufacturing process represented in Figure 2.3 generates the basic glass for the manufacture of other types of glass. The process starts in an oven, in which the raw material is melted at approximately 1550°C. The molten glass is then brought to a shallow 1000°C tank containing molten tin. The choice of tin is due to its wide range of temperature from its liquid physical state (232°C to 2270°C) and high density when compared to glass. The glass spreads evenly over the tin and is moved through rollers that by their speed control the thickness of the final glass, which can vary from 2 mm to 25 mm. The lower the speed, the greater the thickness. The production is continued in a long oven called "lehr", where the glass is cooled slowly to avoid the appearance of residual tensions inside the glass.

The final manufacturing process is completed by cutting the panel to the desired size, washing and inspecting with machines that ensure the removal of visual imperfections.

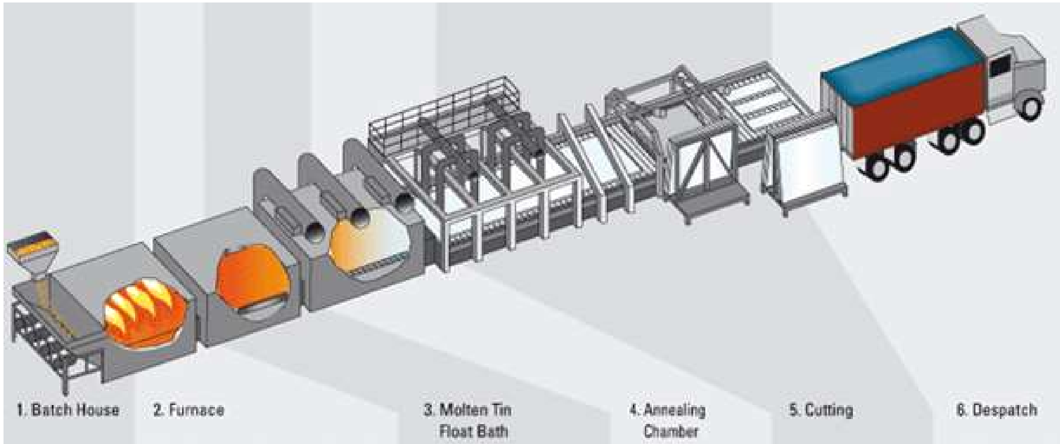


Figure 2.3 – Float manufacturing process.
Source: Adapted from Metro Performance Glass (2018).

When the glass is laminated, the face of the glass that has been through the tin, should be the outer face and not the face facing the adherent material, as there is a diffusion of tin atoms that can negatively influence the contact with the adherent material. Besides, the mechanical resistance of this face is lower than the face that is facing the air, because it passes through the rollers, which may cause minor surface failures. Therefore, this face must be the face to be compressed.

2.2 GLASS TYPES

The range of the glass variety can be obtained with the type of treatment that the glass receives, resulting in the following types:

a) Annealed Glass (Float): ordinary glass, smooth, transparent and used as raw material to produce other types of glass, such as tempered, semi-tempered, laminated, insulated, silk-screened and mirrors;
b) Tempered Glass: classified as safety glass, undergoes a heat treatment in which stresses are introduced properly, improving its strength. The idea is to create tensile tensions in the core of the plate, where there are no cracks and therefore ensure good tensile strength and compressive stresses of their faces, as shown in Figure 2.4. The residual compressive surface stress is in the range of 80 to 170 MPa. The disadvantages of this type of glass are that when laminated, it does not have post-breakage resistance because it breaks into small pieces and it can’t be punctured after the treatment;

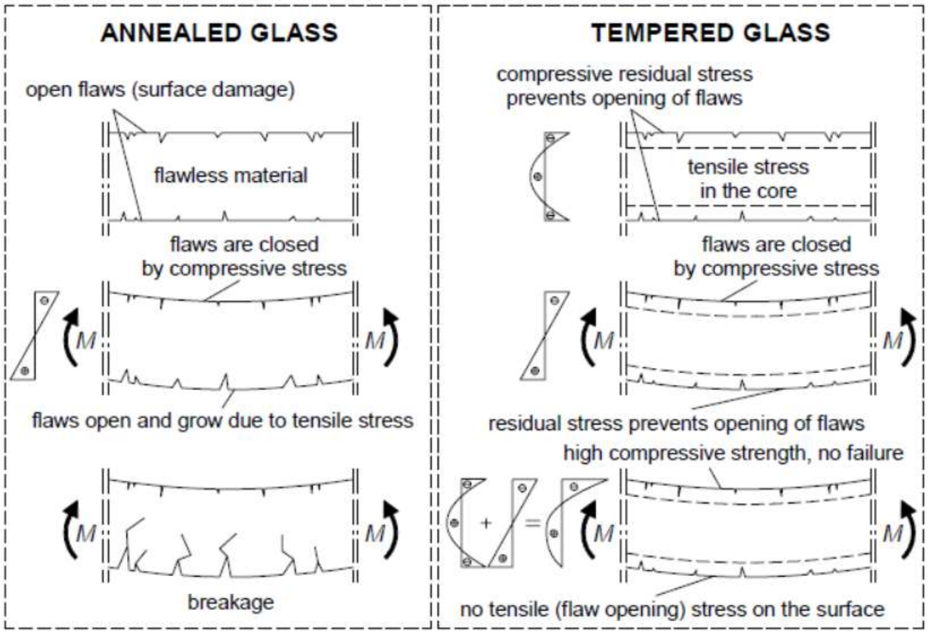


Figure 2.4 – Comparison between the annealed and tempered glass behavior due to bending stresses. Source: HALDIMANN; LUIBLE; OVEREND (2008).

c) Semi tempered glass: as the tempered glass, it undergoes a heat treatment. However, this treatment is done at lower temperatures than for tempered glass, generating lower tensions and consequently less resistance. The residual compressive surface stress is in the range of 40 to 80 MPa. The advantage of this type of glass, when compared to tempered glass, is that when breaking, its pieces are larger and thus offers greater safety post-breakage when laminated;

d) Laminated glass: consists of 2 or more glass sheets bonded through adhering material. Also classified as safety glass, because when breaking, the shards tend to remain glued to the layer of adherent material. This will be studied more deeply in this work;

e) Double or insulated glass: similar to laminated glass, but the 2 layers of glass are initially sealed in ways that guarantee an empty space between the parallel plates. In the empty space, air or dehydrated gas (second seal) is introduced, giving stability to the assembly;

f) Wire glass: consists of sheets of glass which are wired with metal inside during the manufacturing process. When it breaks, the shrapnel tends to stick to such wires, which gives it the title of safety glass;

g) Absorbent thermal glass: they are able to absorb a minimum of 20% of the infrared rays, providing reduction of the heat that enters the building.

2.3 GLASS PROPERTIES

In this section the physical, mechanical and thermal properties of the glass are presented in a general context in Table 2.1.

Table 2.1– Soda Lime Silica Glass Properties.

Property	Unit	Value
Density	kg/m^3	2500
Hardness	Mohs	6.0 to 6.5
Abrasion Resistance	times stronger than granite	16
Young's Modulus (E)	GPa	70.0 to 71.7
Possion Ratio		0.20 to 0.23
Tensile strength	MPa	30 to 70
Compressive strength	MPa	1000
Specific Heat	J/Kg°C	720 to 795
Thermal Conductivity	$W \cdot m^{-1} \cdot K^{-1}$	0.72 to 1.00
Linear dilatation	$°C^{-1}$	$9 \cdot 10^{-6}$

Source: Adapted from Haldimann et al (2008, p.7), Henriques (2010, p.13) and ABNT NBR NM 294 (2004).

It is important to note that such properties are subject to change depending on the composition, manufacturing process and post-processing treatment of the glass.

2.4 INTERLAYER

The laminated glass is composed by glass plies and interlayers. Those interlayers are adherent materials produced with polymers, which have viscoelastic properties.

In addition to gluing one glass to the other, the adherent layer has other functions as: in case of fracture, it does not influence the other glass ply and keeps the shards glued to the film ensuring the security of glass; transmit the loads from one plie to the other and increase the stiffness of the set.

There are many types of interlayers. The most common is the polyvinyl butyral (PVB) because of its cost benefit. Although there are other interlayers in the market such as the *SentryGlasPlus* (SGP) from *DuPont* that provides better qualities for laminated glass influencing on elastic behavior as can be noticed in Table 2.3 to Table 2.5, however, it is more expensive.

The PVB foil has a thickness of 0.38 mm but it can be made by more than one foil, making the set thicker. Its properties are presented in Table 2.2.

Table 2.2 – PVB adherent material properties.

Property	Unit	Value
Density	g/cm³	1.075
Shear Modulus	GPa	0 to 4
Possion's Ratio		0.5
Tensile strenght	MPa	20
Linear dilatation	$10^{-6} \cdot °C^{-1}$	80

Source: HENRIQUES (2010).

According to Sanches (2013), some standards recommend that the shear resistance of PVB shouldn't be considered on the design, however, it increases the stiffness of the set.

Table 2.3 to Table 2.5 present the Young Modulus and Shear Modulus for PVB and SGP for different load durations and temperatures.

Table 2.3 – PVB and SGP properties for 3 seconds of load duration.

	E [MPa]		G [MPa]	
	PVB	**SentryGlas**	**PVB**	**SentryGlas**
10 °C	24.1	681	8.06	236
20 °C	24.1	612	8.06	211
30 °C	2.91	413	0.97	141
40 °C	1.83	187	0.61	63
50 °C	1.32	78.8	0.44	26.4
60 °C	0.01	24.5	0.00333	8.18
70 °C	0.01	8.78	0.00333	2.93
80 °C	0.01	3.96	0.00333	1.32

Source: Kuraray (2019).

Table 2.4 – PVB and SGP properties for 1 hour of load duration.

	E [MPa]		G [MPa]	
	PVB	**SentryGlas**	**PVB**	**SentryGlas**
10 °C	2.52	597	0.84	206
20 °C	2.52	493	0.84	169
30 °C	1.32	178	0.44	59.9
40 °C	0.7	27.8	0.23	9.28
50 °C	0.16	12.6	0.052	4.2
60 °C	0.01	5.1	0.00333	1.7
70 °C	0.01	2.52	0.00333	0.84
80 °C	0.01	0.96	0.00333	0.32

Source: Kuraray (2019).

Table 2.5 – PVB and SGP properties for 10 years of load duration.

	E [MPa]		**G [MPa]**	
	PVB	**SentryGlas**	**PVB**	**SentryGlas**
10 °C	0.8	448	0.27	153
20 °C	0.8	256	0.27	87
30 °C	0.16	15.9	0.052	5.31
40 °C	0.16	8.84	0.052	2.95
50 °C	0.16	6	0.052	2
60 °C	0.01	2.91	0.00333	0.97
70 °C	0.01	1.35	0.00333	0.48
80 °C	0.01	0.54	0.00333	0.18

Source: Kuraray (2019).

It is essential to study the characteristics of the interlayer to be used before its application. The PVB interlayer has a good performance when submitted to low temperatures and short duration loads. Although, at long duration loads and high temperatures, the shear transfer is significantly reduced. At those conditions, the PVB still have the function to glue one glass to the other, however makes the plates to work with no coupling. It means that they work as isolated plates.

Unlike PVB, the *SentryGlasPlus* (SGP) transfers up to 100% of the shear. In that way, the laminated glass could work even better as it was a monolithic plate.

This work focuses on PVB interlayer because it is the most used in the market nowadays.

3 STANDARDS AND GUIDELINES

The design of structural glass demands the study of its properties and the knowledge of standards guidelines. On this chapter it is presented the main design guidelines of each of the following standards: ASTM E2751 (2017) – "Standard Practice for Design and Performance of Supported Laminated Glass Walkways", ASTM E1300 (2016) – "Standard Practice for Determining Load Resistance of Glass in Buildings.", prEN 16612 (2013) – "Determination of the load resistance of glass panes" and AS 1288 (2006) – "Glass in Buildings – Selection and Installation".

3.1 DESIGN ACCORDING TO ASTM E2751 AND ASTM E1300

The ASTM E2751 (2017) is the specific standard for the design of glass walkways. It recommends the use of laminated glass on walkways and indicates that the calculation procedure must be developed based on engineering mechanics formulas or Finite Element analysis. It is mentioned on the standard that the allowable glass stresses for nominal load conditions should be extracted from ASTM E1300 (2016).

The method presented for the dimensioning of laminated glass was taken from ASTM E1300 (2016), which determines the maximum allowable load, called Load Resistance (LR) and the deflection for each type of glass. The initial hypotheses adopted by the standard are a uniform perpendicular loading for a short time (3 seconds) or a long period (30 days) and a probability of breakage of 8 ‰ for 20 years of return period.

The standard presents four possible conditions of support, which are continuously supported by one, two, three or four edges. This work will focus on plates continuously supported by two and four edges.

It presents two methods for determining the permissible load and deflection for laminated glass. The first is called Basic Procedure and the second Analytical Procedure.

3.1.1 Basic Procedure

For the determination of the load resistance, it is necessary to find two coefficients, the Non-Factored Load (NFL) and the Glass Type Factor (GTF).

The NFL is the maximum load value with a duration of 3 seconds associated with a probability of breakage of 8 ‰ for a monolithic glass. This factor should be read in the NFL chart for PVB laminated glass. The charts vary depending on how many edges of the plate are supported and with the thickness of the plate. For PVB laminated glass simply supported along two parallel edges the chart is presented in Figure 3.1 for thicknesses varying from 6 mm to 19 mm. For PVB laminated glass simply supported along four edges the chart is presented in Figure 3.2 for 10mm thickness. There are other charts for different thickness varying from 5 mm to 19 mm.

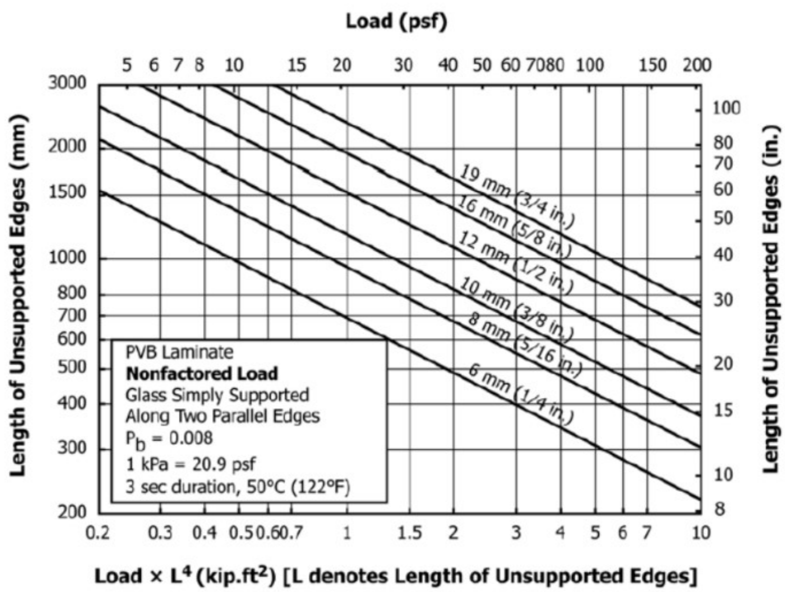


Figure 3.1–Non-Factored Load (NFL) chart for PVB laminated glass simply supported along two parallel edges.
Source: ASTM E1300 (2016).

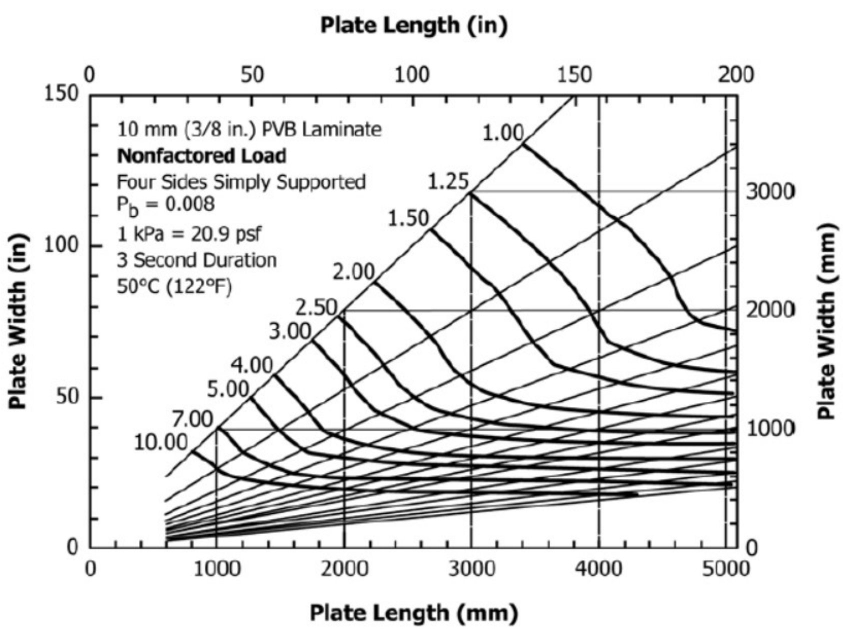


Figure 3.2–Non-Factored Load (NFL) chart for PVB laminated glass simply supported along four edges for 10 mm thickness.
Source: ASTM E1300 (2016).

The Glass Type Factor (GTF) is the coefficient that allows the determination of the load resistance for other types of glass other than monolithic and should be read in Table 3.1.

Table 3.1 –Glass type factor (GTF).

Glass Type	Short Duration Load (3s)	Long Duration Load (30 days)
AN	1.0	0.43
HS	2.0	1.3
FT	4.0	3.0

Source: ASTM E1300 (2016).

The glass types in Table 3.1 are annealed (AN) glass, heat strengthened (HS) glass and fully tempered (FT) glass.

The load resistance is given by the multiplication of these two factors, as presented in equation (3.1).

$$LR = NFL \cdot GTF \text{ [kPa]} \tag{3.1}$$

The maximum lateral deflection should be determined through the deflection chart for PVB laminated glass. The charts also vary depending on how many edges of the plate are supported and with the thickness of the plate. For PVB laminated glass simply supported along two parallel edges the chart is presented in Figure 3.3 for thicknesses varying from 6 mm to 19 mm. For PVB laminated glass simply supported along four edges the chart is presented in Figure 3.4 for 10 mm thickness. There are other charts for different thickness varying from 5 mm to 19 mm.

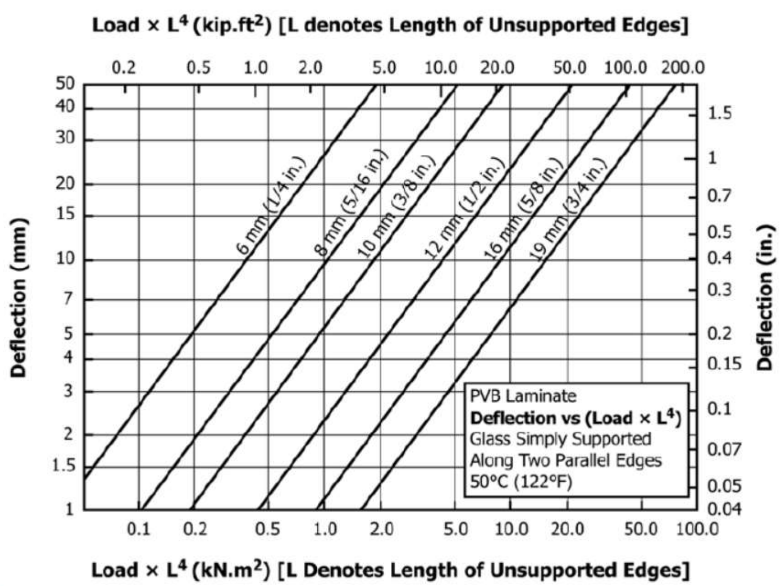


Figure 3.3– Deflection chart for PVB laminated glass simply supported along two parallel edges.
Source: ASTM E1300 (2016).

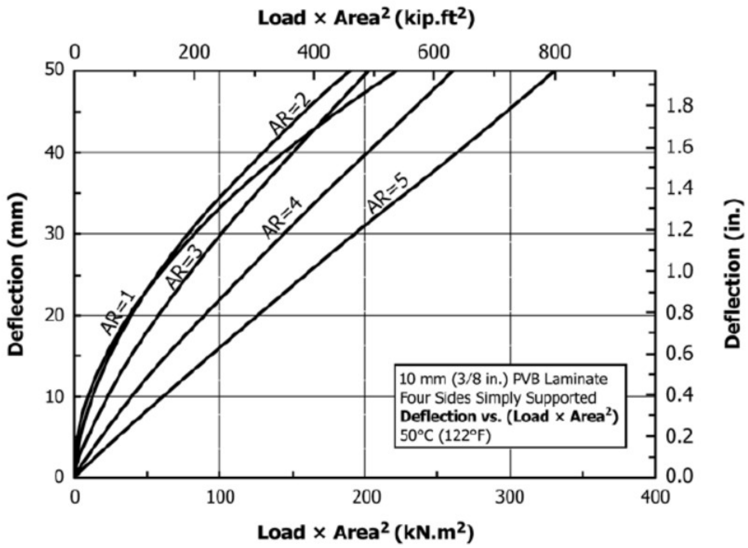


Figure 3.4 – Deflection chart for PVB laminated glass simply supported along four edges for 10 mm thickness.
Source: ASTME E1300 (2016)

If the deflection is out of the chart, see Appendix X1 of ASTM E1300 (2016).

3.1.2 Analytical Procedure

The standard also permits the calculation of stresses and deflection of laminated glass through the Analytical Method. This calculation is made by determining the effective thickness of glass for stresses and deflection, which can be used in engineering mechanics formulas or in Finite Elements Method. The method can be applied to laminated glasses with two plates, which can have the same or different thicknesses.

The shear transfer coefficient is determined according to equation (3.2). The properties from equations (3.3) to (3.6) must be calculated to define the shear transfer.

$$\Gamma = \frac{1}{1 + 9.6 \cdot \dfrac{E \cdot I_S \cdot h_v}{G \cdot {h_s}^2 \cdot a^2}} \quad (3.2)$$

where,

$$I_S = h_1 \cdot {h_{s;2}}^2 + h_2 \cdot {h_{s;1}}^2 \quad (3.3)$$

$$h_{s;1} = \frac{h_s \cdot h_1}{h_1 + h_2} \quad (3.4)$$

$$h_{s;2} = \frac{h_s \cdot h_2}{h_1 + h_2} \tag{3.5}$$

$$h_s = 0.5 \cdot (h_1 + h_2) + h_v \tag{3.6}$$

where,

Γ is the shear transfer coefficient;

h_v is the adherent material thickness;

h_1 is the minimum thickness of the first plate of glass;

h_2 is the minimum thickness of the second plate of glass;

E is the glass Young's modulus of elasticity;

a is the smallest in-plane dimension of bending of the laminated plate;

G is the interlayer complex shear modulus.

The minimum thickness should be taken from Table 3.2 for the correspondent nominal thickness.

Table 3.2– Minimum and nominal thickness of glass.

Nominal Thickness or Designation, mm (in.)	Minimum Thickness, mm (in.)
2.0 (picture)	1.80 (0.071)
2.5 (3/32)	2.16 (0.085)
2.7 (lami)	2.59 (0.102)
3.0 (1/8)	2.92 (0.115)
4.0 (5/32)	3.78 (0.149)
5.0 (3/16)	4.57 (0.180)
6.0 (1/4)	5.56 (0.219)
8.0 (5/16)	7.42 (0.292)
10.0 (3/8)	9.02 (0.355)
12.0 (1/2)	11.91 (0.469)
16.0 (5/8)	15.09 (0.595)
19.0 (3/4)	18.26 (0.719)
22.0 (7/8)	21.44 (0.844)
25.0 (1)	24.61 (0.969)

Source: ASTM E1300 (2016).

There are some exceptions: the laminated glass compound by two panels of 6 mm thickness with an adherent layer of 0.38 mm or 0.76 mm, the nominal thickness of the laminated glass will be 12 mm. For panels with 2.5 mm thickness with a middle interlayer of 1.52 mm, the thickness of the glass will be 5 mm.

For glass panels with 4 mm of thickness, regardless of the middle interlayer thickness, the thickness of the laminated glass is going to be 8 mm.

The effective thickness for deflection ($h_{ef;w}$) is determined by equation (3.7).

$$h_{ef;w} = \sqrt[3]{{h_1}^3 + {h_2}^3 + 12\Gamma \cdot I_s} \tag{3.7}$$

The effective thickness to the bending stresses ($h_{i;ef;w}$) for each plate is determined by equations (3.8) and (3.9).

$$h_{1;ef;\sigma} = \sqrt{\frac{{h_{ef;w}}^3}{h_1 + 2 \cdot \Gamma \cdot h_{s;2}}} \tag{3.8}$$

$$h_{2;ef;\sigma} = \sqrt{\frac{{h_{ef;w}}^3}{h_2 + 2 \cdot \Gamma \cdot h_{s;1}}} \tag{3.9}$$

The standard also presents the maximum allowable edge stress of the plate to each type of glass and different edge finishes treatment. The stresses are defined as represented in Table 3.3 for a breakage probability of 8‰ and 3 seconds of load duration.

Table 3.3– Maximum allowable edge stress of the plate.

	Clean Cut Edges MPa (psi)	Seamed Edges MPa (psi)	Polished Edges MPa (psi)
Annealed	16.6 (2400)	18.3 (2650)	20.0 (2900)
Heat-strengthened	N/A*	36.5 (5300)	36.5 (5300)
Tempered	N/A	73.0 (10600)	73.0 (10600)

* N/A-Not Applicable

Source: ASTM E1300 (2016).

The allowable stresses must be verified in Table 3.4 for the respective type of glass and load duration.

Table 3.4–Allowable Stress.

Glass Type	3 sec MPa (psi)	10-min MPa (psi)	60-min MPa (psi)	Permanent MPa (psi)
Annealed	18.3 [2650]	13.2 [1902]	11.7 [1701]	5.7 [827]
Heat-strengthened	36.5 [5300]	30.9 [4482]	29.2 [4235]	20.3 [2944]
Tempered	73.0 [10600]	65.3 [9471]	63.0 [9137]	49.4 [7165]

Source: ASTM E2751 (2017).

In case the load has other duration than 3 seconds for short duration and 30 days for the long duration, it is necessary to calculate an equivalent load that corresponds to the standard duration of 3 seconds or 30 days, as presented in equation (3.10).

$$LR_{(duration)} = LR_{3s} \cdot Conversion\ Factor \tag{3.10}$$

The conversion factor must be taken from Table 3.5.

Table 3.5–Conversion factor of load duration.

Duration	Factor
3 s	1.00
10 s	0.93
60 s	0.83
10 min	0.72
60 min	0.64
12 h	0.55
24 h	0.53
1 week	0.47
1 month (30 days)	0.43
1 year	0.36
beyond 1 year	0.31

Source: ASTM E1300 (2016).

In case there are loads with different duration, it is necessary to combine them with their respective load duration.

Firstly, it is necessary to identify each load and its duration. Then, the values must be applied at equation (3.11) to calculate the equivalent load to 3 seconds of load duration.

$$q_3 = \sum_{i=1}^{i=j} q_i \cdot \left[\frac{d_i}{3}\right]^{\frac{1}{n}} \tag{3.11}$$

where,

q_3 is the magnitude of the 3-s duration uniform load;

q_i is the magnitude of the load having duration d_i;

d_i is the load duration in seconds;

n is the constant depending on the type of glass (16 for AN glass; 37 for HS glass and 59 for FT glass).

The ASTM E1300 (2016) specifies that the probability of breakage (P_b) must be less or equal to 8‰. This factor depends on the type of glass and stresses. It can be calculated as on the equation (3.12), using the factors from equations (3.13) to (3.15).

$$P_b = 1 - e^{-B} \quad (3.12)$$

$$B = k \cdot \sum_{i=1}^{N} \left(c_i \cdot \left(\frac{t_d}{60s} \right)^{\frac{1}{n}} \cdot (\sigma_{máx} - RCSS) \right)^m \cdot A_i \quad (3.13)$$

$$c_i = -0.005 \cdot r_i^6 + 0.022 \cdot r_i^5 + 0.055 \cdot r_i^4 + 0.039 \cdot r_i^3 + 0.031 \cdot r_i^2 + 0.06 \cdot r_i + 0.8 \quad (3.14)$$

$$r_i = \frac{(\sigma_{min;i} - RCSS)}{(\sigma_{máx;i} - RCSS)} \quad (3.15)$$

where,

k is surface flaw parameter (2.86 x 10^{-53} N^{-7} m^{12});

m is flaw parameter = 7;

N is number of stress values;

t_d is the duration of loading;

n is a constant depending on the type of glass (16 for AN glass; 37 for HS glass and 59 for FT glass);

$\sigma_{máx,i}$ is the i^{th} maximum principal stress;

$\sigma_{mín,i}$ is the i^{th} minimum principal stress;

$RCSS$ is the residual compressive surface stress (0 MPa for AN glass, 24.0 MPa for HS glass and 69.0 MPa for FT glass);

A_i is the i^{th} tributary area corresponding to the principal stresses in m^2.

In case the adherent material is not PVB, it is only permitted to use the charts if the Young Modulus of the adherent layer is greater than or equal to 1.5 MPa (PVB Young Modulus), the shear modulus is greater than or equal to 0.4 MPa (PVB Shear Modulus) and the adherent layer is monolithic and greater than 0.38mm.

3.2 DESIGN ACCORDING TO PREN 16612

The prEN16612 (2013) determine the allowed applied loads through the Simplified Method. Two conditions must be checked: the maximum allowable stresses for the ultimate limit state (ULS) and the maximum allowable deflection for the serviceability limit state (SLS).

3.2.1 Simplified Method

Analogously to ASTM E1300 (2016), the effective thickness of the laminated glass is used for determination of strength.

The effective thickness for deflection ($h_{ef;w}$) is calculated by equation (3.16).

$$h_{ef;w} = \sqrt[3]{\Sigma\, h_k^{\ 3} + 12 \cdot \omega \cdot (\Sigma h_k \cdot h_{m,k}^{\ 2})} \qquad (3.16)$$

The effective thickness for bending stress ($h_{ef;\sigma;j}$) for each plate is calculated by equation (3.17).

$$h_{ef;\sigma;j} = \sqrt{\frac{h_{ef;w}^{\ 3}}{h_j + 2 \cdot \omega \cdot h_{m;j}}} \qquad (3.17)$$

where,

ω is a coefficient that represents the shear transferring due to the adherent material. This coefficient can vary from 0 to 1. It is zero when there is not any shear transfer and 1 when the transfer is 100%;

h_k and h_j are the glass plates thickness;

$h_{m,k}$ and $h_{m;j}$ are the distances from the center of the laminated glass to the center of each layer of glass, according to Figure 3.5.

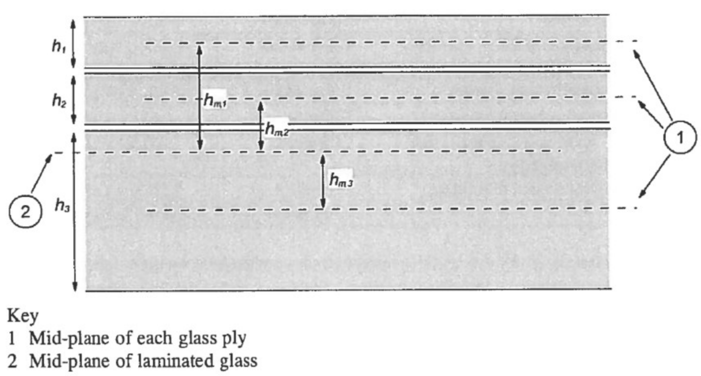


Figure 3.5 – Representation distances from the center of the laminated glass to the center of each layer of glass.
Source: prEN 16612 (2013)

The ω value to be used for the adherent material and a specific material, depends on the Family stiffness to which this material belongs. Those values are tabulated according to Table 3.6.

Table 3.6 - ω value associated with adherent material thickness.

Load Case	Family 0	Family 1	Family 2	Family 3
Wind load (Mediterranean areas)	0	0	0.1	0.6
Wind load (other areas)	0	0.1	0.3	0.7
Personal load - normal duty	0	0	0.1	0.5
Personal load - crowds	0	0	0	0.3
Snow loads - external canopies	0	0	0.1	0.3
Snow loads - roofs	0	0	0	0.1
Permanent loads	0	0	0	0

Source: prEN 16612 (2013)

The standard suggests that the calculation of applied stresses and deflections on rectangular plates supported on all edges should be calculated by the following method.

The maximum tensile bending stress (σ_{max}) should be calculated as presented in equation (3.18).

$$\sigma_{max} = k_1 \cdot \frac{A}{h^2} \cdot F_d \tag{3.18}$$

The maximum deflection (w_{max}) should be calculated as presented in equation (3.19).

$$w_{max} = k_4 \cdot \frac{A^2}{h^3} \cdot \frac{F_d}{E} \tag{3.19}$$

where,

A is the plate area;

h is the nominal thickness of the plate;

F_d is the design value of the combination of actions;

k_1 and k_4 are the coefficients (Table 3.7 and Table 3.8) that depend on the ratio between the plate dimensions (λ) and the uniformly distributed load (P^*), as presented in equation (3.20);

λ is the aspect ratio given by the proportion of the plate dimensions (a/b).

$$P^* = \left(\frac{A}{4 \cdot h^2}\right)^2 \cdot \frac{F_d}{E} \tag{3.20}$$

Table 3.7 – k_1 values.

	p*										
λ = a/b	**0**	**1**	**2**	**3**	**5**	**10**	**20**	**50**	**100**	**200**	**300**
1.0	0.268	0.261	0.244	0.223	0.190	0.152	0.135	0.130	0.129	0.128	0.128
0.9	0.287	0.278	0.258	0.234	0.197	0.155	0.137	0.131	0.130	0.129	0.129
0.8	0.304	0.295	0.273	0.247	0.205	0.159	0.138	0.131	0.130	0.130	0.130
0.7	0.314	0.306	0.285	0.261	0.218	0.165	0.140	0.130	0.129	0.129	0.129
0.6	0.314	0.309	0.294	0.274	0.235	0.176	0.143	0.129	0.127	0.126	0.126
0.5	0.300	0.298	0.290	0.279	0.253	0.197	0.151	0.128	0.124	0.123	0.122
0.4	0.268	0.268	0.266	0.262	0.252	0.221	0.171	0.129	0.119	0.116	0.116
0.3	0.217	0.217	0.217	0.216	0.215	0.208	0.189	0.141	0.116	0.107	0.105
0.2	0.149	0.149	0.149	0.149	0.149	0.149	0.148	0.140	0.123	0.100	0.091
0.1	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.074	0.073

Source: prEN 16612 (2013).

Table 3.8 – k_4 values.

	p*										
λ = a/b	**0**	**1**	**2**	**3**	**5**	**10**	**20**	**50**	**100**	**200**	**300**
1.0	0.0461	0.0414	0.0354	0.0310	0.0255	0.0189	0.0137	0.0088	0.0062	0.0044	0.0036
0.9	0.0452	0.0409	0.0351	0.0309	0.0254	0.0188	0.0136	0.0088	0.0062	0.0044	0.0036
0.8	0.0437	0.0399	0.0346	0.0305	0.0253	0.0188	0.0136	0.0087	0.0062	0.0044	0.0036
0.7	0.0404	0.0377	0.0333	0.0297	0.0248	0.0186	0.0136	0.0087	0.0062	0.0044	0.0036
0.6	0.0354	0.0339	0.0309	0.0281	0.0240	0.0183	0.0134	0.0087	0.0062	0.0044	0.0036
0.5	0.0287	0.0281	0.0267	0.0251	0.0222	0.0176	0.0132	0.0086	0.0062	0.0044	0.0036
0.4	0.0208	0.0207	0.0204	0.0199	0.0187	0.0159	0.0125	0.0085	0.0061	0.0044	0.0036
0.3	0.0128	0.0128	0.0127	0.0127	0.0125	0.0119	0.0105	0.0079	0.0059	0.0043	0.0035
0.2	0.0059	0.0059	0.0059	0.0059	0.0059	0.0059	0.0058	0.0055	0.0048	0.0038	0.0033
0.1	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015

Source: prEN 16612 (2013)

Resistant stresses ($f_{g;d}$) shall be calculated for tempered glass according to equation (3.21).

$$f_{g;d} = \frac{k_{mod} \cdot k_{sp} \cdot f_{g;k}}{\gamma_{M;A}} + \frac{k_v \cdot (f_{b;k} - f_{g;k})}{\gamma_{M;V}} \tag{3.21}$$

where,

$f_{g;k}$ is the characteristic value of bending stress of annealed glass (45 N/mm^2);

$f_{b;k}$ is the characteristic value of bending stress of prestressed glass (Table 3.12);

k_{mod} is the factor of the load duration (Table 3.10 or equation (3.22));

k_{sp} is the factor for the glass surface profile (Table 3.9);

$\gamma_{M;A}$ is the material partial factor for annealed glass (1.6);

$\gamma_{M;V}$ is the material partial factor for surface prestress (1.2);

k_v is the factor for the strengthening of prestressed glass (1.0 for horizontal hardening and 0.6 for vertical hardening, as presented in Table 3.11).

Table 3.9 $-\mathrm{k_{sp}}$ values.

Glass Material (wichever glass composition)	Factor for the glass surface profile k_{sp} As produced (1)	Sandblasted (2)
Float Glass	1.0	0.6
Drawn sheet glass	1.0	0.6
Enamelled float or drawn sheet glass (1)	(1.0)	(0.6)
Patterned glass	0.75	0.45
Enamelled patterned glass (1)	(0.75)	(0.45)
Polished wired glass	0.75	0.45
Patterned wired glass	0.6	0.36

Source: prEN 16612 (2013).

Table 3.10 $-\mathrm{k_{mod}}$ values.

Action	Load duration	k_{mod}
personnel loads	short, single (1)	0.89
wind	single gust	1.00
snow	intermediate (2)	0.44
climatic loads	intermediate	0.50
dead load, self weight	permanent	0.29

Source: prEN 16612 (2013).

The modification coefficient (k_{mod}) also can be calculated by the equation (3.22).

$$\mathrm{k_{mod}} = 0.663 \cdot \mathrm{t}^{-\frac{1}{16}} \quad \text{where } 0.25 < \mathrm{k_{mod}} < 1.0 \tag{3.22}$$

where,

t is the load duration in hours.

Table 3.11 $-\mathrm{k_v}$.values

Manufacturing process	**Strengthening factor,** k_v
Horizontal toughening (or other process without the use of tongs or other devices to hold the glass)	1.0
Vertical toughening (or other process using tongs or other devices to hold the glass)	0.6

Source: prEN 16612 (2013)

Table 3.12 – Values for characteristic bending strength $f_{b;k}$.for prestressed glass.

Glass material per product (whichever composition)	thermally thoughened safety glass to EN 1250, and heat soaked thermally thoughened safety glass to EN 14179	heat strengthened glass to EN 1863	chemically strengthened glass to EN 12337
float glass or drawn sheet glass	120 N/mm²	70 N/mm²	150 N/mm²
patterned glass	90 N/mm²	55 N/mm²	100 N/mm²
enamelled float or drawn sheet glass	75 N/mm²	45 N/mm²	-
enamelled patterned glass	75 N/mm²	45 N/mm²	-

Source: prEN 16612 (2013)

3.3 DESIGN ACCORDING TO AS 1288

The Australian standard covers glass for buildings. According to AS 1288 (2006) its scope is: *"[…] the selection and installation of glass in buildings, subject to wind loading, human impact, and special applications such as overhead glazing, balustrades and glass assemblies".*

The AS 1288 (2006) uses the minimum thickness for the design of glass, as presented in Table 3.13. For laminated glass, the minimum thickness is the sum of each ply disregarding the interlayer thickness.

Table 3.13 – Minimum Thickness.

Nominal thickness (mm)	Minimum thickness (mm)
Monolithic glass	
3	2.8
4	3.8
5	4.8
6	5.8
8	7.7
10	9.7
12	11.7
15	14.5
19	18.0
25	23.5
Laminated glass	
5	4.6
6	5.6
8	7.6
10	9.6
12	11.6
16	15.4
20	19.4
24	23.4
Wired glass	
6	5

Source: AS 1288 (2006).

The design is based on ultimate (ULS) and serviceability (SLS) limit states. The loads shall be determined by AS/NZS 1170.1 (2002) – "Structural Design Actions-Part 1: Permanent, imposed and other actions" and AS/NZS 1170.2 (2002) – "Structural Design Actions-Part 2: Wind actions". For snow and earthquake actions, the parts 3 and 4 should be verified. The combinations of loads are specified on AS/NZS 1170.0 (2002) – "Structural Design Actions-Part 0: General Principles".

For the ULS the design action effect (S*) must be lower than the ultimate capacity (ϕR_u) as shown in equation (3.23). The design action is determined by elastic structural analysis applying the defined loads. The ultimate capacity shall be determined by equation (3.24) which is based on the characteristic tensile strength of glass determined by equation (3.25) for parts away from the edge of glass panes or by equation (3.26) at the edge of glass panes.

$$S* \leq \emptyset \cdot R_u \quad (3.23)$$

$$\emptyset \cdot R_u = \emptyset \cdot c_1 \cdot c_2 \cdot c_3 \cdot [f'_t \cdot X] \quad (3.24)$$

$$f'_t = -9.85 \cdot ln\, t + 71.34 \quad (3.25)$$

$$f'_t = -7.88 \cdot ln\, t + 57.07 \quad (3.26)$$

where,

$\emptyset$ is the capacity reduction factor (0.67);

R_u is the nominal capacity;

c_1 is the glass type factor (Table 3.14);

c_2 is the surface type factor (Table 3.15);

c_3 is the load duration factor (Table 3.16);

f'_t is the characteristic tensile strength of the glass in megapascals (Equations (3.25) and (3.26));

t is the minimum thickness of glass in millimeters.

X is the geometric factor which depends on the size and conditions of support of the glass.

The geometric factor for bending of a glass plate supported on two edges is presented in equation (3.27).

$$X = \frac{b \cdot t^2}{6} \tag{3.27}$$

where,

b is the width of the pane in millimeters.

Table 3.14 – Glass type factor (c_1)

Glass type	c1
Ordinary annealed	1.0
Heat-strengthened	1.6*
Toughened	2.5*
Wired	0.5

Source: AS 1288 (2006).

The standard specifies that the values for heat-strengthened glass can be used for plates with a residual compressive surface stress of 24 MPa and the values for toughened glass can be used for glass with a residual compressive surface stress of 69 MPa. For surface stresses higher than these values, the glass type factor shall be determined by equation (3.28).

$$c_1 = (f'_t + \text{minimum induced surface compression stress}) \,/\, f'_t \tag{3.28}$$

Table 3.15 – Surface type factor (c_2)

Type	c2
Untreated (flat or curved)	1.0
Sand-blasted or etched*	0.4
Acid etched*	1.0
Patterned*	1.0

Source: AS 1288 (2006).

Table 3.16 – Load duration factor (c_3)

Load duration	c3
Short-term load duration (wind)	1.00
Medium-term load duration (e.g., acess imposed actions on roof lights and actions on balustrades) on heat strengthened and toughened glass (monolitic and laminated)	1.00
Medium-term load duration (e.g., acess imposed actions on roof lights and actions on balustrades) on annealed glass (monolitic and laminated)	0.72
Long-term load duration (e.g., dead, some components of live) on heat strengthened and toughened glass (monolitic and laminated)	0.50
Long-term load duration (e.g., dead, hydrostatic, some components of live) on annealed glass (monolitic and laminated)	0.31

Source: AS 1288 (2006).

It is defined on the standard that a short-term load duration is around 3 seconds, the medium-term load duration is up to 10 minutes and the long-term load duration is up to 1 year or longer.

For the SLS the deflection is limited to Span/60 for two, three or four supported edges or to height/30 for cantilevers.

The AS 1288 (2006) also specifies the influence of the load duration on laminated glass. For short load durations, the total minimum thickness of the glass shall be used. For medium and long load durations, it is necessary to determine the percentage of the load that is resisted by each ply of the glass. This proportion is determined by the larger value between the equations (3.29) and (3.30).

$$k_{sheet} = \frac{{t_{sheet}}^3}{\sum_i {t_i}^3} \tag{3.29}$$

$$k_{sheet} = \frac{t_{sheet}^{\ 2}}{\sum_i t_i^{\ 2}} \tag{3.30}$$

where,

k_{shee} is the load-sharing factor of each ply;

t_{sheet} is the thickness of the ply being checked;

t_i is the thickness of each ply on the assembly;

i is the number of plies on the assembly.

The k_{sheet} is 0.5 for laminated glass with two plates of the same thickness.

The standard suggests that, alternatively, a full non-linear analysis can be done to study the behavior of the set by modeling the glass and interlayer sheets.

3.4 LATERAL TORSIONAL BUCKLING

The lateral torsional buckling is an effect that can occur on beams submitted to bending stresses. According to Haldimann et al (2008), it is a combination of lateral deformation and twisting of the structural element, as presented in Figure 3.6. This effect must be verified.

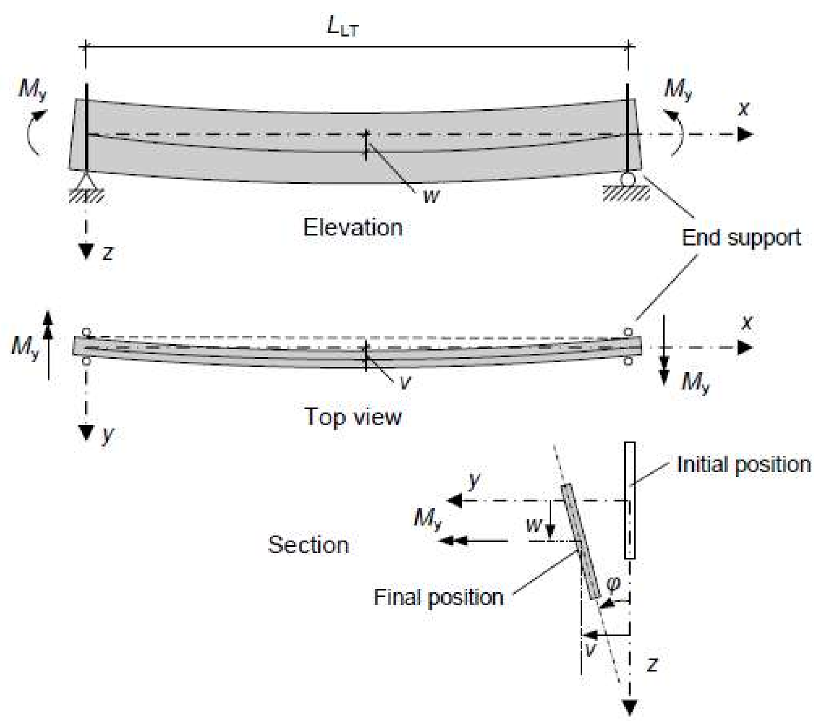


Figure 3.6 – Lateral Torsional Buckling.
Source: Haldimann et al (2008).

The critical torsional buckling moment shall be determined as in equations (3.31) to (3.39) for a laminated glass with three glass panes.

$$M_{cr,LT} = C_1 \cdot \frac{\pi^2 \cdot E \cdot I_Z}{L_{LT}^2} \cdot \left[\sqrt{C_2 \cdot Z_a + \frac{G \cdot K \cdot L_{LT}^2}{\pi^2 \cdot E \cdot I_Z}} + C_2 \cdot Z_a \right] \tag{3.31}$$

$$E \cdot I_Z = E \cdot I_S \cdot \left(\frac{\alpha \cdot \beta \cdot \pi^2 + \alpha + 1}{1 + \pi^2 \cdot \beta} \right) \tag{3.32}$$

$$\alpha = \frac{2 \cdot I_1 + I_2}{I_S} \tag{3.33}$$

$$\beta = \frac{t_{int}}{2 \cdot G_{int} \cdot h \cdot z_1^2} \cdot \frac{E \cdot I_S}{L_{LT}^2} \tag{3.34}$$

$$I_S = 2 \cdot h \cdot t_1 \cdot z_1^2 \tag{3.35}$$

$$G \cdot K_{eff} = G \cdot K_{glass1} + G \cdot K_{glass2} + G \cdot K_{glass3} + G \cdot K_{comp} \tag{3.36}$$

$$K_{glass,i} = \frac{h \cdot t_i^3}{3} \tag{3.37}$$

$$G \cdot K_{comp} = G \cdot I_{S,comp} \cdot \left(1 - \frac{2}{\lambda \cdot h} \cdot tanh \frac{\lambda \cdot h}{2} \cdot \right) \tag{3.38}$$

$$I_{S,comp} = 2 \cdot (t_2 + 2 \cdot t_{int} + t_1)^2 \cdot t_1 \cdot h \tag{3.39}$$

$$\lambda = \sqrt{\frac{G_{int} \cdot (t_1 + t_2)}{G \cdot t_1 \cdot t_2 \cdot t_{int}}} \tag{3.40}$$

where,

$M_{cr,LT}$ is the critical torsional buckling moment;

C_1 and C_2 are factor that depend on the bending moment format (Table 3.17);

$E \cdot I_Z$ is the flexural stiffness;

$G \cdot K$ is the torsional stiffness;

L_{LT} is the distance between effectively rigid buckling restrains;

Z_a is the distance between the load application point and the gravity center of the element;

t_{int} is the interlayer thickness;

G_{int} is the interlayer shear modulus;

t_i is the thickness of each glass ply;

h is the beam height;

I_i is the glass inertia of each glass ply.

Table 3.17 – Lateral Torsional Buckling Factors.

Bending moment	C_1	C_2
Constant	1.0	–
Linear (zero at mid span)	2.7	–
Parabolic (zero at both extremities)	1.13	0.46
Triangular (zero at both extremities and maximum at mid span)	1.36	0.55

Source: Haldimann et al (2008).

The AS 1288 (2006) presents recommendations for calculating the critical torsional buckling moment for end-supported beams of bisymmetrical cross section, depending on the beam restraints conditions. Three conditions are considered: beams with intermediate buckling restraints, beams with no intermediate buckling restraints and continuously restrained beams.

The first condition is for beams with intermediate buckling restrain and is presented in equations (3.41) and (3.42).

$$M_{cr} = \frac{g_1}{L_{ay}} \cdot \sqrt{(\mathrm{E} \cdot \mathrm{I})_y \cdot (G \cdot J)} \tag{3.41}$$

$$\mathrm{J} = \frac{d \cdot \mathrm{b}^3}{3} \cdot \left(1 - 0.63 \cdot \frac{b}{d}\right) \tag{3.42}$$

where,

M_{cr} is the critical torsional buckling moment;

g_1 is the coefficient for slenderness factor of bisymmetrical beams (Table 3.18);

L_{ay} is the distance between effectively rigid buckling restraints;

$(\mathrm{E} \cdot \mathrm{I})_y$ is the effective rigidity for bending about the minor axis;

$(G \cdot J)$ is the effective torsional rigidity;

b is the depth of the fin;

d is the breadth of the fin.

Table 3.18 – Coefficients for slenderness factor (g1) of bisymmetrical beams with intermediate buckling restrains.

Moment parameter (β) (see Figure C1 (c))	**Free restraint condition***	**Fixed restraint condition***
1.0	3.10	6.30
0.5	4.10	8.20
0.0	5.50	11.10
-0.5	7.30	14.40
-1.0	8.00	14.00

*The buckling restraints must prevent roatation of the beam about the z-axis. The terms 'free' amd 'fixed' restraint condition refer to the possibility for rotation of the beam about y-y axis at restraints locations, as shown in Figure C1.

Source: AS 1288 (2006).

The second condition is for beams with no intermediate buckling restraints and is presented in equation (3.43).

$$M_{cr} = \frac{g_2}{L_{ay}} \cdot \sqrt{(\mathrm{E} \cdot \mathrm{I})_y \cdot (G \cdot J)} \cdot \left[1 - g_3 \cdot \left(\frac{y_h}{L_{ay}}\right) \cdot \sqrt{\frac{(\mathrm{E} \cdot \mathrm{I})_y}{(G \cdot J)}}\right] \tag{3.43}$$

where,

g_2 and g_3 are constants that depend on the bending moment format (Table 3.19);

y_h is the height above centroid of the point of load application.

The third and last condition is for continuously restrained beams and is presented in equation (3.44).

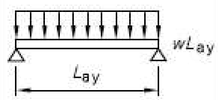
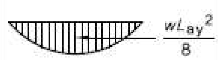
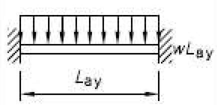
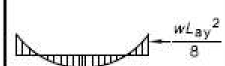
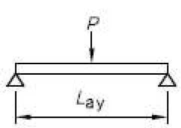
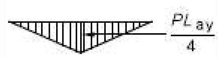
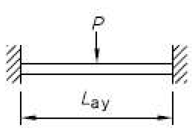
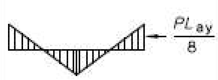
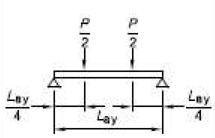
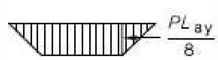
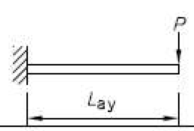
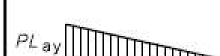
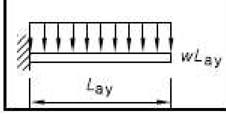
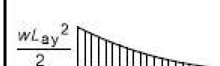
$$M_{cr} = \frac{\left(\frac{\pi}{L_{ay}}\right)^2 \cdot (\mathrm{E} \cdot \mathrm{I})_y \cdot \left[\frac{d^2}{12} + {y_0}^2\right] + (G \cdot J)}{(2 \cdot y_0 + y_h)} \tag{3.44}$$

where,

y_0 is the location from the neutral axis of the loading point.

After the calculation of the critical torsional buckling moment (M_{cr}), it should be checked if any design moment is below the value of the M_{cr} divided by a safety coefficient factor of 1.7.

Table 3.19 – Coefficients for slenderness factor of bisymmetrical beams with no intermediate buckling restrains.

Loading	Bending moment (M)	Condition of end restraint against rotation about y-y axis*	Slenderness factors	
			g_2	g_3
		Free Fixed	3.6 6.1	1.4 1.8
		Free Fixed	4.1 5.4	4.9 5.2
		Free Fixed	4.2 6.7	1.7 2.6
		Free Fixed	5.3 6.5	4.5 5.3
		Free Fixed	3.3 —	1.3 —
		Fixed	4.0	2.0
		Fixed	6.4	2.0

Source: AS 1288 (2006).

4 A GLASS SLAB DESIGN

In this chapter, the design of a 1600 x 1600 mm^2 tempered laminated glass slab working under two different conditions of support is presented. The glass plate is composed of three tempered glass sheets of 10 mm thickness and two PVB interlayers with 1.52 mm thickness each.

As recommended and rule of practice only two sheets are considered in the design as the third is placed by redundancy for safety. Thus, if one of the sheets breaks due to unforeseen circumstances, the plate – with two sheets – will have the design strength to support the project loads.

As already mentioned, the load duration has a high influence on glass resistance. The longer the duration, the lower the resistance. Considering that this slab is for a pedestrian walkway, the load duration would be around 10 minutes. However, it was adopted 60 minutes of load duration for safety.

The design was performed following the ASTM Basic Procedure, ASTM Analytical Procedure, prEN Simplified Method, and the Australian Standard (AS) design criteria.

Firstly, the maximum allowable load was determined using the ASTM Basic Procedure. Subsequently, this load was applied to the slab using the ASTM Analytical Method, the prEN 16612 Simplified Method and the AS Design Criteria and results obtained with the four methods were compared.

The overload considered was the Load Resistance determined by the ASTM Basic Procedure minus the self-weight of the structure.

4.1 GLASS SLAB SUPPORTED ON FOUR EDGES

4.1.1 ASTM Basic Procedure

The first step is to determine the effective thickness of the laminated glass plate. According to Table 4.1, for 10 mm nominal thickness, the minimum thickness is 9.02 mm.

Table 4.1 – Nominal and minimum thickness.

Nominal Thickness or Designation, mm (in.)	Minimum Thickness, mm (in.)
2.0 (picture)	1.80 (0.071)
2.5 (3/32)	2.16 (0.085)
2.7 (lami)	2.59 (0.102)
3.0 (1/8)	2.92 (0.115)
4.0 (5/32)	3.78 (0.149)
5.0 (3/16)	4.57 (0.180)
6.0 (1/4)	5.56 (0.219)
8.0 (5/16)	7.42 (0.292)
10.0 (3/8)	9.02 (0.355)
12.0 (1/2)	11.91 (0.469)
16.0 (5/8)	15.09 (0.595)
19.0 (3/4)	18.26 (0.719)
22.0 (7/8)	21.44 (0.844)
25.0 (1)	24.61 (0.969)

Source: Adapted from ASTM E1300 (2016)

The effective thickness is the sum of the minimum thickness of the two plates and the interlayer. In this case, the effective thickness is 19.56 mm and it is adopted the nearest lower thickness on the charts of the standard, which is 19 mm.

For laminated glass supported by four edges and for 19 mm thickness, the chart from Figure 4.1 should be used for short durations loads (3 seconds).

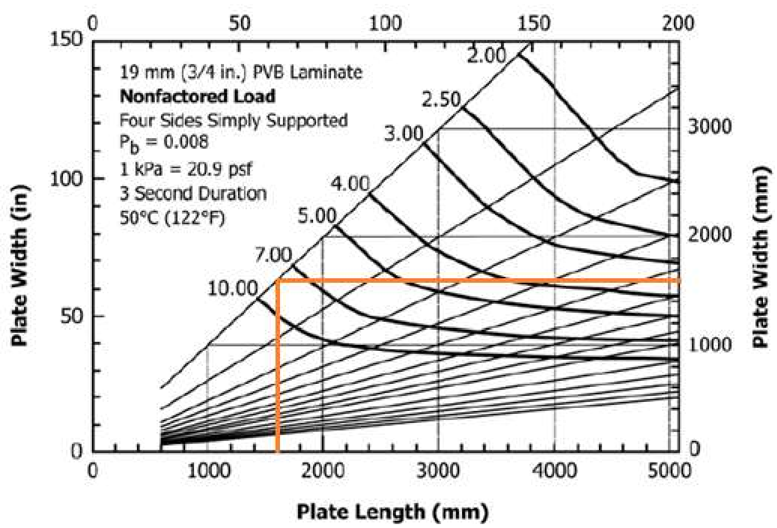


Figure 4.1 – NFL for 19mm laminated glass supported by 4 edges chart.
Source: Adapted from ASTM E1300 (2016).

Entering the length and width of 1600 mm, the correspondent short-duration Non-Factored Load is 8.5 kPa.

According to the type of glass and load duration is determined a Glass Type Factor (GTF) according to Table 4.2. For tempered glass, the GTF for short duration is 4.0.

Table 4.2 –Glass Type Factor (GTF).

Glass Type	Short Duration Load (3s)	Long Duration Load (30 days)
AN	1.0	0.43
HS	2.0	1.3
FT	4.0	3.0

Source: Adapted from ASTM E1300 (2016).

The load resistance is calculated by the multiplication of the Non-Factored Load by the Glass Type Factor, as presented in equation (4.1).

$$\mathrm{LR} = \mathrm{NFL} \cdot \mathrm{GTF} = 8.5 \cdot 4.0 = 34\,\mathrm{kPa} \tag{4.1}$$

The Load Resistance of 34 kPa is determined for a short duration of 3 seconds. For the duration of 60 minutes, it is necessary to reduce the resistance multiplying it by a conversion factor of 0.64, according to the Table 4.3. The 60 minutes Load Resistance calculation is presented in equation (4.2).

Table 4.3 –Conversion factor for load duration.

Duration	Factor
3 s	1.00
10 s	0.93
60 s	0.83
10 min	0.72
60 min	0.64
12 h	0.55
24 h	0.53
1 week	0.47
1 month (30 days)	0.43
1 year	0.36
beyond 1 year	0.31

Source: Adapted from ASTM E1300 (2016).

$$\mathrm{LR}_{60\ \mathrm{minutes}} = \mathrm{LR}_{3\ \mathrm{seconds}} \cdot 0.64 = 34 \cdot 0.64 = 21.76\,\mathrm{kPa} \tag{4.2}$$

To determine the deflection, it is necessary to use the correspondent chart of the set of diagrams chosen for 19 mm laminated glass supported by four edges. The aspect ratio (AR) is the ratio between the large and the smaller plate sizes. In this case, both are 1600 mm and AR is 1.0.

Multiplying the Load Resistance by the squared area of the plate, as presented in equation (4.3), and combining it with the AR, it is possible to obtain the deflection.

$$\mathrm{LR} \cdot \mathrm{A}^2 = 21.76 \cdot (1.6 \times 1.6)^2 = 142.61\,\mathrm{kNm}^2 \tag{4.3}$$

According to the chart in Figure 4.2, for AR equal to 1.0 and Load x Area^2 equals to 142.61kNm^2, the deflection is roughly 16 mm, around 1% of the plate size.

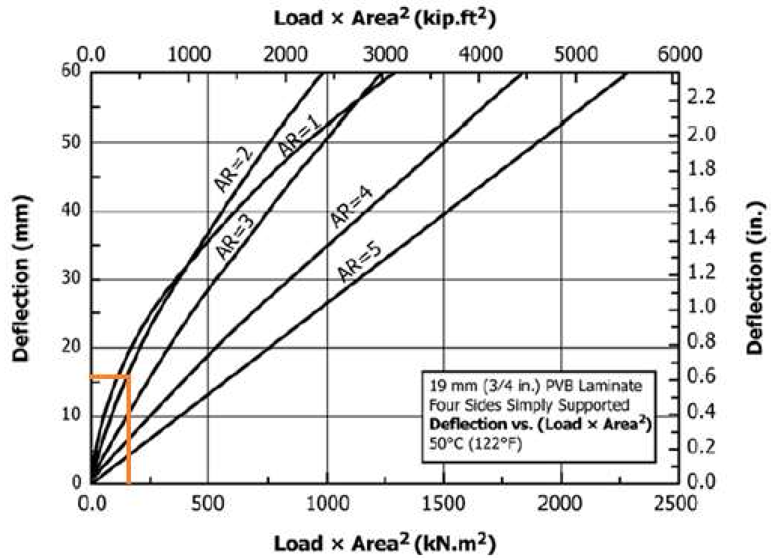


Figure 4.2 – Deflection for 19mm laminated glass supported by 4 edges chart.
Source: Adapted from ASTM E1300 (2016).

4.1.2 ASTM Analytical Procedure

The Analytical Procedure consists of determining the effective thickness of glass for further determination of stresses and deflections using engineering mechanics formulas or Finite Element Method.

Firstly, it is necessary to determine the shear transfer coefficient through the step by step presented on the equations (4.4) to (4.13).

According to Table 4.1, the minimum thickness of the plates ($h_1 and\ h_2$) for 10 mm nominal thickness is 9.02 mm.

$$\mathrm{h_s} = 0.5 \cdot (\mathrm{h_1} + \mathrm{h_2}) + \mathrm{h_v} \tag{4.4}$$

$$\mathrm{h_s} = 0.5 \cdot (9.02 + 9.02) + 1.52 = 10.54\ \mathrm{mm} \tag{4.5}$$

$$\mathrm{h_{s;1}} = \frac{\mathrm{h_s} \cdot \mathrm{h_1}}{\mathrm{h_1} + \mathrm{h_2}} \tag{4.6}$$

$$\mathrm{h_{s;1}} = \frac{10.54 \cdot 9.02}{9.02 + 9.02} = 5.27\ \mathrm{mm} \tag{4.7}$$

$$\mathrm{h_{s;2}} = \frac{\mathrm{h_s} \cdot \mathrm{h_2}}{\mathrm{h_1} + \mathrm{h_2}} \tag{4.8}$$

$$h_{s;2} = \frac{10.54 \cdot 9.02}{9.02 + 9.02} = 5.27 \text{ mm} \tag{4.9}$$

The inertia is calculated with equations (4.10) and (4.11).

$$I_S = h_1 \cdot {h_{s;2}}^2 + h_2 \cdot {h_{s;1}}^2 \tag{4.10}$$

$$I_S = 9.02 \cdot 5.27^2 + 9.02 \cdot 5.27^2 = 501.023 \text{ mm}^3 \tag{4.11}$$

For calculating the shear transfer (ɼ), it is necessary to know the glass Young Modulus (E) and the interlayer shear modulus (G). On this example, E is taken as 70000 MPa and the interlayer shear modulus is taken to be equal to 0.052 MPa, corresponding to a PVB interlayer at to 50ºC under a 60 minutes load duration.

$$ɼ = \frac{1}{1 + 9.6 \cdot \frac{E \cdot I_S \cdot h_v}{G \cdot {h_s}^2 \cdot a^2}} \tag{4.12}$$

$$ɼ = \frac{1}{1 + 9.6 \cdot \frac{70000 \cdot 501.023 \cdot 1.52}{0.052 \cdot 10.54^2 \cdot 1600^2}} = 0.028 \tag{4.13}$$

The effective thickness for deflection ($h_{ef;w}$) is determined with equations (4.14) and (4.15).

$$h_{ef;w} = \sqrt[3]{{h_1}^3 + {h_2}^3 + 12ɼ \cdot I_s} \tag{4.14}$$

$$h_{ef;w} = \sqrt[3]{9.02^3 + 9.02^3 + 12 \cdot 0.028 \cdot 501.023} = 11.78 \text{ mm} \tag{4.15}$$

The effective thickness to the bending stresses ($h_{i;ef;\sigma}$) for each plate are determined by equations (4.16) and (4.17).

$$h_{1=2;ef;\sigma} = \sqrt{\frac{{h_{ef;w}}^3}{h_1 + 2 \cdot ɼ \cdot h_{s;2}}} \tag{4.16}$$

$$h_{1=2;ef;\sigma} = \sqrt{\frac{11.78^3}{9.02 + 2 \cdot 0.028 \cdot 5.27}} = 13.25 \text{ mm} \tag{4.17}$$

For calculating the maximum stresses and deflection, should be used a Finite Element Program. It was used the ©DLUBAL – RFEM 5.16 Software with the add on module for glass, RF-GLASS.

The load applied was calculated on the ASTM Basic Procedure. This load was chosen to enable the comparison between the stresses generated using different methods and standards. For this method, the load was divided into self-weight (0.75 kN/m^2) and overload (21.01 kN/m^2) and the combination of load was the sum of both loads, as presented in equation (4.18).

$$p = 0.750 + 21.01 = 21.76 \text{ kN/m}^2 \tag{4.18}$$

The maximum stresses were calculated to the correspondent thickness of 13.25 mm and have a maximum value of 86.53 MPa. It occurs at the center of the plate, as shown in Figure 4.3.

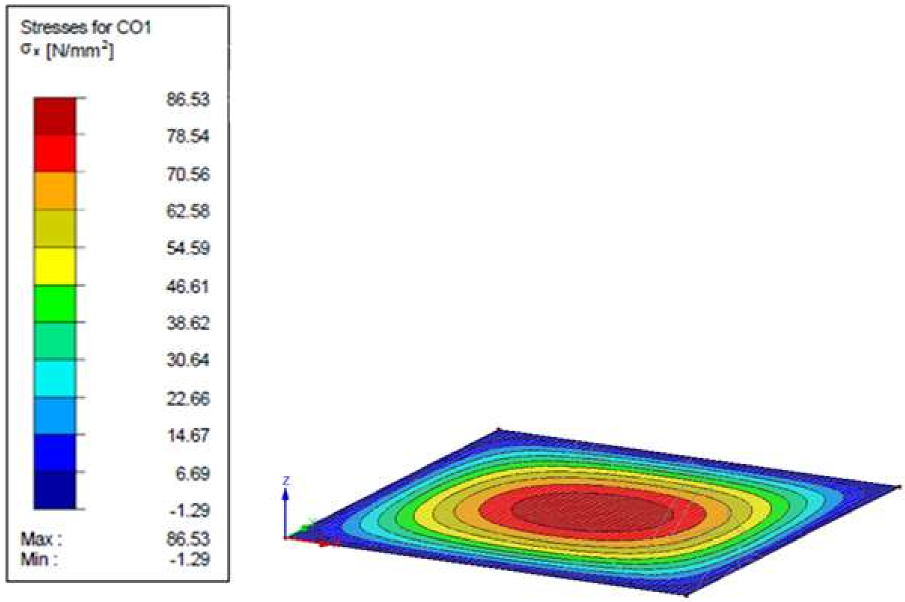


Figure 4.3 – Stresses on the plate according to ASTM effective thicknesses.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The deflections were calculated to the correspondent thickness of 11.58 mm and have a maximum value of 57.8 mm. It occurs at the center of the plate, as shown in Figure 4.4.

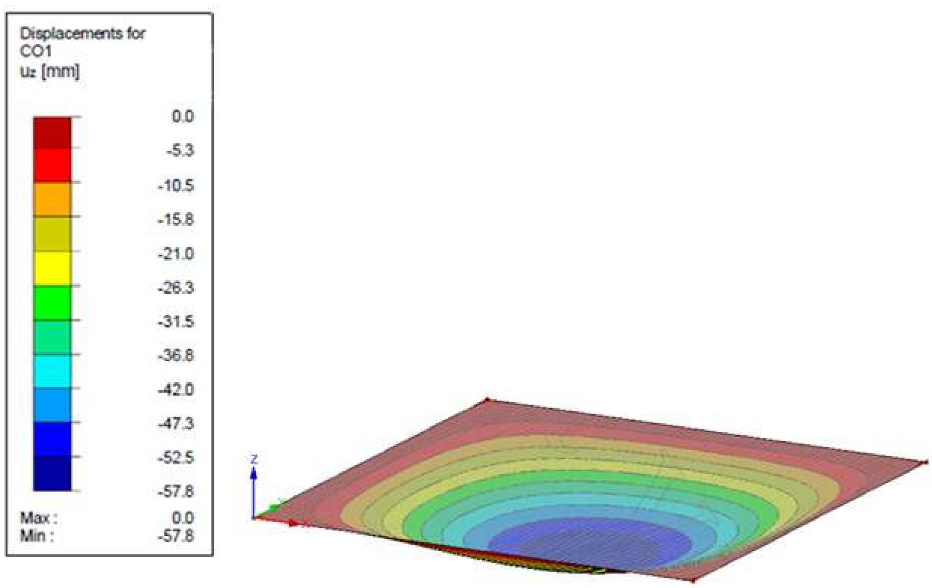


Figure 4.4 – Deflections on the plate according to ASTM effective thicknesses.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The maximum stress is outside the limit allowed by ASTM standards. The maximum allowable stress is 63 MPa, according to Table 3.4 for tempered glass and 60 minutes of load duration.

Limiting the stress to 63 MPa, the maximum load that can be applied on the slab is 15.84 kN/m^2. Therefore, the maximum overload is 15.09 kN/m^2 as shown in equation (4.19).

$$\text{Overload} = 15.84 - 0.750 = 15.09\,\text{kN/m}^2 \qquad (4.19)$$

A new model was generated in the ©DLUBAL – RFEM 5.16 with the new load case to demonstrate that the stress would be within the expected value. The results can be checked in Figure 4.5.

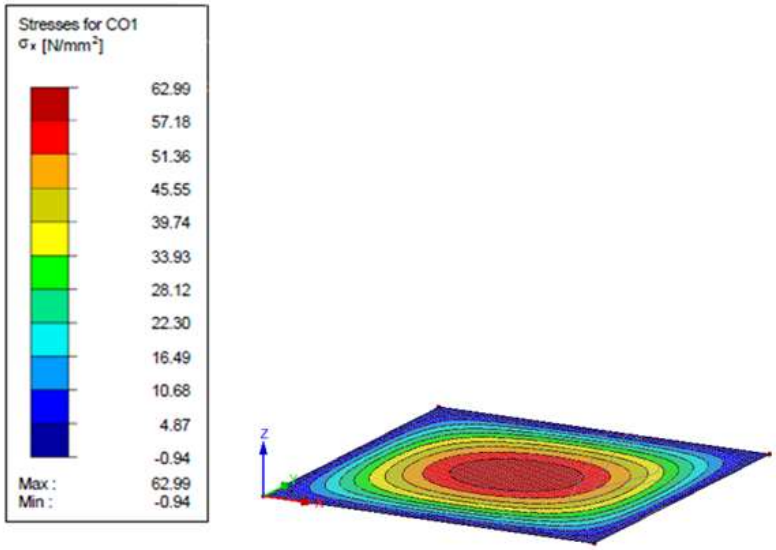


Figure 4.5 – Stresses on the plate according to new load case for limited stress.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The deflections were calculated to the new load case and have a maximum value of 42 mm. It occurs at the center of the plate, as shown in Figure 4.6.

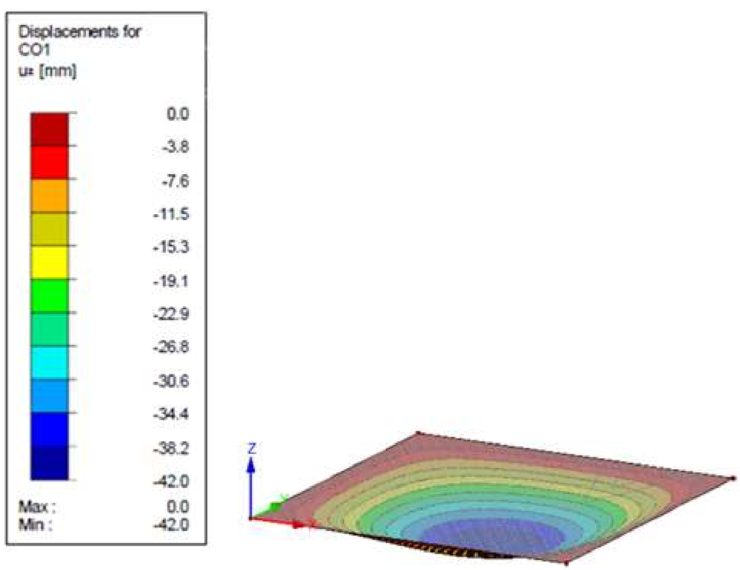


Figure 4.6 – Deflections on the plate according to new load case for limited stress.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The ASTM standards does not establish a specific value for the glass deflection. ASTM E2751 (2017) determines that *"Deflection of the floor members shall conform to relevant building code requirements".* The German standard, DIN 18008-1 (2010), suggests a maximum deflection of Span/100 and this limit was adopted on this work.

Limiting the deflection to 16 mm, the maximum load to be applied on the slab is 6.03 kN/m², therefore the maximum overload is 5.28 kN/m². The deflections are presented in Figure 4.7 and the stresses in Figure 4.8.

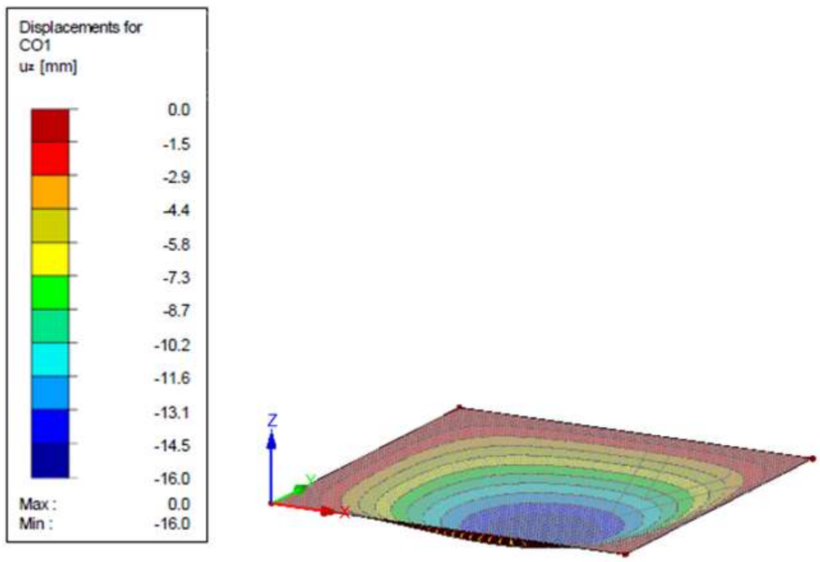


Figure 4.7 – Deflections on the plate according to new load case for limited deflection.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

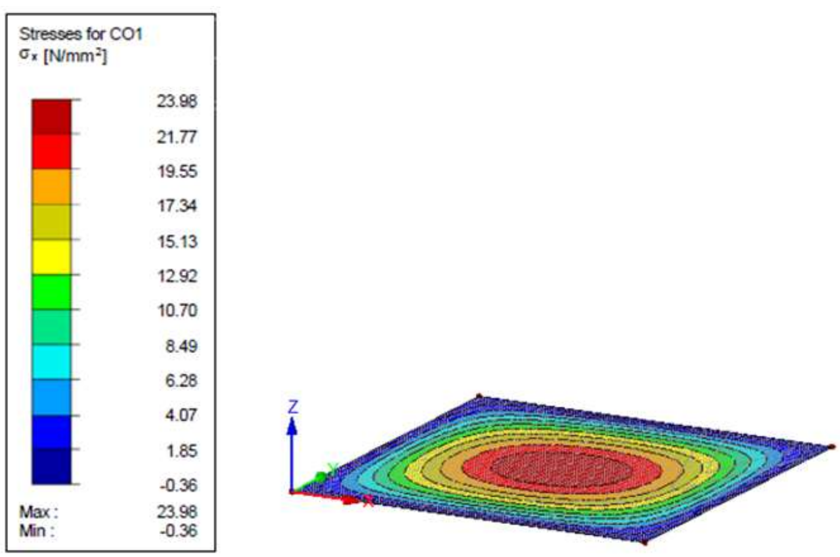


Figure 4.8 – Stresses on the plate according to new load case for limited deflection.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

4.1.3 prEN Simplified Method

Analogously to ASTM E1300 (2016), the simplified method consists of determining the effective thickness of glass for further determination of stresses and deflections.

The modification factor depends on the duration of the load in hours and can be calculated as in equations (4.20) and (4.21).

$$\mathrm{k_{mod}} = 0.663 \cdot \mathrm{t}^{\left(-\frac{1}{16}\right)} \tag{4.20}$$

$$\mathrm{k_{mod}} = 0.663 \cdot 1^{\left(-\frac{1}{16}\right)} = 0.663 \tag{4.21}$$

The design value of stress can be calculated with equations (4.22) and (4.23).

$$\mathrm{f_{g;d}} = \frac{\mathrm{k_{mod}} * \mathrm{k_{sp}} * \mathrm{f_{g;k}}}{\gamma_{\mathrm{M;A}}} + \frac{\mathrm{k_v} * (\mathrm{f_{b;k}} - \mathrm{f_{g;k}})}{\gamma_{\mathrm{M;V}}} \tag{4.22}$$

$$\mathrm{f_{g;d}} = \frac{0.663 * 1.0 * 45}{1.6} + \frac{1.0 * (120 - 45)}{1.2} = 81.15\ \mathrm{MPa} \tag{4.23}$$

The ω is the coefficient that represents the shear transfer. The prEN 16612 (2013) does not specify which Family each interlayer belongs to. Therefore, it was adopted Family 0, according to Table 3.6, because it presents a null shear transfer and it would be in favor of safety.

The effective thickness for deflection ($h_{ef;w}$) is calculated by equations (4.24) and (4.25).

$$\mathrm{h_{ef;w}} = \sqrt[3]{\Sigma\, \mathrm{h_k}^3 + 12 \cdot \omega \cdot (\Sigma \mathrm{h_k} \cdot \mathrm{h_{m,k}}^2)} \tag{4.24}$$

$$\mathrm{h_{ef;w}} = \sqrt[3]{10^3 + 10^3 + 12 \cdot 0 \cdot [(10 \cdot 5.76^2) + (10 \cdot 5.76^2)]} = 12.60\ \mathrm{mm} \tag{4.25}$$

The effective thickness for bending stress ($h_{\mathrm{ef};\sigma;\mathrm{j}}$) for each plate is calculated by (4.26) and (4.27).

$$\mathrm{h_{ef;\sigma;j}} = \sqrt{\frac{\mathrm{h_{ef;w}}^3}{\mathrm{h_j} + 2 \cdot \omega \cdot \mathrm{h_{m;j}}}} \tag{4.26}$$

$$\mathrm{h_{ef;\sigma;j}} = \sqrt{\frac{12.60^3}{10 + 2 \cdot 0 \cdot 5.76}} = 14.14\ \mathrm{mm} \tag{4.27}$$

For calculating the maximum stress and deflection, the same Finite Element Program is used - the ©DLUBAL – RFEM 5.16 Software with the add on module for glass, RF-GLASS.

The load applied was calculated on the ASTM Basic Procedure. This load was chosen to enable the comparison between the stresses generated using different methods and standards. For this method, the load was divided into self-weight (0.75 kN/m^2) and an overload of 21.01 kN/m^2 with combinations made according to the EN 1990 (2009) "Eurocode 0 - Basis of Structural Design" for ULS and SLS, as presented in equations (4.28) and (4.29).

$$\text{ULS: } F_d = 1.35 \cdot 0.750 + 1.5 \cdot 21.01 = 32.527 \text{ kN/m}^2 \quad (4.28)$$

$$\text{SLS: } F_d = 0.750 + 0.4 \cdot 21.01 = 9.154 \text{ kN/m}^2 \quad (4.29)$$

The maximum stresses were calculated to the correspondent effective thickness of 14.14 mm and had a maximum value of 113.61 MPa, occurring as expected at the center of the plate (Figure 4.9).

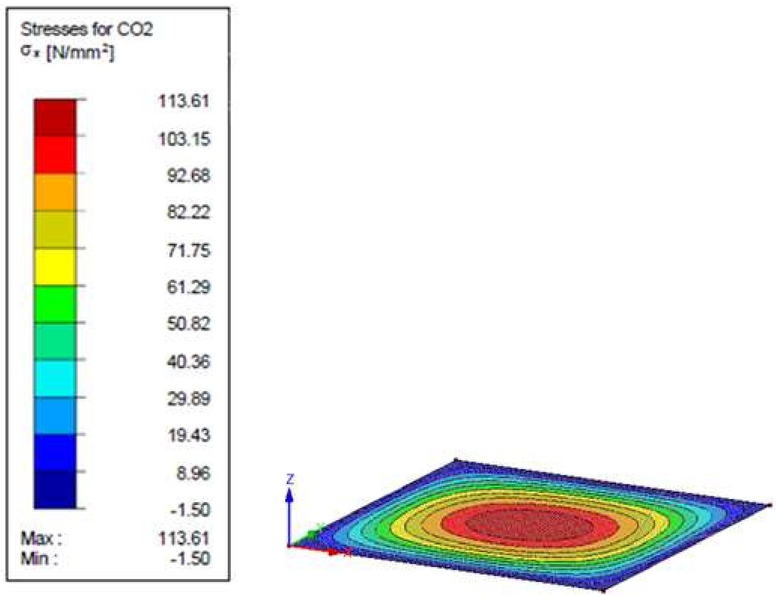


Figure 4.9 – Stresses on the plate according to prEN effective thicknesses.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The deflections were calculated to the correspondent effective thickness of 12.60 mm and had a maximum value of 19.9 mm. It occurs at the center of the plate, as shown in Figure 4.10.

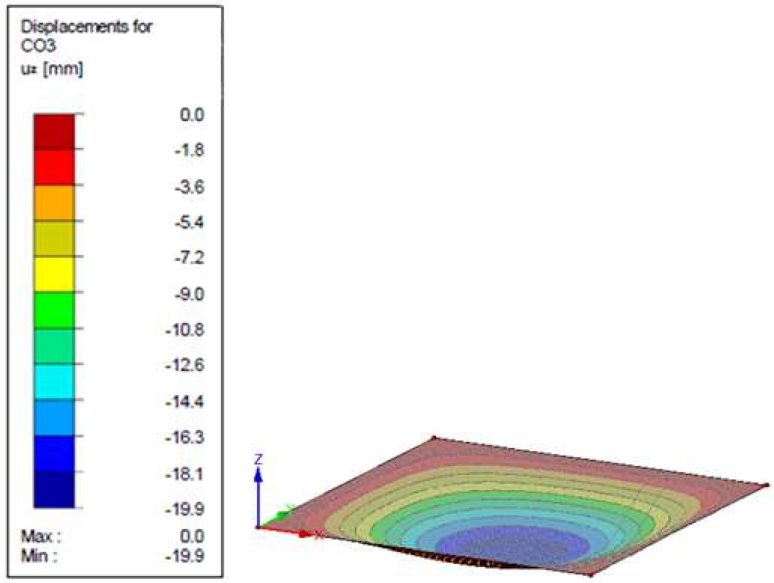


Figure 4.10 – Deflections on the plate according to prEN effective thicknesses.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The maximum stress is outside the limit allowed by prEN16612 (2013) standard. The stress design value is 81.15 MPa, as calculated in equation (4.23).

Limiting the stress to 81.15 MPa, the maximum load that can be applied on the slab is 23.23 $\mathrm{kN/m^2}$. Therefore, the maximum overload is 14.81 $\mathrm{kN/m^2}$ as shown in equation (4.30).

$$\text{Overload} = \frac{23.23 - (1.35 \cdot 0.75)}{1.5} = 14.81\ \mathrm{kN/m^2} \tag{4.30}$$

The load combinations used for the model are presented in equations (4.31) and (4.32).

$$\text{ULS: } \mathrm{F_d} = 1.35 \cdot 0.750 + 1.5 \cdot 14.81 = 23.23\ \mathrm{kN/m^2} \tag{4.31}$$

$$\text{SLS: } \mathrm{F_d} = 0.750 + 0.4 \cdot 14.81 = 6.67\ \mathrm{kN/m^2} \tag{4.32}$$

A new model was generated in the ©DLUBAL – RFEM 5.16 with the new load case to demonstrate that the stress would be within the expected value. The results can be checked in Figure 4.11.

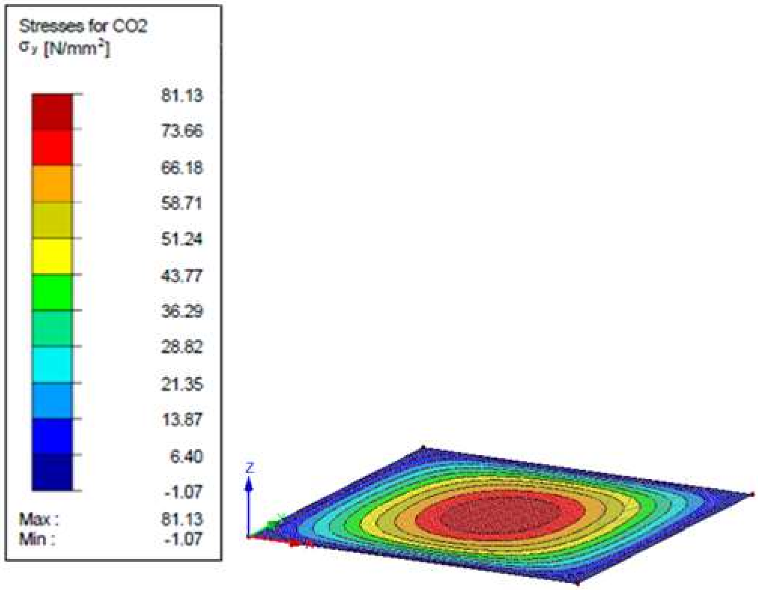


Figure 4.11 – Stresses on the plate according to new load case for limited stress.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The deflections were calculated to the new load case and had a maximum value of 14.5 mm. It occurs at the center of the plate, as shown in Figure 4.12.

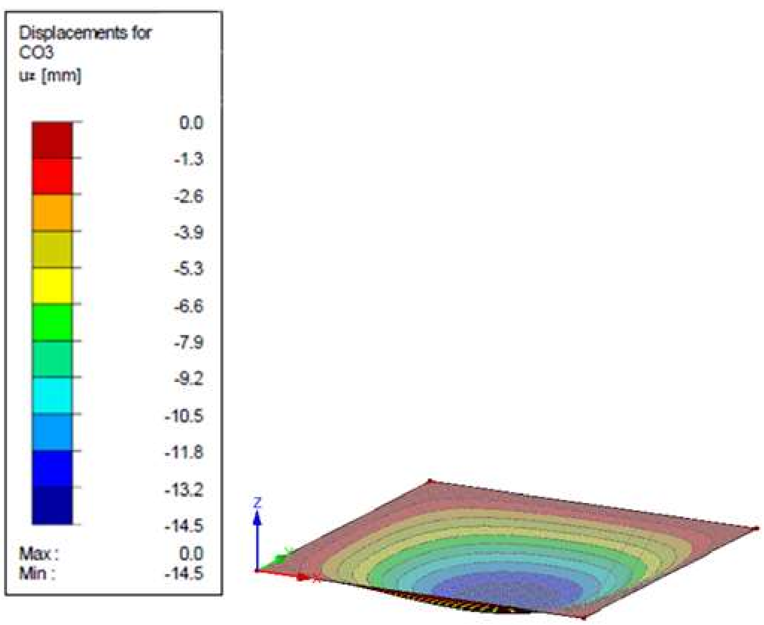


Figure 4.12 – Deflections on the plate according to new load case for limited stress.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The prEN 16612 (2013) standard determines that *"In absence of any specific requirement, deflections shall be limited to Span/65 or 50 mm, whichever is the lower value".* The German standard, DIN 18008-1 (2010), suggests a maximum deflection of Span/100, a limit that is adopted, which is, therefore 16 mm.

4.1.4 AS 1288 Design Criteria

The AS 1288 requires that the stresses must be checked for the assembly and for each plate isolated.

For the assembly, the glass nominal thickness is determined by the sum of the two glass plates thicknesses, as presented in equation (4.33). The minimum thickness is the correspondent value for the glass assembly.

$$t_{\mathrm{nominal}} = 10 + 10 = 20\ \mathrm{mm} \tag{4.33}$$

According to Table 3.13, the minimum thickness for a laminated glass of 20 mm of nominal thickness is 19.40 mm.

The characteristic tensile strength of glass was determined by equations (4.34) and (4.35) for parts away from the edge of the glass panes.

$$f'_t = -9.85 \cdot ln\, t + 71.34 \tag{4.34}$$

$$f'_t = -9.85 \cdot ln\,(19.40) + 71.34 = 42.13\, MPa \tag{4.35}$$

The ultimate capacity ($\phi \cdot R_u$) shall be determined as shown in equations (4.36) and (4.37). The coefficients c_1, c_2 and c_3 where respectively determined according to Table 3.14, Table 3.15 and Table 3.16.

The capacity reduction factor is 0.67. The glass type factor (c_1) is 2.5 for toughened glass, the surface type factor (c_2) is 1.0 for untreated flat glass and the load duration factor is 1.0 for short-term and medium-term load durations for laminated toughened glass.

$$\emptyset \cdot R_u = \emptyset \cdot c_1 \cdot c_2 \cdot c_3 \cdot [f'_t \cdot X] \tag{4.36}$$

$$\emptyset \cdot R_u = 0.67 \cdot 2.5 \cdot 1.0 \cdot 1.0 \cdot [42.13] = 70.57\, MPa \tag{4.37}$$

For calculating the maximum stress and deflection, should be used a Finite Element Program. It was used the ©DLUBAL – RFEM 5.16 Software with the add on module for glass, RF-GLASS.

Analogously to prEN 16612, the load applied was the one calculated on the ASTM Basic Procedure, to enable the comparison between standards. The load was divided into self-weight (0.75 kN/m^2) and overload (21.01 kN/m^2). The combinations were made according to the AS/NZS 1170.0 (2002) – “Structural Design Actions-Part 0: General Principles” for ULS and SLS.

The ULS combination is presented in equation (4.38) and the SLS combination, in equation (4.39).

$$\text{ULS: } \mathrm{F_d} = 1.20 \cdot 0.750 + 1.5 \cdot 21.01 = 32.415\ \mathrm{kN/m^2} \tag{4.38}$$

$$\text{SLS: } \mathrm{F_d} = 0.750 + 0.6 \cdot 21.01 = 13.356\ \mathrm{kN/m^2} \tag{4.39}$$

The maximum stresses were calculated to the correspondent thickness of 19.40 mm, as presented in Figure 4.13. The maximum stress occurs at the center of the plate and has a value of 60.28 MPa, as shown in Figure 4.14 and the maximum deflection has a value of 8.00 mm and is presented in Figure 4.16.

Layer No.	A Layer Type	B Material Description	C Thickness t [mm]	D Limit Stress σ_{limit} [N/mm²]	E Modulus of Elast. E [N/mm²]	F Shear Modulus G [N/mm²]	G Poisson's Ratio ν [-]
1	Glass	Thermally Toughened Float Glass	19.40	70.570	70000.000	28455.300	0.230

Figure 4.13 – Glass assembly using minimum thickness on ©DLUBAL – RFEM 5.16.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

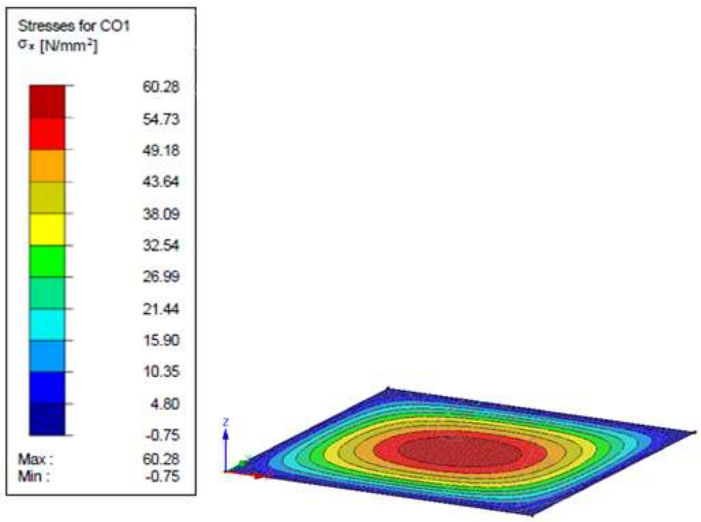


Figure 4.14 – Stresses on the plate according to AS 1288 minimum thickness.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

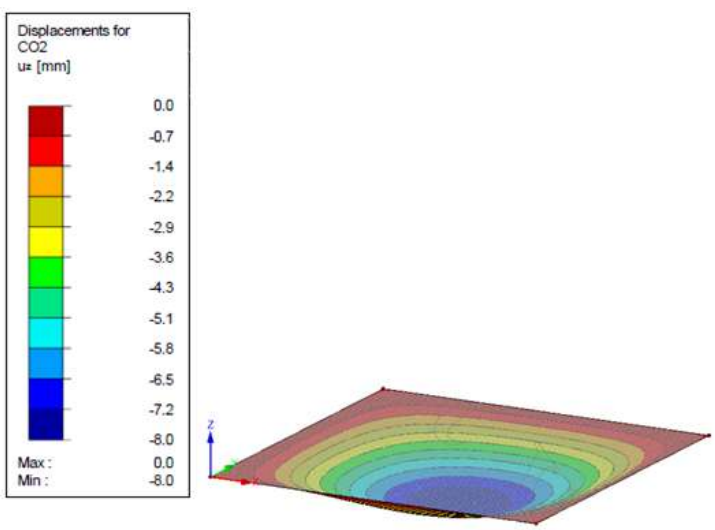


Figure 4.15 – Deflections on the plate according to AS 1288 minimum thickness.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

In accordance to AS 1288 (2006) for medium and long load durations, it is necessary to determine the percentage of the load that is resisted by each ply of the glass. For two plates of equal thickness, each one is responsible for 50% of the load.

The minimum thickness for an isolated plate is 9.7mm, which is the respective thickness for one plate of 10 mm nominal thickness. The characteristic tensile strength of glass was determined for the new thickness by equations (4.40) and (4.41) for parts away from the edge of the glass panes.

$$f'_t = -9.85 \cdot ln\, t + 71.34 \quad (4.40)$$

$$f'_t = -9.85 \cdot ln\,(9.70) + 71.34 = 48.96\, MPa \quad (4.41)$$

The ultimate capacity (ϕ·R_u) shall be determined as shown in equations (4.42) and (4.43). The coefficients c_1, c_2 and c_3 were respectively determined according to Table 3.14, Table 3.15 and Table 3.16.

The capacity reduction factor is 0.67. The glass type factor (c_1) is 2.5 for toughened glass, the surface type factor (c_2) is 1.0 for untreated flat glass and the load duration factor is 1.0 for short-term and medium-term load durations for laminated toughened glass.

$$\emptyset \cdot R_u = \emptyset \cdot c_1 \cdot c_2 \cdot c_3 \cdot [f'_t \cdot X] \quad (4.42)$$

$$\emptyset \cdot R_u = 0.67 \cdot 2.5 \cdot 1.0 \cdot 1.0 \cdot [48.96] = 82.00\, MPa \quad (4.43)$$

The maximum stresses were calculated defining each component of the glass assembly on ©DLUBAL – RFEM 5.16, as presented in Figure 4.16.

	A	B	C	D	E	F	G
Layer No.	Layer Type	Material Description	Thickness t [mm]	Limit Stress σ_{limit} [N/mm²]	Modulus of Elast. E [N/mm²]	Shear Modulus G [N/mm²]	Poisson's Ratio ν [-]
1	Glass	Thermally Toughened Float Glass	9.70	82.000	70000.000	28455.300	0.230
2	Foil	PVB 50 °C loading until 1 hour	1.52		1.600	0.534	0.499
3	Glass	Thermally Toughened Float Glass	9.70	82.000	70000.000	28455.300	0.230

Figure 4.16 – Glass assembly using glass layers and interlayers on ©DLUBAL – RFEM 5.16.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The maximum stress occurs at the center of the plate and has a value of 120.10 MPa, as shown in Figure 4.17.

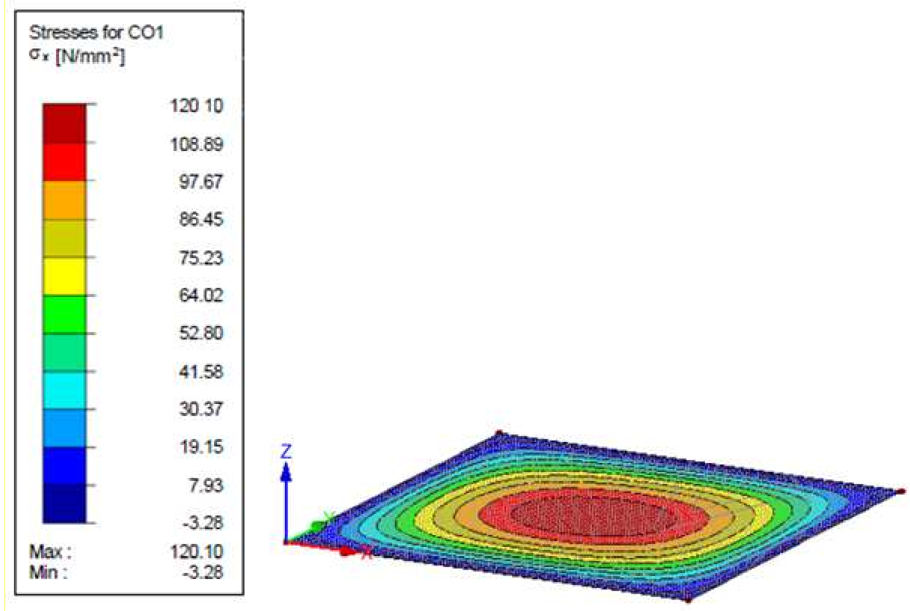


Figure 4.17 – Stresses on the plate according to AS 1288.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The deflections were calculated for SLS combination of loads. The maximum deflection occurs at the center of the plate and has a value of 31.7 mm, as shown in Figure 4.18.

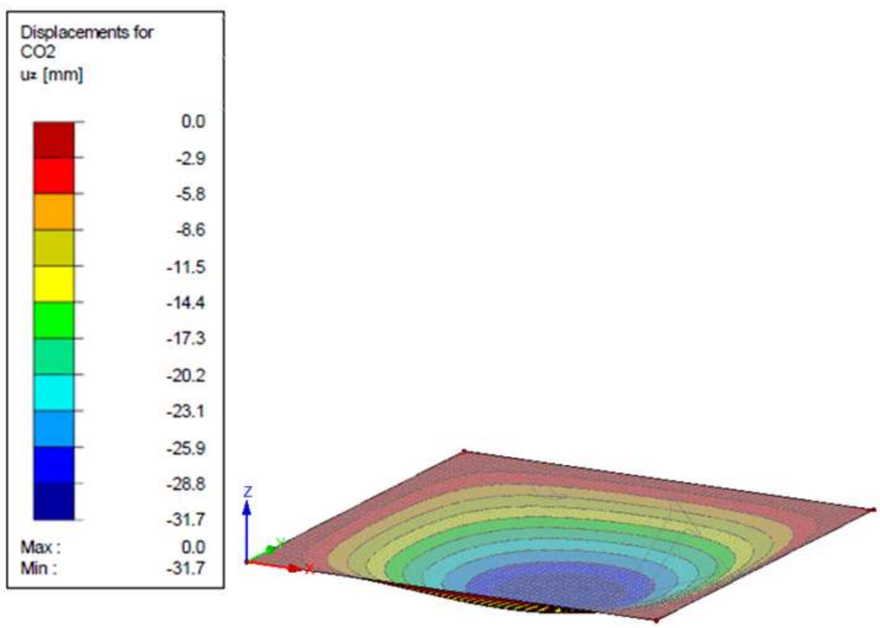


Figure 4.18 – Deflections on the plate according to AS 1288.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The maximum stress is outside the limit allowed by AS 1288 (2006) standard, which is 82.00 MPa, as calculated in equation (4.43).

Limiting the stress to 82.00 MPa, the maximum load that can be applied on the slab is 22.13 $\mathrm{kN/m^2}$. Therefore, the maximum overload is 14.15 $\mathrm{kN/m^2}$ as shown in equation (4.44).

$$\text{Overload} = \frac{22.13 - (1.20 \cdot 0.75)}{1.5} = 14.15\ \mathrm{kN/m^2} \quad (4.44)$$

The new load combinations used for the model are presented in equations (4.45) and (4.46).

$$\text{ULS: } \mathrm{F_d} = 1.20 \cdot 0.750 + 1.5 \cdot 14.15 = 22.13\ \mathrm{kN/m^2} \quad (4.45)$$

$$\text{SLS: } \mathrm{F_d} = 0.750 + 0.6 \cdot 14.15 = 9.24\ \mathrm{kN/m^2} \quad (4.46)$$

A new model was generated in the ©DLUBAL – RFEM 5.16 with the new load case to demonstrate that the stress would be within the expected value. The results can be checked in Figure 4.19.

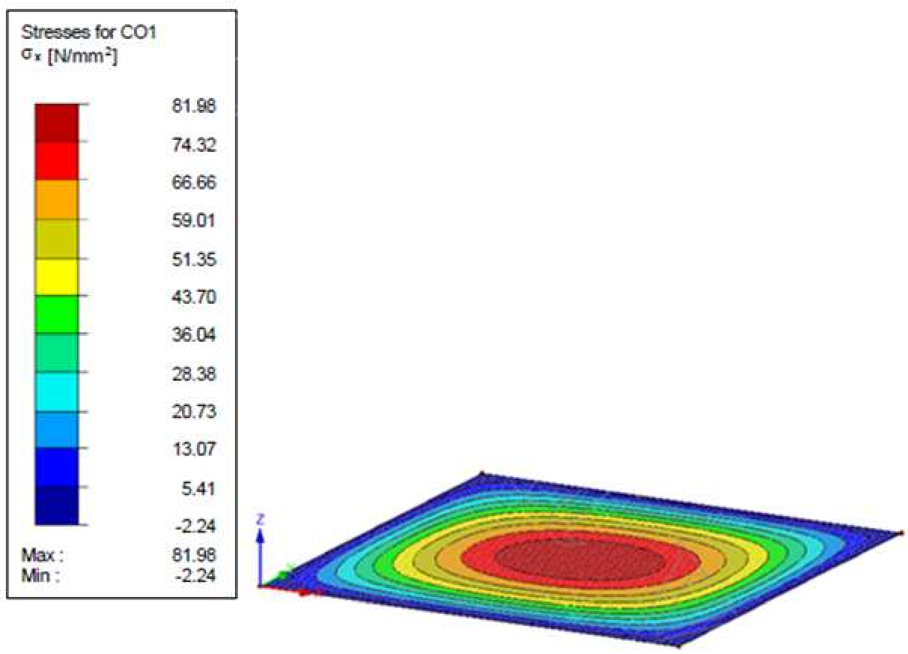


Figure 4.19 – Stresses on the plate according to AS 1288. and new load case for limited stress. Source: ©DLUBAL – RFEM 5.16 – Author (2019).

The deflections were calculated to the new load case and have a maximum value of 21.90 mm. It occurs at the center of the plate, as shown in Figure 4.20.

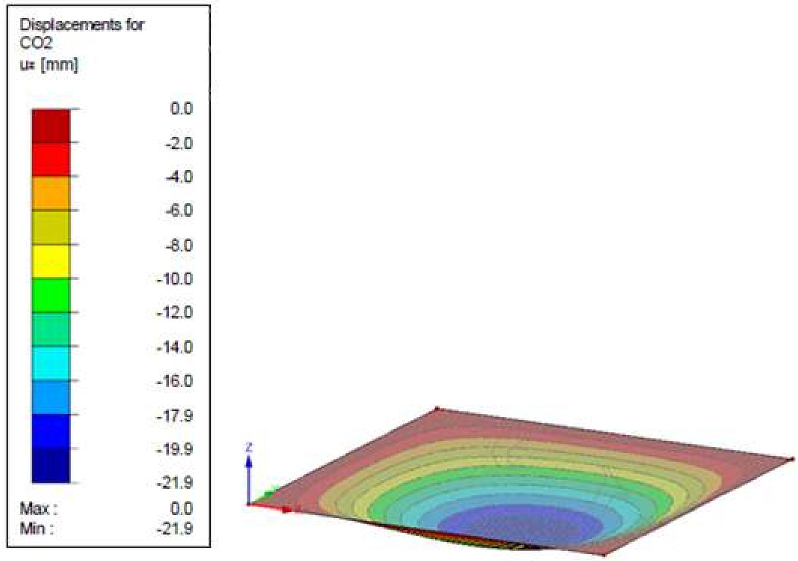


Figure 4.20 – Deflection on the plate according to AS 1288. and new load case for limited stress.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

As mentioned on heading 3.3, the AS 1288 (2006) deflection is limited to Span/60, which would be 26.67mm, therefore the deflection of 21.90 mm would be within the limit. To compare with the other standards presented on this work, it was checked also for the DIN 18008-1 (2010) limit of Span/100, which would be 16 mm. In this case the deflection of 21.90 mm is over the limit.

Limiting the deflection to 16 mm, the maximum SLS combination load to be applied on the slab is 6.75 kN/m², therefore the maximum overload is 10 kN/m². The deflections are presented in Figure 4.21 and the stresses in Figure 4.22.

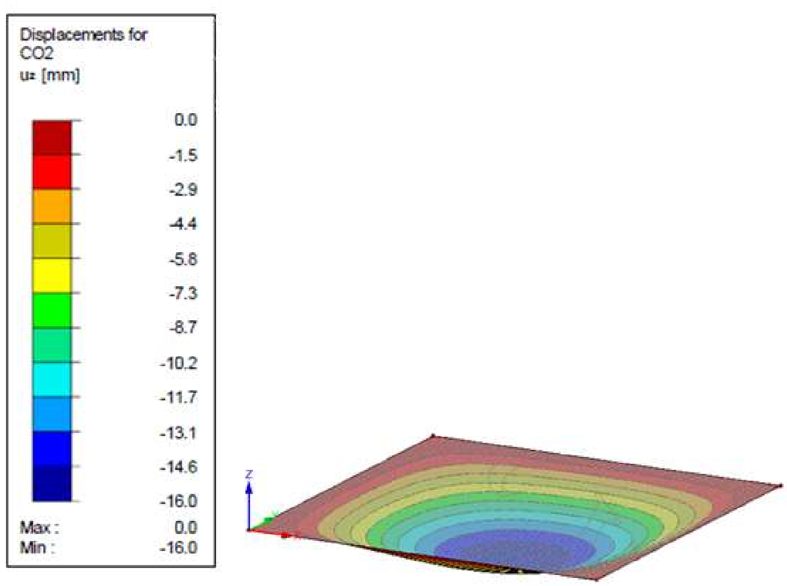


Figure 4.21 – Deflections on the plate according to AS 1288. and new load case for limited deflection.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

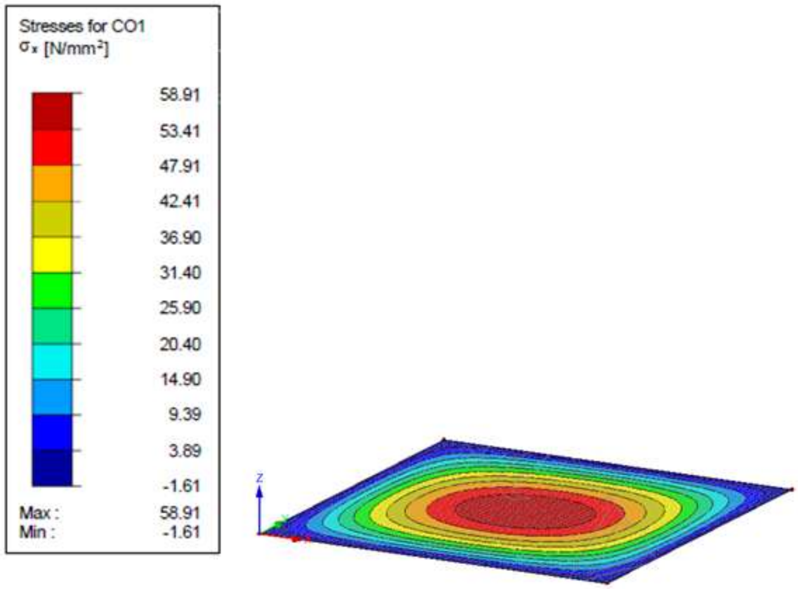


Figure 4.22 – Stresses on the plate according to AS 1288. and new load case for limited deflection.
Source: ©DLUBAL – RFEM 5.16 – Author (2019).

4.2 GLASS SLAB SUPPORTED ON TWO PARALLEL EDGES

4.2.1 ASTM Basic Procedure

The first step is to determine the effective thickness. As presented on heading 4.1.1, the effective thickness adopted was 19 mm.

For laminated glass supported by two edges, the chart from Figure 4.23 should be used.

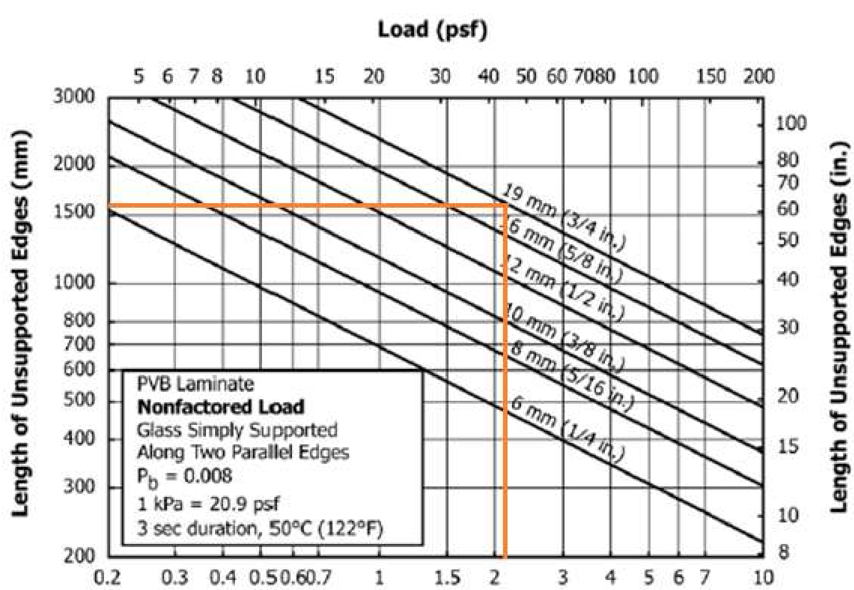


Figure 4.23 – NFL laminated glass supported by two edges chart.
Source: Adapted from ASTM E1300 (2016).

Entering the unsupported edge of 1600 mm, creating a horizontal line until the line of 19 mm effective thickness is found, rebound in a vertical line, to define the Non-Factored Load of 2.15 kPa.

According to the type of glass and load duration, the Glass Type Factor is determined according to Table 4.2. For tempered glass, the factor for short duration is 4.0.

The load resistance is calculated by the multiplication of the Non-Factored Load by the Glass Type Factor, as in equation (4.47).

$$\mathrm{LR} = \mathrm{NFL} \cdot \mathrm{GTF} = 2.15 \cdot 4.0 = 8.60\,\mathrm{kPa} \tag{4.47}$$

The Load Resistance is determined for a short duration of 3 seconds. For the duration of 60 minutes, it is necessary to reduce the resistance multiplying it per 0.64, according to Table 4.3. The 60 minutes Load Resistance is presented in equation (4.48).

$$\mathrm{LR}_{60\ \mathrm{minutes}} = \mathrm{LR}_{3\ \mathrm{seconds}} \cdot 0.64 = 8.60 \cdot 0.64 = 5.504\,\mathrm{kPa} \tag{4.48}$$

To determine the deflection, is necessary to use the correspondent chart of the set chosen for 19 mm laminated glass supported by two edges, presented in Figure 4.24.

Multiplying the Load Resistance by the length of the plate high to four, as presented in equation (4.49), and combining it with the effective thickness, it is possible to obtain the deflection.

$$\mathrm{LR} \cdot \mathrm{L}^4 = 5.504 \cdot 1.6^4 = 36.07\,\mathrm{kNm}^2 \tag{4.49}$$

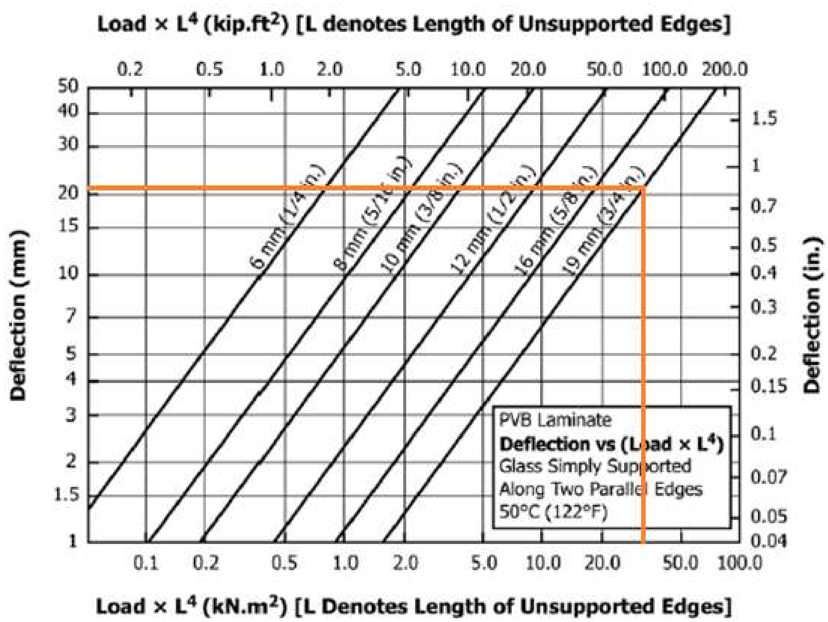


Figure 4.24 – Deflection for laminated glass supported by two edges chart.
Source: Adapted from ASTM E1300 (2016).

In the chart of Figure 4.24, for load times length high to four equals to 36.07 kNm² and 19mm thickness, the deflection is 21.5 mm.

4.2.2 ASTM Analytical Procedure

The analytical procedure consists of determining the effective thickness of glass for further determination of stresses and deflections using engineering mechanics formulas or Finite Element Method. Therefore, the effective thicknesses are the same as determined on heading 4.1.2, which are 13.25 mm for stress and 11.78 mm for deflection.

The stresses can be determined as a bi supported beam with engineering mechanics formulas as presented in equation (4.50) and the moment as in equation (4.51).

$$\sigma = \frac{M}{W} \tag{4.50}$$

$$M = \sigma \cdot W \tag{4.51}$$

The section modulus was calculated per meter of plate. Therefore, b was adopted equal to 1.0 m, as presented in equation (4.52).

$$W = \frac{b \cdot h^2}{6} = \frac{1 \cdot 0.01325^2}{6} = 2.926042 \cdot 10^{-5}\,m^3 \tag{4.52}$$

The maximum allowable surface stress is presented in Table 3.4. For tempered glass with load duration of 60 minutes, it is 63 MPa.

The maximum load was calculated to the allowable stress limit, as presented in equations (4.53) to (4.55).

$$M = 63 \cdot 10^3 \cdot 2.926042 \cdot 10^{-5} = 1.83\ kNm \tag{4.53}$$

$$M = \frac{p \cdot L^2}{8} \tag{4.54}$$

$$p = \frac{8 \cdot M}{L^2} = \frac{8 \cdot 1.83}{1.6^2} = 5.72\ kN/m \tag{4.55}$$

The deflection can be determined as a bi supported beam with engineering mechanics formulas as presented in equations (4.56) and (4.57).

$$I = \frac{b \cdot h^3}{12} = \frac{1 \cdot 0.01178^3}{12} = 1.362243 \cdot 10^{-7}\,m^4 \tag{4.56}$$

$$\delta máx = \frac{5 \cdot p \cdot L^4}{384 \cdot E \cdot I} = \frac{5 \cdot p \cdot 1.6^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 1.362243 \cdot 10^{-7}} = 8.95 \cdot p \tag{4.57}$$

Applying the load calculated in equation (4.55) in equation (4.57), the deflection obtained is 51.2 mm.

The German standard, DIN 18008-1 (2010), suggests a maximum deflection of Span/100 and this limit was adopted on this work. Limiting the deflection to 16 mm, the maximum load to be applied on the slab is 1.78 kN/m², therefore, the maximum allowable overload is 1.03 kN/m².

4.2.3 prEN Simplified Method

The simplified method consists of determining the effective thickness of glass for further determination of stresses and deflections. Therefore, the effective thicknesses are the same as determined on heading 4.1.3, which are 14.14 mm for stresses and 12.60 mm for deflection.

The stresses can be determined as a bi supported beam with engineering mechanics formulas as presented in equation (4.58) and the moment as in equation (4.59).

$$\sigma = \frac{M_d}{W} \tag{4.58}$$

$$M_d = \sigma_d \cdot W \tag{4.59}$$

The section modulus was calculated per meter of plate, therefore, b was adopted equal to 1.0 m, as presented in equation (4.60).

$$W = \frac{b \cdot h^2}{6} = \frac{1 \cdot 0.01414^2}{6} = 3.332327 \cdot 10^{-5}\,m^3 \tag{4.60}$$

The design value of stress was determined in equation (4.23) as 81.15 MPa. The maximum overload that can be applied limiting the stress to this value is calculated in equations (4.61) to (4.65).

$$M_d = 81.15 \cdot 10^3 \cdot .332327 \cdot 10^{-5} = 2.70\,kNm \tag{4.61}$$

$$M_d = 1.35 \cdot M_{gk} + 1.5 \cdot M_{qk} \tag{4.62}$$

$$M_d = 1.35 \cdot \left(\frac{g_{sw} \cdot L^2}{8}\right) + 1.5 \cdot \left(\frac{q \cdot L^2}{8}\right) \tag{4.63}$$

$$2.70 = 1.35 \cdot \left(\frac{0.75 \cdot 1.6^2}{8}\right) + 1.5 \cdot \left(\frac{q \cdot 1.6^2}{8}\right) \tag{4.64}$$

$$q = 4.95\,kN/m^2 \tag{4.65}$$

where,

g_{sw} is the self-weight load;

q is the overload;

M_{gk} is the characteristic bending moment due to dead load;

M_{qk} is the characteristic bending moment due to overload;

M_d is the design bending moment.

The deflection can be determined as a bi supported beam with engineering mechanics formulas as presented in equations (4.66) to (4.69).

$$I = \frac{b \cdot h^3}{12} = \frac{1 \cdot 0.01260^3}{12} = 1.66698 \cdot 10^{-7}\, m^4 \tag{4.66}$$

$$F_d = g_{sw} + 0.4 \cdot q \tag{4.67}$$

$$F_d = 0.75 + 0.4 \cdot 4.95 = 2.73\, kN/m^2 \tag{4.68}$$

$$\delta máx = \frac{5 \cdot p \cdot L^4}{384 \cdot E \cdot I} = \frac{5 \cdot 2.73 \cdot 1.6^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 1.66698 \cdot 10^{-7}} = 19.96\, mm \tag{4.69}$$

The German standard, DIN 18008-1 (2010), suggests a maximum deflection of Span/100 and this limit was adopted on this work. Therefore, limiting the deflection to 16 mm, the maximum overload to be applied on the slab is 3.59 kN/m². Then, the maximum combined load is 2.18 kN/m², as calculated in equation (4.70).

$$F_d = 0.75 + 0.4 \cdot 3.59 = 2.18\, kN/m^2 \tag{4.70}$$

4.2.4 AS 1288 Design Criteria

The AS 1288 requires that the stresses must be checked for the assembly and for each plate isolated.

For the assembly, the glass minimum thickness for a 20 mm nominal thickness laminated glass was determined on heading 4.1.4 and had a value of 19.40 mm. The characteristic tensile strength of glass was determined by equation (4.35) for parts away from the edge of the glass panes and had a value of 42.13 MPa. The ultimate capacity ($\phi \cdot R_u$) is 70.57 MPa, as determined in equation (4.37).

The stresses can be determined as a bi supported beam with engineering mechanics formulas as presented in equation (4.71) and the moment as in equation (4.72).

$$\sigma_d = \frac{M_d}{W} \tag{4.71}$$

$$M_d = \sigma_d \cdot W \tag{4.72}$$

The section modulus was calculated per meter of plate, therefore, b was adopted equal to 1.0 m, as presented in equation (4.73).

$$W = \frac{b \cdot h^2}{6} = \frac{1 \cdot 0.01940^2}{6} = 6.272667 \cdot 10^{-5}\, m^3 \tag{4.73}$$

The maximum overload that can be applied, limiting the stress to this value, is calculated in equations (4.74) to (4.78).

$$M_d = 70.57 \cdot 10^3 \cdot 6.272667 \cdot 10^{-5} = 4.43\, kNm\ (for\ 2\ plates) \tag{4.74}$$

$$M_d = 1.20 \cdot M_{gk} + 1.5 \cdot M_{qk} \tag{4.75}$$

$$M_d = 1.20 \cdot \left(\frac{g_{sw} \cdot L^2}{8}\right) + 1.5 \cdot \left(\frac{q \cdot L^2}{8}\right) \quad (4.76)$$

$$4.43 = 1.20 \cdot \left(\frac{0.75 \cdot 1.6^2}{8}\right) + 1.5 \cdot \left(\frac{q \cdot 1.6^2}{8}\right) \quad (4.77)$$

$$q = 8.63 \text{ kN/m}^2 \quad (4.78)$$

The deflection can be determined as a bi supported beam with engineering formulas as presented in equations (4.79) to (4.82).

$$I = \frac{b \cdot h^3}{12} = \frac{1 \cdot 0.01940^3}{12} = 6.084487 \cdot 10^{-7} \text{ m}^4 \quad (4.79)$$

$$F_d = g_{sw} + 0.6 \cdot q \quad (4.80)$$

$$F_d = 0.75 + 0.6 \cdot 8.63 = 5.92 \text{ kN/m}^2 \quad (4.81)$$

$$\delta\text{máx} = \frac{5 \cdot p \cdot L^4}{384 \cdot E \cdot I} = \frac{5 \cdot 5.92 \cdot 1.6^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 6.084487 \cdot 10^{-7}} = 11.86 \text{ mm} \quad (4.82)$$

As mentioned in Section 3.3, the AS 1288 (2006) deflection is limited to Span/60, which would be 26.67mm. Therefore, the deflection of 11.86 mm would be within the limit. To compare with the other standards presented on this work, it was also checked for the DIN 18008-1 (2010) limit of Span/100, which would be 16 mm. In this case the deflection of 11.86 mm is also within the limit.

In accordance to AS 1288 (2006) for medium and long load durations, it is necessary to determine the percentage of the load that is resisted by each ply of the glass. For two plates of equal thickness, each one is responsible for 50% of the load.

The minimum thickness for an isolated plate is 9.7mm, which is the respective thickness for one plate of 10 mm nominal thickness. The characteristic tensile strength of glass was determined for the new thickness by equation (4.41) as 48.96 MPa for parts away from the edge of the glass panes and the ultimate capacity ($\phi \cdot R_u$) was determined in equation (4.43) as 82.00 MPa.

The section modulus was calculated per meter of plate, therefore, b was adopted equal to 1.0 m, as presented in equation (4.83).

$$W = \frac{b \cdot h^2}{6} = \frac{1 \cdot 0.00970^2}{6} = 1.568167 \cdot 10^{-5} \text{ m}^3 \quad (4.83)$$

The maximum overload that can be applied limiting the stress to this value is calculated in equations (4.84) to (4.89).

$$M_d = 82 \cdot 10^3 \cdot 1.568167 \cdot 10^{-5} = 1.285 \text{ kNm } (\textit{per plate}) \quad (4.84)$$

$$M_d = 1.20 \cdot M_{gk} + 1.5 \cdot M_{qk} \quad (4.85)$$

$$M_d = 1.20 \cdot \left(\frac{g_{sw} \cdot L^2}{8}\right) + 1.5 \cdot \left(\frac{q \cdot L^2}{8}\right) \tag{4.86}$$

$$1.285 = 1.20 \cdot \left(\frac{0.375 \cdot 1.6^2}{8}\right) + 1.5 \cdot \left(\frac{q \cdot 1.6^2}{8}\right) \tag{4.87}$$

$$q = 2.38 \text{ kN/m}^2 \text{ (per plate)} \tag{4.88}$$

$$q = 2 \cdot 2.38 = 4.76 \text{ kN/m}^2 \text{ (for 2 plates)} \tag{4.89}$$

The deflection can be determined as a bi supported beam with engineering formulas as presented in equations (4.90) to (4.93).

$$I = \frac{b \cdot h^3}{12} = \frac{1 \cdot 0.00970^3}{12} = 7.605608 \cdot 10^{-8} \text{ m}^4 \tag{4.90}$$

$$F_d = g_{sw} + 0.6 \cdot q \tag{4.91}$$

$$F_d = 0.375 + 0.6 \cdot 2.38 = 1.80 \text{ kN/m}^2 \tag{4.92}$$

$$\delta máx = \frac{5 \cdot p \cdot L^4}{384 \cdot E \cdot I} = \frac{5 \cdot 1.80 \cdot 1.6^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 7.605608 \cdot 10^{-8}} = 28.85 \text{ mm} \tag{4.93}$$

As mentioned on heading 3.3, the AS 1288 (2006) deflection is limited to Span/60, which would be 26.67mm, therefore the deflection of 28.85 mm is over the limit. To compare with the other standards presented on this work, it was checked also for the DIN 18008-1 (2010) limit of Span/100, which would be 16 mm. In this case the deflection of 28.85 mm is also over the limit.

Therefore, limiting the deflection to 16 mm, the maximum overload to be applied on the slab is 1.04 kN/m² per plate as presented on equation (4.95) and 2.08 kN/m² for two plates, as presented on equation (4.96). Then, the maximum combined load is 1.00 kN/m², as calculated in equation (4.94).

$$F_d = 0.375 + 0.6 \cdot 1.04 = 1.00 \text{ kN/m}^2 \ (per\ plate) \tag{4.94}$$

$$q = 1.04 \text{ kN/m}^2 \text{ (per plate)} \tag{4.95}$$

$$q = 2.08 \text{ kN/m}^2 \text{ (for 2 plates)} \tag{4.96}$$

5 LABORATORY TESTS

The laboratory tests consisted of testing five prototypes of laminated tempered glass with three layers of glass. Three of them were tested as slabs with perpendicular loads and the other two were tested as beams with in-plane loads.

The main goal of the tests was to analyze the behavior of slabs and beams when submitted to bending stresses. The machine controls the load V applied on the center of a steel beam, which weight is 0.15 kN and is centered with the glass slab or beam. It transfers the load P on two points equally distant from the center, as presented in equation (5.1) generating a constant and pure bending stress.

$$P = \frac{V + 0.15}{2} \tag{5.1}$$

In order to determine the loads to be applied on the laboratory tests, the rupture expected loads were calculated by ASTM, prEN and AS standards.

5.1 SLABS

The slabs laboratory tests consisted of testing three prototypes of tempered laminated glass beams with three layers.

The three prototypes that were tested as slabs have the following dimensions: 1600 mm of length, the thickness of 10mm for each layer of glass plus the thickness of 1.52 mm of PVB between each glass plate and 200 mm of width. Those glasses were tested with perpendicular loads, as shown in Figure 5.1 and Figure 5.2.

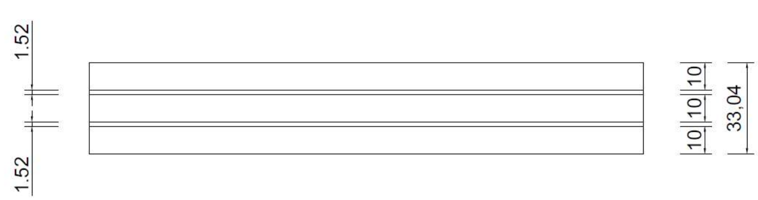


Figure 5.1 – Slab cross section (millimeters).
Source: Author (2019).

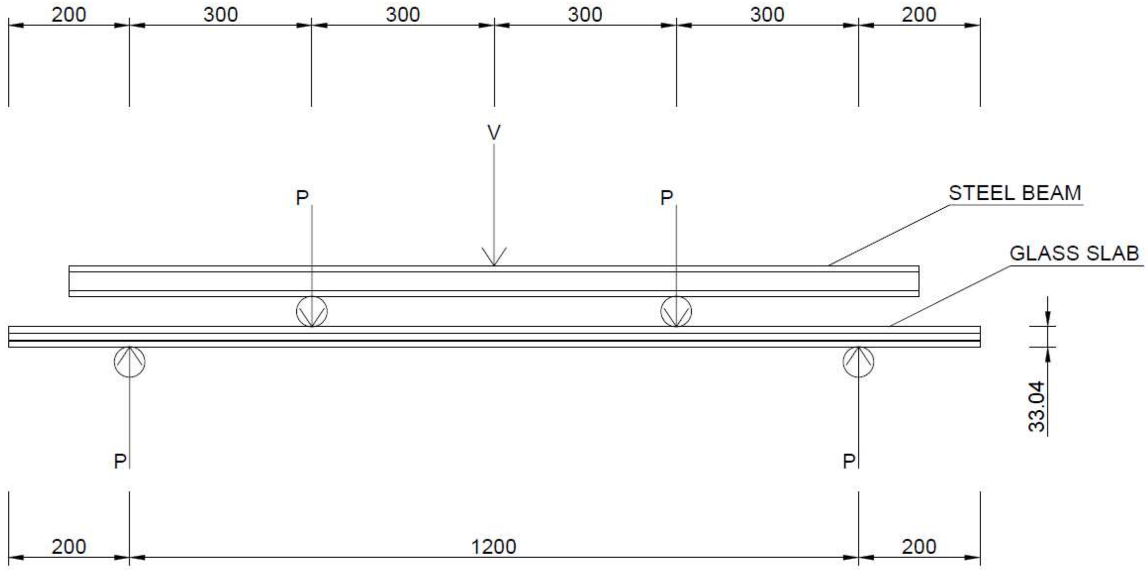


Figure 5.2 – Slab tests set up (millimeters).
Source: Author (2019).

5.1.1 Rupture load according to ASTM guidelines

The effective thickness for deflection was calculated for tri-laminated glass with 10 mm thick plates with 1.52 mm of PVB interlayer between each plate. The shear transfer factor (ɼ) was adopted as null for comparison with prEN 16612 (2013).

The properties from equations (5.2) to (5.4) were calculated for the determination of the effective thickness.

$$h_s = \frac{10}{2} + 1.52 + 10 + 1.52 + \frac{10}{2} = 23.04\ \text{mm} \tag{5.2}$$

$$I_S = \sum h_i \cdot {h_{s;i}}^2 \tag{5.3}$$

$$I_S = 10 \cdot 11.52^2 + 10 \cdot 0 + 10 \cdot 11.52^2 = 2654.208\ \text{mm}^3 \tag{5.4}$$

The effective deflection thickness ($h_{ef;w}$) was calculated as in equations (5.5) and (5.6).

$$h_{ef;w} = \sqrt[3]{{h_1}^3 + {h_2}^3 + 12ɼ \cdot I_s} \tag{5.5}$$

$$h_{ef;w} = \sqrt[3]{10^3 + 10^3 + 10^3 + 12 \cdot 0 \cdot 2654.208} = 14.42\ \text{mm} \tag{5.6}$$

The effective stress thicknesses ($h_{i;ef;\sigma}$) for each plate were calculated as in equations (5.7) to (5.8).

$$h_{1;ef;\sigma} = \sqrt{\frac{{h_{ef;w}}^3}{h_1 + 2 \cdot ɼ \cdot h_{s;2}}} \tag{5.7}$$

$$h_{1;ef;\sigma} = \sqrt{\frac{14.42^3}{10 + 2 \cdot 0 \cdot 11.52}} = 17.32 \text{ mm} \tag{5.8}$$

The self-weight and the moment due to the self-weight, were calculated according to equations (5.9) and (5.10).

$$g_{sw} = 0.03 \cdot 0.20 \cdot 25 = 0.15 \text{ kN/m} \tag{5.9}$$

$$M_{sw} = \frac{g_{sw} \cdot L^2}{8} - \frac{g_{canti} \cdot L_{canti}{}^2}{2} = \frac{0.15 \cdot 1.20^2}{8} - \frac{0.15 \cdot 0.20^2}{2} = 0.024 \text{ kNm} \tag{5.10}$$

The section modulus was calculated with the stress effective thickness, as presented in equation (5.11).

$$W = \frac{b \cdot h^2}{6} = \frac{0.20 \cdot 0.01732^2}{6} = 10^{-5} \text{ m}^3 \tag{5.11}$$

The inertia was calculated with the deflection effective thickness, as in equation (5.12).

$$I = \frac{b \cdot h^3}{12} = \frac{0.20 \cdot 0.01442^3}{12} = 4.997 \cdot 10^{-8} \text{ m}^4 \tag{5.12}$$

ASTM E2751 (2017) describes the allowable stresses according to Table 3.4. For tempered glass and 3 seconds of load duration it is 73 MPa and for 10 minutes load duration, 65.3 MPa.

For 3 seconds of load duration, the total moment for the allowable stress of 73 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.13) to (5.16).

$$M = 73 \cdot 10^3 \cdot 10^{-5} = 0.730 \text{ kNm} \tag{5.13}$$

$$M = M_{live\ load} + M_{sw} \tag{5.14}$$

$$M_{live\ load} = M - M_{sw} \tag{5.15}$$

$$M_{live\ load} = 0.703 - 0.024 = 0.706 \text{ kNm} \tag{5.16}$$

Therefore, according to calculations in equations (5.17) to (5.20), the maximum load to be applied is 4.55kN.

$$M_{live\ load} = P \cdot a \tag{5.17}$$

$$0.706 = P \cdot 0.3 \tag{5.18}$$

$$P = 2.35 \text{ kN} \tag{5.19}$$

$$V = 2 \cdot 2.35 - 0.15 = 4.55 \text{ kN} \tag{5.20}$$

The immediate deflection due to the maximum applied load and the self-weight is 34.42 mm, as calculated in equations (5.21) to (5.23).

$$\delta = \frac{5 \cdot g_{sw} \cdot L^4}{384 \cdot E \cdot I} + \frac{P \cdot a}{24 \cdot E \cdot I} \cdot (3 \cdot L^2 - 4 \cdot a^2) \tag{5.21}$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.20^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 4.997 \cdot 10^{-8}} + \frac{2.35 \cdot 0.30 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 4.997 \cdot 10^{-8}} (3 \cdot 1.2^2 - 4 \cdot 0.3^2) \tag{5.22}$$

$$\delta = 1.16 + 33.26 = 34.42 \text{ mm} \tag{5.23}$$

For 10 minutes of load duration, the total moment for the allowable stress of 65.3 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.24) to (5.27).

$$M = 65.3 \cdot 10^3 \cdot 10^{-5} = 0.653 \text{ kNm} \tag{5.24}$$

$$M = M_{\text{live load}} + M_{sw} \tag{5.25}$$

$$M_{\text{live load}} = M - M_{sw} \tag{5.26}$$

$$M_{\text{live load}} = 0.653 - 0.024 = 0.629 \text{ kNm} \tag{5.27}$$

Therefore, according to calculations in equations (5.28) to (5.31), the maximum load to be applied is 4.05kN.

$$M_{\text{live load}} = P \cdot a \tag{5.28}$$

$$0.629 = P \cdot 0.3 \tag{5.29}$$

$$P = 2.10 \text{ kN} \tag{5.30}$$

$$V = 2 \cdot 2.10 - 0.15 = 4.05 \text{ kN} \tag{5.31}$$

The immediate deflection due to the maximum applied load and the self-weight is 30.872 mm, as calculated in equations (5.32) to (5.34).

$$\delta = \frac{5 \cdot g_{sw} \cdot L^4}{384 \cdot E \cdot I} + \frac{P \cdot a}{24 \cdot E \cdot I} \cdot (3 \cdot L^2 - 4 \cdot a^2) \tag{5.32}$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.20^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 4.997 \cdot 10^{-8}} + \frac{2.10 \cdot 0.30 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 4.997 \cdot 10^{-8}} (3 \cdot 1.2^2 - 4 \cdot 0.3^2) \tag{5.33}$$

$$\delta = 1.16 + 29.712 = 30.872 \text{ mm} \tag{5.34}$$

5.1.2 Rupture load according to prEN guideline

The effective thickness for deflection was calculated for tri-laminated glass with 10 mm thick plates with 1.52 mm of PVB interlayer between each plate, as presented in equations (5.35) to (5.39). The shear transfer factor (ω) was adopted as zero according to Table 3.6, for "Family 0".

$$h_{m,1=3} = \frac{10}{2} + 1.52 + \frac{10}{2} = 11.52 \text{ mm} \tag{5.35}$$

$$h_{m,2} = 0 \tag{5.36}$$

$$h_{ef;w} = \sqrt[3]{\Sigma\, h_k^{\,3} + 12 \cdot \omega \cdot (\Sigma h_k \cdot h_{m,k}^{\,2})} \tag{5.37}$$

$$h_{ef;w} = \sqrt[3]{10^3 + 10^3 + 10^3 + 12 \cdot 0 \cdot (10 \cdot 11.52^2 + 10 \cdot 11.52^2 + 10 \cdot 11.52^2)} \tag{5.38}$$

$$h_{ef;w} = 14.42\ \mathrm{mm} \tag{5.39}$$

The effective stress thicknesses were calculated for each plate as in equations (5.40) to (5.42) for the worst case of $h_{m,k}$, which are $h_{m,k,1}$ and $h_{m,k,3}$.

$$h_{ef;\sigma;j} = \sqrt{\frac{h_{ef;w}^{\,3}}{h_j + 2 \cdot \omega \cdot h_{m;j}}} \tag{5.40}$$

$$h_{ef;\sigma;j} = \sqrt{\frac{14.42^3}{10 + 2 \cdot 0 \cdot 11.52}} \tag{5.41}$$

$$h_{ef;\sigma;j} = 17.32\ \mathrm{mm} \tag{5.42}$$

For prEN16612 (2013), the tensile strengths shall be calculated as follows.

The coefficient k_{mod} was calculated according to equations (5.43) to (5.45) for 3 second and 10 minutes load duration.

$$k_{mod} = 0.663 \cdot t^{-\frac{1}{16}} \quad \text{where } 0.25 < k_{mod} < 1.0 \tag{5.43}$$

$$k_{mod} = 0.663 \cdot \frac{3}{3600}^{-\frac{1}{16}} = 1.0 \tag{5.44}$$

$$k_{mod} = 0.663 \cdot \frac{10^{-\frac{1}{16}}}{60} = 0.74 \tag{5.45}$$

O k_{sp} was adopted as 1.0 for float glass as produced (without treatments), as shown in Table 3.9.

O k_v foi was adopted as 1.0 for horizontally produced tempered glass, as shown in Table 3.11.

The value of $f_{g;k}$ was adopted as 45 MPa as indicated by standard and the value of $f_{b;k}$ was adopted as 120 MPa for tempered float glass, as shown in Table 3.12.

Therefore, the design value of stress for 3 seconds of load duration should be 90.625 MPa, as presented in equation (5.46).

$$f_{g;d} = \frac{1 \cdot 1 \cdot 45}{1.6} + \frac{1 \cdot (120 - 45)}{1.2} = 28.125 + 62.5 = 90.625\ \mathrm{MPa} \tag{5.46}$$

For the test, as it is desired to determine the maximum load, the resistance reduction coefficients will not be considered. Therefore, the characteristic value of stress is 120 MPa, as presented in equation (5.47).

$$f_{g;d} = 1 \cdot 1 \cdot 45 + 1 \cdot (120 - 45) = 45 + 75 = 120 \text{ MPa} \tag{5.47}$$

Therefore, the design value of stress for 10 minutes of load duration should be 83.312 MPa, as presented in equation (5.48).

$$f_{g;d} = \frac{0.74 \cdot 1 \cdot 45}{1.6} + \frac{1 \cdot (120 - 45)}{1.2} = 20.812 + 62.5 = 83.312 \text{ MPa} \tag{5.48}$$

For the test, as it is desired to determine the maximum load, the resistance reduction coefficients will not be considered. Therefore, the characteristic value of stress is 108.30 MPa, as presented in equation (5.49).

$$f_{g;d} = 0.74 \cdot 1 \cdot 45 + 1 \cdot (120 - 45) = 33.30 + 75 = 108.30 \text{ MPa} \tag{5.49}$$

The self-weight and the moment due to the self-weight, were calculated according to equations (5.50) to (5.51).

$$g_{sw} = 0.03 \cdot 0.20 \cdot 25 = 0.15 \text{ kN/m} \tag{5.50}$$

$$M_{sw} = \frac{g_{sw} \cdot L^2}{8} - \frac{g_{canti} \cdot {L_{canti}}^2}{2} = \frac{0.15 \cdot 1.20^2}{8} - \frac{0.15 \cdot 0.20^2}{2} = 0.024 \text{ kNm} \tag{5.51}$$

The section modulus was calculated with the stress effective thickness, as presented in equation (5.52).

$$W = \frac{b \cdot h^2}{6} = \frac{0.20 \cdot 0.01732^2}{6} = 10^{-5} \text{ m}^3 \tag{5.52}$$

The inertia was calculated with the deflection effective thickness, as in equation (5.53).

$$I = \frac{b \cdot h^3}{12} = \frac{0.20 \cdot 0.01442^3}{12} = 4.997 \cdot 10^{-8} \text{ m}^4 \tag{5.53}$$

For 3 seconds of load duration, the total moment for the allowable stress of 120 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.54) to (5.57).

$$M = 120 \cdot 10^3 \cdot 10^{-5} = 1.20 \text{ kNm} \tag{5.54}$$

$$M = M_{\text{live load}} + M_{sw} \tag{5.55}$$

$$M_{\text{live load}} = M - M_{sw} \tag{5.56}$$

$$M_{\text{live load}} = 1.20 - 0.024 = 1.176 \text{ kNm} \tag{5.57}$$

Therefore, according to calculations in equations (5.58) to (5.61), the maximum load to be applied is 7.69kN.

$$M_{\text{live load}} = P \cdot a \tag{5.58}$$

$$1.176 = \mathrm{P} \cdot 0.3 \tag{5.59}$$

$$\mathrm{P} = 3.92\ \mathrm{kN} \tag{5.60}$$

$$\mathrm{V} = 2 \cdot 3.92 - 0.15 = 7.69\ \mathrm{kN} \tag{5.61}$$

The immediate deflection due to the maximum applied load and the self-weight is 56.631mm, as calculated in equations (5.62) to (5.64).

$$\delta = \frac{5 \cdot \mathrm{g_{sw}} \cdot \mathrm{L}^4}{384 \cdot \mathrm{E} \cdot \mathrm{I}} + \frac{\mathrm{P} \cdot \mathrm{a}}{24 \cdot \mathrm{E} \cdot \mathrm{I}} \cdot (3 \cdot \mathrm{L}^2 - 4 \cdot \mathrm{a}^2) \tag{5.62}$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.20^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 4.997 \cdot 10^{-8}} + \frac{3.92 \cdot 0.30 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 4.997 \cdot 10^{-8}} (3 \cdot 1.2^2 - 4 \cdot 0.3^2) \tag{5.63}$$

$$\delta = 1.158 + 55.473 = 56.631\ \mathrm{mm} \tag{5.64}$$

For 10 minutes of load duration, the total moment for the characteristic value of stress of 108.30 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.65) to (5.68).

$$\mathrm{M} = 108.30 \cdot 10^3 \cdot 10^{-5} = 1.083\ \mathrm{kNm} \tag{5.65}$$

$$\mathrm{M} = \mathrm{M_{live\ load}} + \mathrm{M_{sw}} \tag{5.66}$$

$$\mathrm{M_{live\ load}} = \mathrm{M} - \mathrm{M_{sw}} \tag{5.67}$$

$$\mathrm{M_{live\ load}} = 1.083 - 0.024 = 1.059\ \mathrm{kNm} \tag{5.68}$$

Therefore, according to calculations in equations (5.69) to(5.72), the maximum load to be applied is 6.91kN.

$$\mathrm{M_{live\ load}} = \mathrm{P} \cdot \mathrm{a} \tag{5.69}$$

$$1.059 = \mathrm{P} \cdot 0.3 \tag{5.70}$$

$$\mathrm{P} = 3.53\ \mathrm{kN} \tag{5.71}$$

$$\mathrm{V} = 2 \cdot 3.53 - 0.15 = 6.91\ \mathrm{kN} \tag{5.72}$$

The immediate deflection due to the maximum applied load and the self-weight is 51.112 mm, as calculated in equations (5.73) to (5.75).

$$\delta = \frac{5 \cdot \mathrm{g_{sw}} \cdot \mathrm{L}^4}{384 \cdot \mathrm{E} \cdot \mathrm{I}} + \frac{\mathrm{P} \cdot \mathrm{a}}{24 \cdot \mathrm{E} \cdot \mathrm{I}} \cdot (3 \cdot \mathrm{L}^2 - 4 \cdot \mathrm{a}^2) \tag{5.73}$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.20^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 4.997 \cdot 10^{-8}} + \frac{3.53 \cdot 0.30 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 4.997 \cdot 10^{-8}} (3 \cdot 1.2^2 - 4 \cdot 0.3^2) \tag{5.74}$$

$$\delta = 1.158 + 49.954 = 51.112\ \mathrm{mm} \tag{5.75}$$

5.1.3 Rupture load according to AS guideline

The minimum thickness should be calculated for tri-laminated glass with 10 mm thick plates with 1.52 mm of PVB interlayer between each plate. The interlayer thickness is disregarded at the composition of the minimum thickness on AS 1288 (2006). The nominal thickness is presented in equation (5.76).

$$t_{nominal} = 10 + 10 + 10 = 30 \text{ mm} \tag{5.76}$$

The maximum nominal thickness available in Table 3.13 is 24 mm. Therefore, it is necessary to do a full non-linear analysis to study the behavior of the set by modeling the glass and interlayer sheets.

A correspondent minimum thickness was calculated summing the minimum thickness of each isolated plate, as shown in equation (5.77).

$$t_{minimum} = 9.7 + 9.7 + 9.7 = 29.1 \text{ mm} \tag{5.77}$$

The self-weight and the moment due to the self-weight, were calculated according to equations (5.78) to (5.79)

$$g_{sw} = 0.03 \cdot 0.20 \cdot 25 = 0.15 \text{ kN/m} \tag{5.78}$$

$$M_{sw} = \frac{g_{sw} \cdot L^2}{8} - \frac{g_{canti} \cdot L_{canti}{}^2}{2} = \frac{0.15 \cdot 1.20^2}{8} - \frac{0.15 \cdot 0.20^2}{2} = 0.024 \text{ kNm} \tag{5.79}$$

The section modulus was calculated with the stress effective thickness, as presented in equation (5.80).

$$W = \frac{b \cdot h^2}{6} = \frac{0.20 \cdot 0.02910^2}{6} = 2.823 \cdot 10^{-5} \text{ m}^3 \tag{5.80}$$

The inertia was calculated with the deflection effective thickness, as in equation (5.81).

$$I = \frac{b \cdot h^3}{12} = \frac{0.20 \cdot 0.02910^3}{12} = 4.107 \cdot 10^{-7} \text{ m}^4 \tag{5.81}$$

The characteristic tensile strength of glass determined by equations (5.82) and (5.83) for parts away from the edge of glass panes and the ultimate capacity was calculated as shown in equations (5.84) and (5.85), disregarding the capacity reduction factor (Ø).

$$f'_t = -9.85 \cdot ln\, t + 71.34 \tag{5.82}$$

$$f'_t = -9.85 \cdot ln\,(29.1) + 71.34 = 38.13 \text{ MPa} \tag{5.83}$$

$$\emptyset \cdot R_u = \emptyset \cdot c_1 \cdot c_2 \cdot c_3 \cdot [f'_t \cdot X] \tag{5.84}$$

$$R_u = 2.5 \cdot 1.0 \cdot 1.0 \cdot [38.13] = 95.34\, MPa \tag{5.85}$$

For 3 seconds of load duration, the total moment for the allowable stress of 95.34 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.86) to (5.89).

$$M = 95.34 \cdot 10^3 \cdot 2.823 \cdot 10^{-5} = 2.69 \text{ kNm} \tag{5.86}$$

$$M = M_{\text{live load}} + M_{\text{sw}} \tag{5.87}$$

$$M_{\text{live load}} = M - M_{\text{sw}} \tag{5.88}$$

$$M_{\text{live load}} = 2.69 - 0.024 = 2.666 \text{ kNm} \tag{5.89}$$

Therefore, according to calculations in equations (5.90) to (5.93), the maximum load to be applied is 17.62kN.

$$M_{\text{live load}} = P \cdot a \tag{5.90}$$

$$2.666 = P \cdot 0.3 \tag{5.91}$$

$$P = 8.89 \text{ kN} \tag{5.92}$$

$$V = 2 \cdot 8.89 - 0.15 = 17.62 \text{ kN} \tag{5.93}$$

The immediate deflection due to the maximum applied load and the self-weight is 6.885 mm, as calculated in equations (5.94) to (5.96).

$$\delta = \frac{5 \cdot g_{sw} \cdot L^4}{384 \cdot E \cdot I} + \frac{P \cdot a}{24 \cdot E \cdot I} \cdot (3 \cdot L^2 - 4 \cdot a^2) \tag{5.94}$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.20^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 4.107 \cdot 10^{-7}} + \frac{8.89 \cdot 0.30 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 4.107 \cdot 10^{-7}} (3 \cdot 1.2^2 - 4 \cdot 0.3^2) \tag{5.95}$$

$$\delta = 0.141 + 15.31 = 15.45 \text{ mm} \tag{5.96}$$

For medium and long load durations, it is necessary to determine the percentage of the load that is resisted by each ply of the glass. For 10 minutes of load duration, it would be considered as a medium-term load duration and therefore, the minimum thickness used on the design was 9.7mm, which is the respective thickness for one plate of 10 mm nominal thickness.

The characteristic tensile strength of glass determined by equations (5.97) and (5.98) for parts away from the edge of glass panes and the ultimate capacity was calculated as shown in equation (5.99) and (5.100), disregarding the capacity reduction factor (Ø).

$$f'_t = -9.85 \cdot ln\, t + 71.34 \tag{5.97}$$

$$f'_t = -9.85 \cdot ln\,(9.7) + 71.34 = 48.96 \text{ MPa} \tag{5.98}$$

$$\emptyset \cdot R_u = \emptyset \cdot c_1 \cdot c_2 \cdot c_3 \cdot [f'_t \cdot X] \tag{5.99}$$

$$R_u = 2.5 \cdot 1.0 \cdot 1.0 \cdot [48.96] = 122.40\, MPa \tag{5.100}$$

The section modulus was calculated with the stress effective thickness, as presented in equation (5.101).

$$W = \frac{b \cdot h^2}{6} = \frac{0.20 \cdot 0.00970^2}{6} = 3.140 \cdot 10^{-6}\ m^3 \tag{5.101}$$

The inertia was calculated with the deflection effective thickness, as in equation (5.102).

$$I = \frac{b \cdot h^3}{12} = \frac{0.20 \cdot 0.00970^3}{12} = 1.520 \cdot 10^{-8}\ m^4 \tag{5.102}$$

The total moment for the characteristic value of stress of 122.40 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.103) to (5.106).

$$M = 122.40 \cdot 10^3 \cdot 3.140 \cdot 10^{-6} = 0.384\ \text{kNm (for one plate)} \tag{5.103}$$

$$M = M_{\text{live load}} + M_{sw} \tag{5.104}$$

$$M_{\text{live load}} = M - M_{sw} \tag{5.105}$$

$$M_{\text{live load}} = 0.384 - 0.008 = 0.376\ \text{kNm (for one plate)} \tag{5.106}$$

Therefore, according to calculations in equations (5.107) to (5.111), the maximum load to be applied is 7.37kN.

$$M_{\text{live load}} = P \cdot a \tag{5.107}$$

$$0.376 = P \cdot 0.3 \tag{5.108}$$

$$P = 1.253\ \text{kN (for one plate)} \tag{5.109}$$

$$P = 3 \cdot 1.253 = 3.759\ \text{kN (for three plates)} \tag{5.110}$$

$$V = 2 \cdot 3.759 - 0.15 = 7.37\ \text{kN (for three plates)} \tag{5.111}$$

The immediate deflection due to the maximum applied load and the self-weight is 59.553 mm, as calculated in equations (5.112) to (5.114).

$$\delta = \frac{5 \cdot g_{sw} \cdot L^4}{384 \cdot E \cdot I} + \frac{P \cdot a}{24 \cdot E \cdot I} \cdot (3 \cdot L^2 - 4 \cdot a^2) \tag{5.112}$$

$$\delta = \frac{5 \cdot 0.05 \cdot 1.20^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 1.520 \cdot 10^{-8}} + \frac{1.253 \cdot 0.30 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 1.520 \cdot 10^{-8}} (3 \cdot 1.2^2 - 4 \cdot 0.3^2) \tag{5.113}$$

$$\delta = 1.260 + 58.293 = 59.553\ mm \tag{5.114}$$

5.1.4 Calculation Summary Results

The expected loads capacities calculated from ASTM, European and Australian guidelines were summarized in Table 5.1 for 3 seconds of load duration and Table 5.2 for 10 minutes of load duration.

Table 5.1 –Expected load capacity for 3 seconds load duration.

	Self Weight	P	V	Stress	Deflection
	[kN/m]	[kN]	[kN]	[MPa]	[mm]
ASTM Analytical Procedure	0.15	2.35	4.55	73.00	34.42
prEN Simplified Method	0.15	3.92	7.69	120.00	56.63
AS Design Criteria	0.15	8.89	17.62	95.34	15.45

Source: Author (2019).

Table 5.2 –Expected load capacity for 10 minutes load duration.

	Self Weight	P	V	Stress	Deflection
	[kN/m]	[kN]	[kN]	[MPa]	[mm]
ASTM Analytical Procedure	0.15	2.10	4.05	65.30	30.87
prEN Simplified Method	0.15	3.53	6.91	108.30	51.11
AS Design Criteria	0.15	3.76	7.37	122.40	59.55

Source: Author (2019).

5.1.5 Laboratory Test Results

The laboratory tests were performed at LAEDE (Laboratory of acoustics and dynamic and statistical tests) on May 11th of 2019. The testing machine for flexural and compressive strength used is presented in Figure 5.3. The temperature at the day of the testing was 24º C.

Figure 5.3 – Testing Machine.
Source: Author (2019).

The tests on slabs were performed with the setup of as shown in Figure 5.2.

The first prototype was tested with a medium speed of 7 N/s. The load was applied until reach 5 kN and held for 10 minutes. As no rupture occurred, the load was again applied at the same speed until the rupture of the slab, which occurred at 28 kN. The deflection measured was 17.89 mm.

The rupture load was much greater than expected. It took approximately 4700 seconds to the rupture (78 minutes) in which 10 minutes the load was remained constant to verify the creep effect.

The rupture took all the plates to break and there was the detachment between the first and second plates of glass. The third layer turned to dust, remaining glued to the PVB only on the supports, as can be seen in Figure 5.4.

Figure 5.4 – First Slab Prototype Rupture.
Source: Author (2019).

The Load x Time, the Deflection x Time and the Load x Deflection graphics were generated from the data provided by the testing and are presented in Figure 5.5, Figure 5.6 and Figure 5.7.

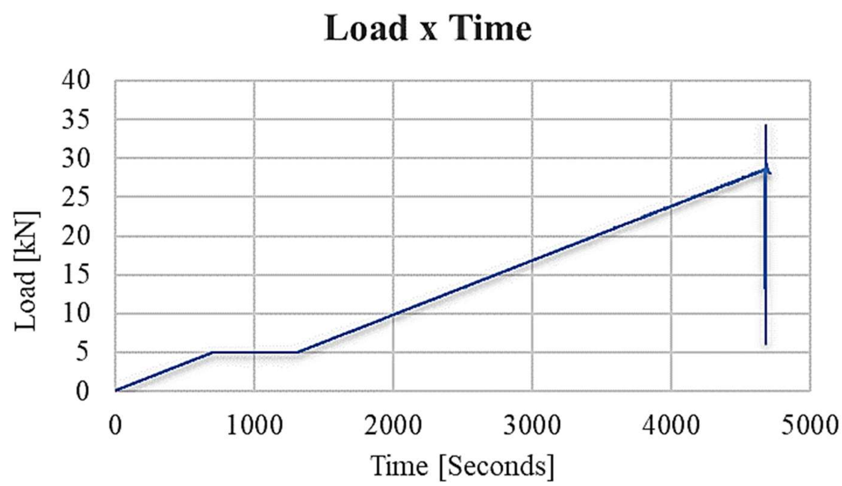


Figure 5.5 – Load x Time Graphic from First Slab Prototype Rupture.
Source: Author (2019).

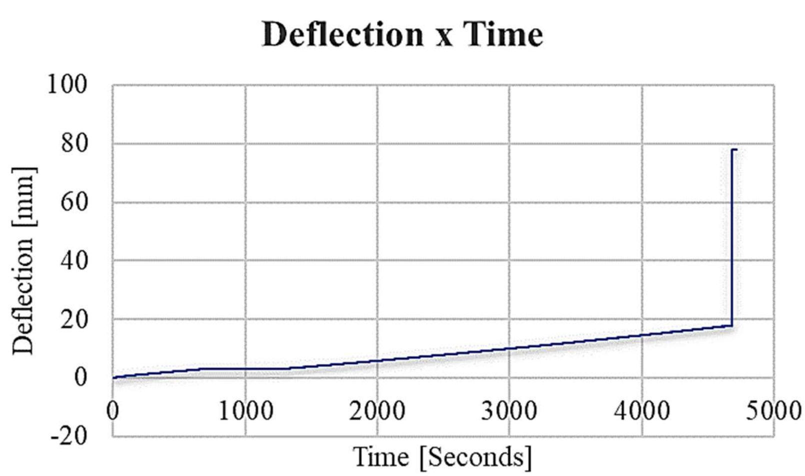


Figure 5.6 – Deflection x Time Graphic from First Slab Prototype Rupture.
Source: Author (2019).

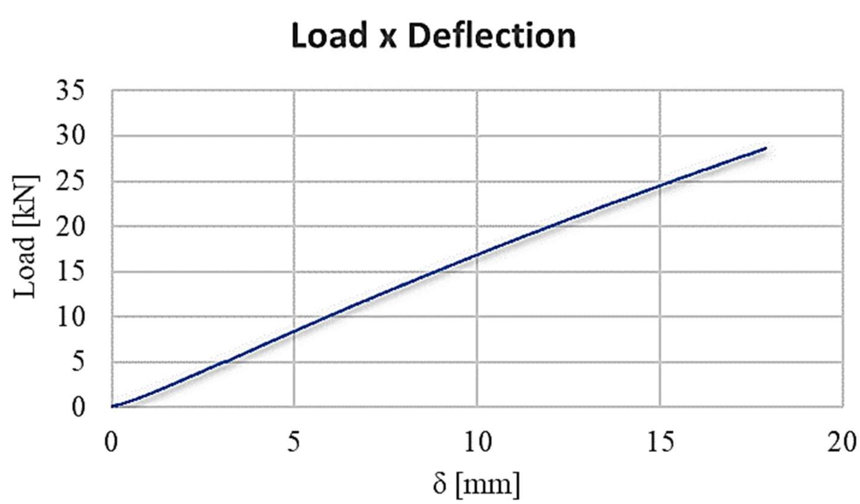


Figure 5.7 – Load x Deflection Graphic from First Slab Prototype Rupture.
Source: Author (2019).

As the load resisted by the first slab was much larger than expected, for the second slab a new load application speed was calculated from the 28 kN resisted by the first one for 10 minutes of load application, as shown in equation (5.115).

$$\mathrm{v} = 28000/(10 \cdot 60) = 47.7\ \mathrm{N/s} \tag{5.115}$$

The second prototype rupture occurred at 34 kN and measured deflection was 20.44 mm, as presented in Figure 5.8.

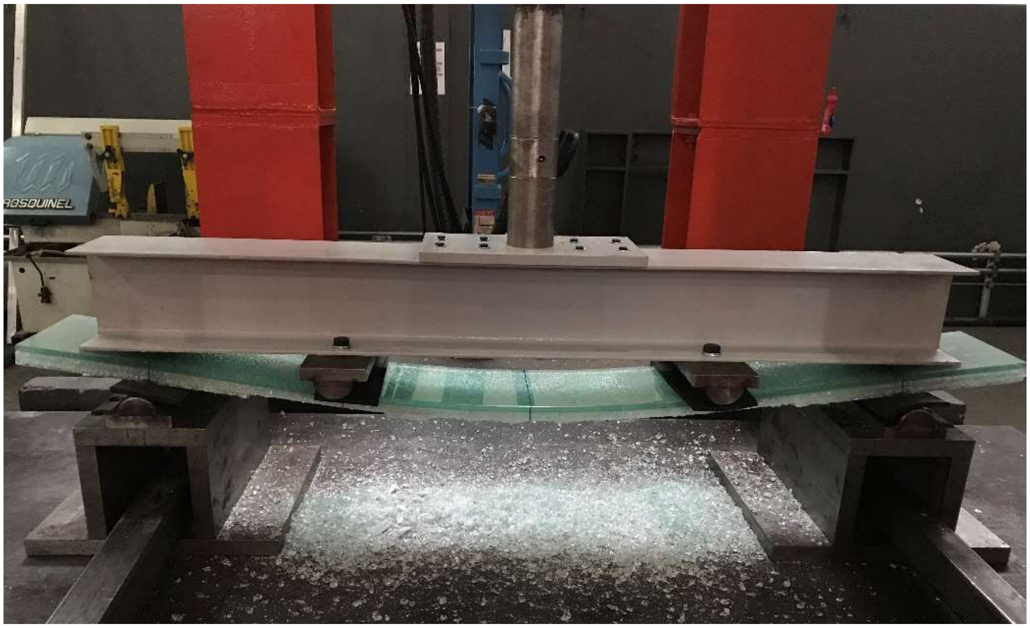


Figure 5.8 – Second Slab Prototype Rupture.
Source: Author (2019).

The Load x Time, the Deflection x Time and the Load x Deflection graphics were generated from the data provided by the testing and are presented in Figure 5.9, Figure 5.10 and Figure 5.11.

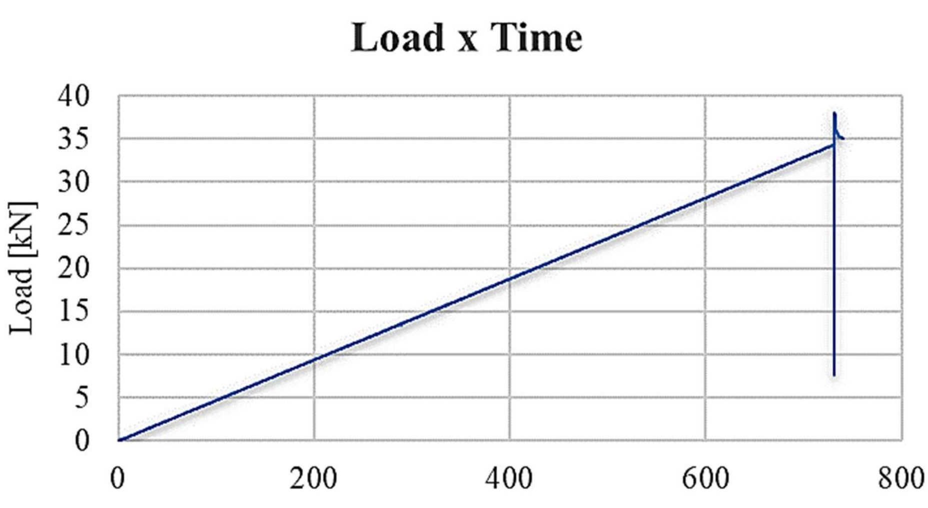


Figure 5.9 – Load x Time Graphic from Second Slab Prototype Rupture.
Source: Author (2019).

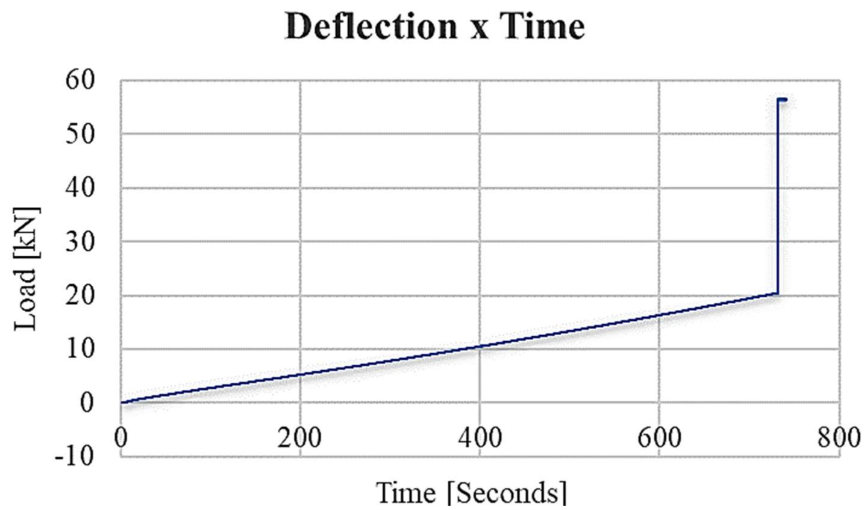


Figure 5.10 – Deflection x Time Graphic from Second Slab Prototype Rupture.
Source: Author (2019).

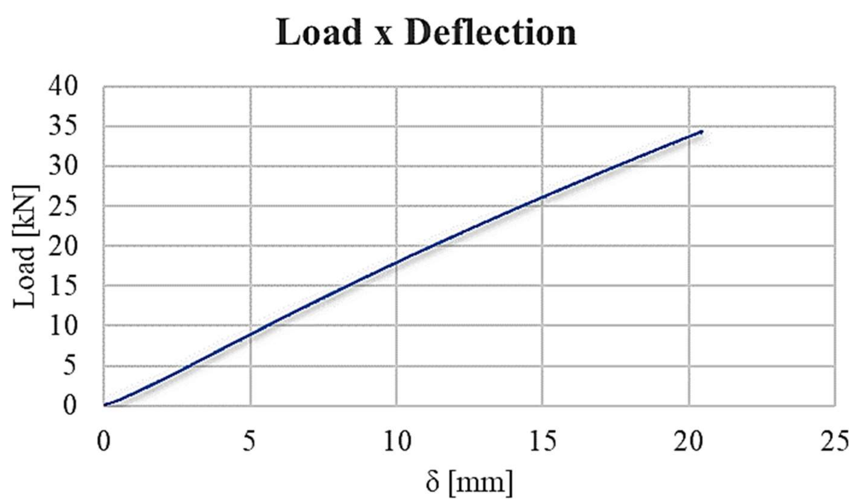


Figure 5.11 – Load x Deflection Graphic from Second Slab Prototype Rupture.
Source: Author (2019).

The third slab was tested exactly as the second and its rupture occurred at 32 kN. The measured deflection was 18.65 mm, as presented in Figure 5.12.

Figure 5.12 – Third Slab Prototype Rupture.
Source: Author (2019).

The last two slabs had equivalent ruptures. The first plate remained intact and the following plates broke, as presented in Figure 5.8 and Figure 5.12. When removed the applied load, the slab returned to its normal position, showing the elastic behavior of the material, as shown in Figure 5.13.

All the slabs had the third plate turned in to dust in the middle of the span remaining glued to the PVB only on the supports. It occurs because it is the plate that is subjected to higher tensile stresses.

Figure 5.13 – Third slab prototype after rupture and load removal.
Source: Author (2019).

The Load x Time, the Deflection x Time and the Load x Deflection graphics were generated from the data provided by the testing and are presented in Figure 5.14, Figure 5.15 and Figure 5.16.

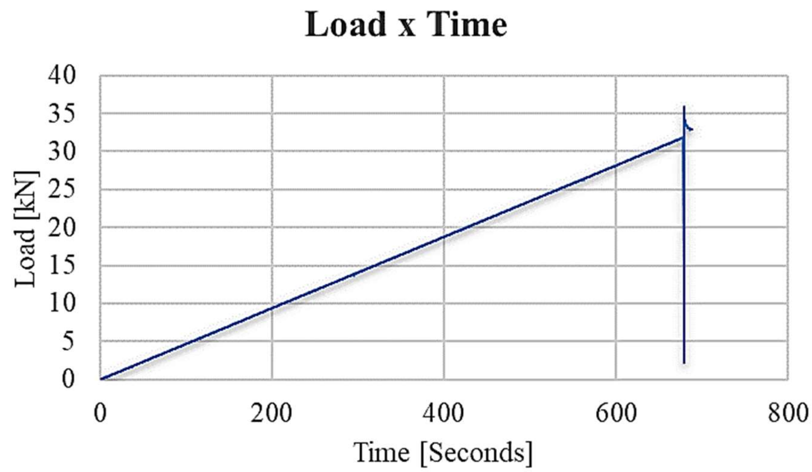


Figure 5.14 – Load x Time Graphic from Third Slab Prototype Rupture.
Source: Author (2019).

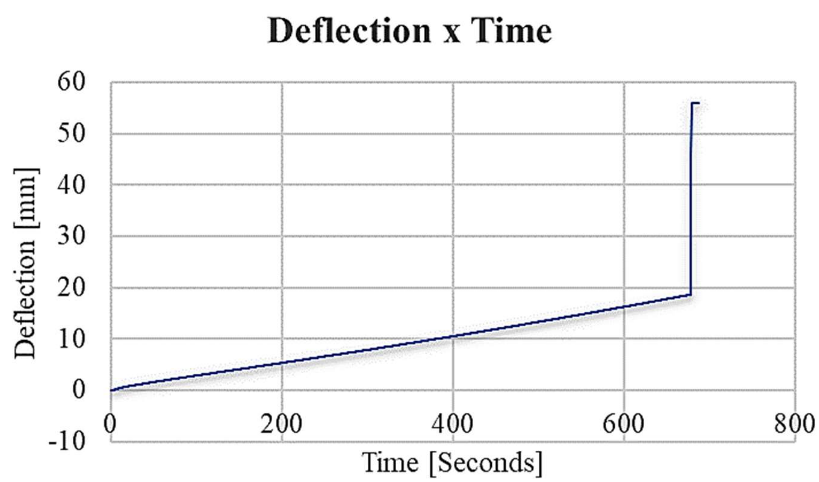


Figure 5.15 – Deflection x Time Graphic from Third Slab Prototype Rupture.
Source: Author (2019).

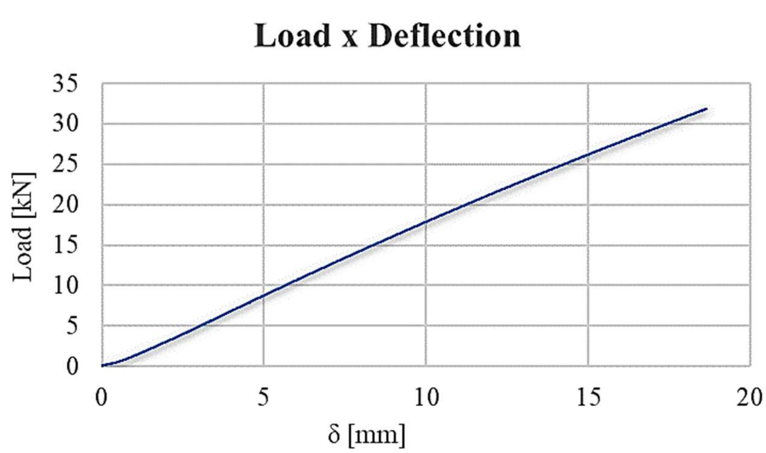


Figure 5.16 – Load x Deflection Graphic from Third Slab Prototype Rupture.
Source: Author (2019).

5.2 BEAMS

The beams laboratory tests consisted of testing three prototypes of tempered laminated glass beams with three layers.

The two prototypes that were tested as beams have the following dimensions: 2000 mm of length, the thickness of 10mm for each layer of glass plus the thickness of 1.52 mm of PVB between each glass plate and 200 mm of width. Those glasses were tested with in-plane loads, as shown in Figure 5.17.

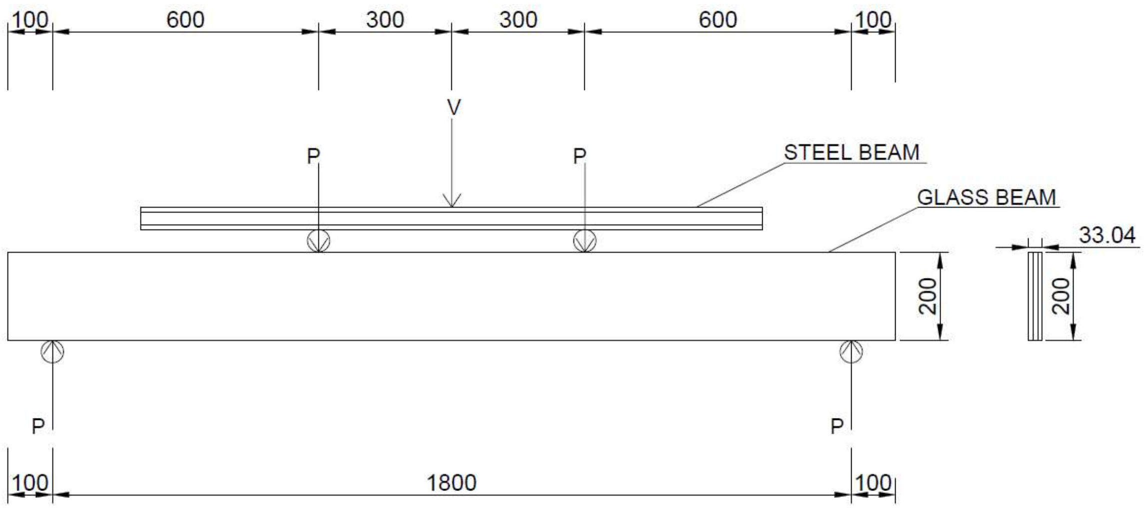


Figure 5.17 – Beams test set up (millimeters).
Source: Author (2019).

The main goal of the test was to analyze the behavior of beams when submitted to bending stresses.

5.2.1 Rupture load according to ASTM guidelines

For in-plane loads, it was considered that the three plates work as a monolithic plate. The self-weight, the moment due to self-weight, the section modulus and the inertia were calculated as presented in equations (5.116) to (5.119).

$$g_{sw} = 0.03 \cdot 0.20 \cdot 25 = 0.15\ kN/m \quad (5.116)$$

$$M_{gsw} = \frac{g_{sw} \cdot L^2}{8} - \frac{g_{sw} \cdot L_{cantilever}{}^2}{2} = \frac{0.15 \cdot 1.80^2}{8} - \frac{0.15 \cdot 0.10^2}{2} = 0.060\ kNm \quad (5.117)$$

$$I = \frac{b \cdot h^3}{12} = \frac{0.03 \cdot 0.20^3}{12} = 0.00002\ m^4 \quad (5.118)$$

$$W = \frac{b \cdot h^2}{6} = \frac{0.03 \cdot 0.20^2}{6} = 0.0002\ m^3 \quad (5.119)$$

ASTM 2751 describes the allowable stresses according to Table 3.4. For tempered glass and 3 seconds of load duration it is 73 MPa and for 10 minutes load duration, 65.3 MPa.

For 3 seconds of load duration, the total moment for the allowable tension of 73 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.120) to (5.123).

$$M = 73 \cdot 10^3 \cdot 0.0002 = 14.6\, kNm \tag{5.120}$$

$$M = M_{live\ load} + M_{sw} \tag{5.121}$$

$$M_{live\ load} = M - M_{sw} \tag{5.122}$$

$$M_{live\ load} = 14.60 - 0.060 = 14.54\, kNm \tag{5.123}$$

Therefore, according to calculations in equations (5.124) to (5.127), the maximum load to be applied is 48.31 kN.

$$M_{live\ load} = P \cdot a \tag{5.124}$$

$$14.54 = P \cdot 0.6 \tag{5.125}$$

$$P = 24.23\, kN \tag{5.126}$$

$$V = 2 \cdot 24.23 - 0.15 = 48.31\, kN \tag{5.127}$$

The immediate deflection due to the maximum applied load and the self-weight is 3.60 mm, as calculated in equations (5.128) to (5.130).

$$\delta = \frac{5 \cdot P \cdot L^4}{384 \cdot E \cdot I} + \frac{P \cdot a}{24 \cdot E \cdot I} \cdot (3 \cdot L^2 - 4 \cdot a^2) \tag{5.128}$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.80^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 0.00002} + \frac{24.23 \cdot 0.60 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 0.00002} (3 \cdot 1.8^2 - 4 \cdot 0.6^2) \tag{5.129}$$

$$\delta = 0.0146 + 3.58 = 3.60\, mm \tag{5.130}$$

For 10 minutes of load duration, the total moment for the allowable tension of 65.3 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.131) to (5.134).

$$M = 65.3 \cdot 10^3 \cdot 0.0002 = 13.06\, kNm \tag{5.131}$$

$$M = M_{live\ load} + M_{sw} \tag{5.132}$$

$$M_{live\ load} = M - M_{sw} \tag{5.133}$$

$$M_{live\ load} = 13.06 - 0.060 = 13.0\ kNm \tag{5.134}$$

Therefore, according to calculations in equations (5.135) to (5.138), the maximum load to be applied is 43.19 kN.

$$M_{live\ load} = P \cdot a \tag{5.135}$$

$$13.00 = P \cdot 0.6 \tag{5.136}$$

$$P = 21.67\ kN \tag{5.137}$$

$$V = 2 \cdot 21.67 - 0.15 = 43.19\ kN \tag{5.138}$$

The immediate deflection due to the maximum applied load and the self-weight is 3.22 mm, as calculated in equations (5.139) to (5.141).

$$\delta = \frac{5 \cdot P \cdot L^4}{384 \cdot E \cdot I} + \frac{P \cdot a}{24 \cdot E \cdot I} \cdot (3 \cdot L^2 - 4 \cdot a^2) \tag{5.139}$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.80^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 0.00002} + \frac{21.67 \cdot 0.60 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 0.00002} (3 \cdot 1.8^2 - 4 \cdot 0.6^2) \tag{5.140}$$

$$\delta = 0.0146 + 3.20 = 3.22\ mm \tag{5.141}$$

5.2.2 Rupture load according to prEN guidelines

For 3 seconds of load duration, the total moment for the allowable tension of 120 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.142) to (5.145).

$$M = 120 \cdot 10^3 \cdot 0.0002 = 24.00\ kNm \tag{5.142}$$

$$M = M_{live\ load} + M_{sw} \tag{5.143}$$

$$M_{live\ load} = M - M_{sw} \tag{5.144}$$

$$M_{live\ load} = 24.00 - 0.060 = 23.94\ kNm \tag{5.145}$$

Therefore, according to calculations in equations (5.146) to (5.149), the maximum load to be applied is 79.65 kN.

$$M_{live\ load} = P \cdot a \quad (5.146)$$

$$23.94 = P \cdot 0.6 \quad (5.147)$$

$$P = 39.90\ kN \quad (5.148)$$

$$V = 2 \cdot 39.90 - 0.15 = 79.65\ kN \quad (5.149)$$

The immediate deflection due to the maximum applied load and the self-weight is 5.91 mm, as calculated in equations (5.150) to (5.152).

$$\delta = \frac{5 \cdot P \cdot L^4}{384 \cdot E \cdot I} + \frac{P \cdot a}{24 \cdot E \cdot I} \cdot (3 \cdot L^2 - 4 \cdot a^2) \quad (5.150)$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.80^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 0.00002} + \frac{39.9 \cdot 0.60 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 0.00002} (3 \cdot 1.8^2 - 4 \cdot 0.6^2) \quad (5.151)$$

$$\delta = 0.0146 + 5.90 = 5.91\ mm \quad (5.152)$$

For 10 minutes of load duration, the total moment for the allowable tension of 108.30 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.153) to (5.156).

$$M = 108.3 \cdot 10^3 \cdot 0.0002 = 21.66\ kNm \quad (5.153)$$

$$M = M_{live\ load} + M_{sw} \quad (5.154)$$

$$M_{live\ load} = M - M_{sw} \quad (5.155)$$

$$M_{live\ load} = 21.66 - 0.060 = 21.60\ kNm \quad (5.156)$$

Therefore, according to calculations in equations (5.157) to (5.160), the maximum load to be applied is 71.85 kN.

$$M_{live\ load} = P \cdot a \quad (5.157)$$

$$21.60 = P \cdot 0.6 \quad (5.158)$$

$$P = 36.00\ kN \quad (5.159)$$

$$V = 2 \cdot 36.00 - 0.15 = 71.85\ kN \quad (5.160)$$

The immediate deflection due to the maximum applied load and the self-weight is 5.33 mm, as calculated in equations (5.161) to (5.163).

$$\delta = \frac{5 \cdot P \cdot L^4}{384 \cdot E \cdot I} + \frac{P \cdot a}{24 \cdot E \cdot I} \cdot (3 \cdot L^2 - 4 \cdot a^2) \tag{5.161}$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.80^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 0.00002} + \frac{36.00 \cdot 0.60 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 0.00002} (3 \cdot 1.8^2 - 4 \cdot 0.6^2) \tag{5.162}$$

$$\delta = 0.00146 + 5.32 = 5.33\ mm \tag{5.163}$$

5.2.3 Rupture load according to AS guidelines

On AS 1288 (2006) the load duration factor is 1.0 for both 3 seconds (short-term) and 10 minutes (medium-term) loads duration, as can be verified in Table 3.16. Therefore, the rupture load will be the same for both.

As presented on heading 5.1.3, the correspondent minimum thickness was calculated summing the minimum thickness of each isolated plate.

$$\mathrm{t_{minimum}} = 9.7 + 9.7 + 9.7 = 29.1\ \mathrm{mm} \tag{5.164}$$

The characteristic tensile strength of glass is 38.13 MPa as determined by equation (5.83) for parts away from the edge of glass panes and the ultimate capacity is 95.34 MPa as calculated in equation (5.85), disregarding the capacity reduction factor (Ø).

For both 3 seconds and 10 minutes of load duration, the total moment for the allowable stress of 95.34 MPa was calculated. Then, the moment due to self-weight of the beam was deducted from it to find the maximum moment that can be generated by the applied load, as presented in equations (5.165) to (5.168).

$$\mathrm{M} = 95.34 \cdot 10^3 \cdot 0.0002 = 19.069\ \mathrm{kNm} \tag{5.165}$$

$$\mathrm{M} = \mathrm{M_{live\ load}} + \mathrm{M_{sw}} \tag{5.166}$$

$$\mathrm{M_{live\ load}} = \mathrm{M} - \mathrm{M_{sw}} \tag{5.167}$$

$$\mathrm{M_{live\ load}} = 19.069 - 0.060 = 19.01\ \mathrm{kNm} \tag{5.168}$$

Therefore, according to calculations in equations (5.169) to (5.172), the maximum load to be applied is 63.21 kN.

$$\mathrm{M_{live\ load}} = \mathrm{P} \cdot \mathrm{a} \tag{5.169}$$

$$19.01 = \mathrm{P} \cdot 0.3 \tag{5.170}$$

$$\mathrm{P} = 31.68\,\mathrm{kN} \tag{5.171}$$

$$\mathrm{V} = 2 \cdot 31.68 - 0.15 = 63.21\,\mathrm{kN} \tag{5.172}$$

The immediate deflection due to the maximum applied load and the self-weight is 9.35 mm, as calculated in equations (5.173) to (5.175).

$$\delta = \frac{5 \cdot \mathrm{g_{sw}} \cdot \mathrm{L}^4}{384 \cdot \mathrm{E} \cdot \mathrm{I}} + \frac{\mathrm{P} \cdot \mathrm{a}}{24 \cdot \mathrm{E} \cdot \mathrm{I}} \cdot (3 \cdot \mathrm{L}^2 - 4 \cdot \mathrm{a}^2) \tag{5.173}$$

$$\delta = \frac{5 \cdot 0.15 \cdot 1.80^4 \cdot 10^3}{384 \cdot 70000 \cdot 10^3 \cdot 0.00002} + \frac{31.68 \cdot 0.60 \cdot 10^3}{24 \cdot 70000 \cdot 10^3 \cdot 0.00002} (3 \cdot 1.8^2 - 4 \cdot 0.6^2) \tag{5.174}$$

$$\delta = 0.00146 + 4.68 = 4.69\,mm \tag{5.175}$$

5.2.4 Calculation Summary Results

The expected loads capacities calculated from American, European and Australian guidelines were summarized in Table 5.3 for 3 seconds of load duration and in Table 5.4 for 10 minutes of load duration.

Table 5.3 –Expected load capacity for 3 seconds load duration.

	Self Weight	P	V	Stress	Deflection
	[kN/m]	[kN]	[kN]	[MPa]	[mm]
ASTM Analytical Procedure	0.15	24.23	48.31	73.00	3.60
prEN Simplified Method	0.15	39.90	79.65	120.00	5.91
AS Design Criteria	0.15	31.68	63.21	95.34	4.69

Source: Author (2019).

Table 5.4 –Expected load capacity for 10 minutes load duration.

	Self Weight	P	V	Stress	Deflection
	[kN/m]	[kN]	[kN]	[MPa]	[mm]
ASTM Analytical Procedure	0.15	21.67	43.19	65.30	3.22
prEN Simplified Method	0.15	36.00	71.85	108.30	5.33
AS Design Criteria	0.15	31.68	63.21	95.34	4.69

Source: Author (2019).

5.2.5 Laboratory Test Results

The slabs laboratory tests were performed at LAEDE laboratory on May 11th of 2019. In the same day, one beam was tested to check the set-up conditions, especially regarding the support restraints. This beam rotated by lateral instability at the support and it was necessary to design supports to avoid it in the next beam tests to be scheduled. The new supports were composed by two ribbed angles with neoprene in each edge of the beam, as shown in Figure 5.18 and Figure 5.22. There were not placed angles at the middle of the span to avoid influencing the support conditions of the beam at this point.

The beams laboratory tests were performed at LAEDE laboratory on June 14th of 2019. The testing machine for flexural and compressive strength used is presented in Figure 5.3. The temperature at the day of the testing was 23º C.

Both prototypes were tested with a medium speed of 120 N/s.

The first prototype rupture occurred at 70.41 kN and the vertical deflection measured was 18.02 mm, as presented in Figure 5.18.

Figure 5.18 – First Beam Prototype Rupture.
Source: Author (2019).

The Load x Time, the Deflection x Time and the Load x Deflection graphics were generated from the data provided by the testing and are presented in Figure 5.19, Figure 5.20 and Figure 5.21.

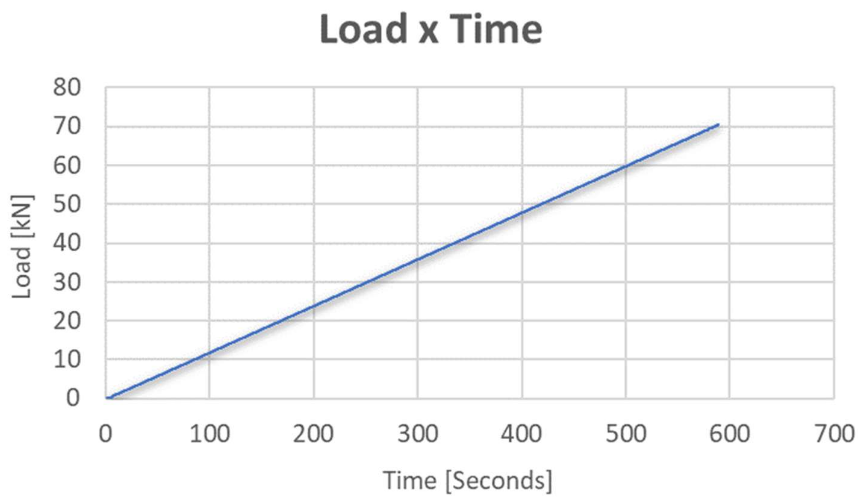


Figure 5.19 – Load x Time Graphic from First Beam Prototype Rupture.
Source: Author (2019).

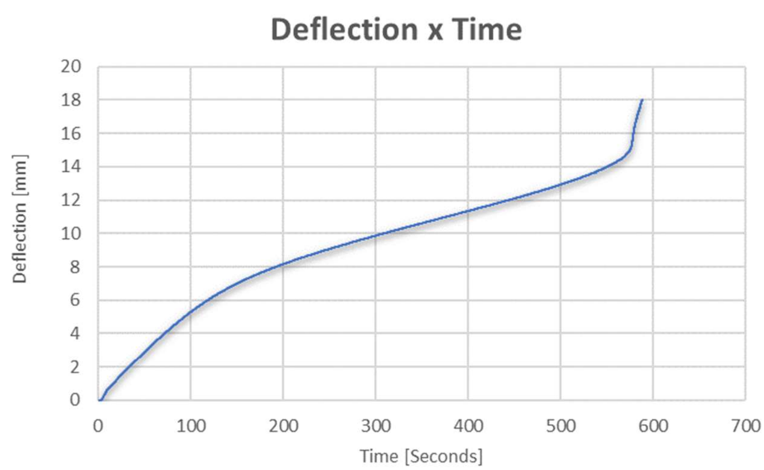


Figure 5.20 – Deflection x Time Graphic from First Beam Prototype Rupture.
Source: Author (2019).

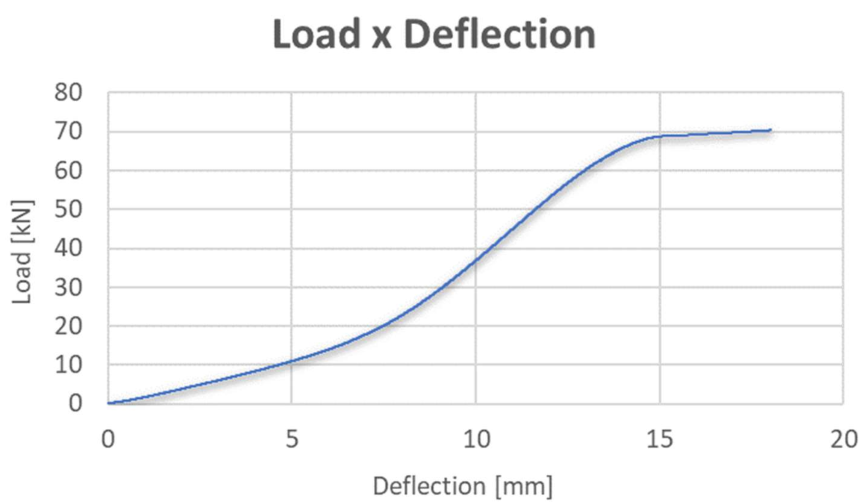


Figure 5.21 – Load x Deflection Graphic from First Beam Prototype Rupture.
Source: Author (2019).

The second prototype rupture occurred at 70.60 kN and the vertical deflection measured was 17.37 mm, as presented in Figure 5.22.

Figure 5.22 – Second Beam Prototype Rupture.
Source: Author (2019).

The Load x Time, the Deflection x Time and the Load x Deflection graphics were generated from the data provided by the testing and are presented in Figure 5.23, Figure 5.24 and Figure 5.25.

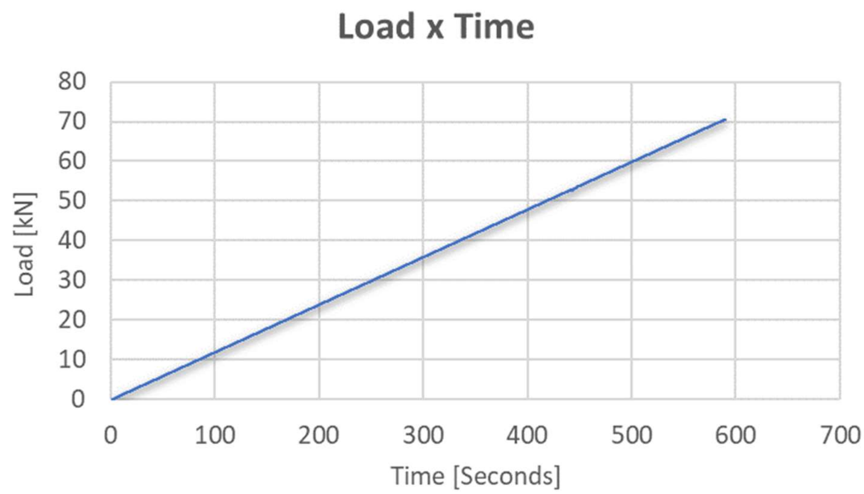


Figure 5.23 – Load x Time Graphic from Second Beam Prototype Rupture.
Source: Author (2019).

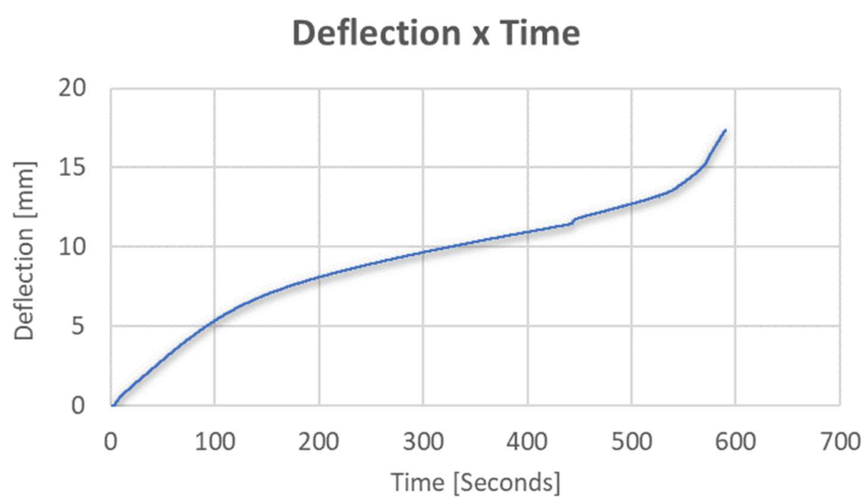


Figure 5.24 – Deflection x Time Graphic from Second Beam Prototype Rupture.
Source: Author (2019).

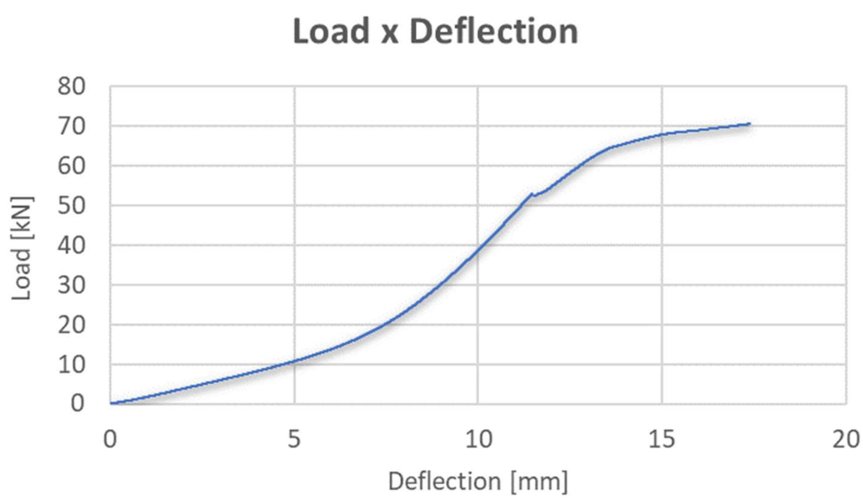


Figure 5.25 – Load x Deflection Graphic from Second Beam Prototype Rupture.
Source: Author (2019).

5.2.6 Lateral Torsional Buckling

The critical torsional buckling moment was calculated according to the equations from Haldimann et al (2008), presented on heading 3.4. The partial and final calculations are presented in Table 5.5. The shear modulus of the interlayer was considered for a PVB at 20°C and one hour of load duration. It resulted on a critical moment of 17.91 kNm, which could be caused by a maximum force V of 59.35 kN applied as shown in Figure 5.17.

Table 5.5– Critical torsional buckling moment calculation.

Glass		
h	mm	200
t1	mm	10
t2	mm	10
t3 = t1	mm	10
LIt	mm	1800
E	MPa	70000
G	MPa	26200
Interlayer		
tint	mm	1.52
Gint	MPa	0.84
Distances		
z1	mm	11.52
z2	mm	11.52
Inertias		
I1	mm^4	16667
I2	mm^4	16667
I3	mm^4	16667
Itorção (J)	mm^4	66667
Iscomp	mm^4	2123366
EIz,eff calculation		
Is	mm^4	530842
α	-	0.094190
β	-	0.390947
J	mm^4	66667
EIz,eff	Nmm^2	11148247196
EIz,eff	**kNm^2**	**11.15**
GIz,eff calculation		
λ	-	0.002054
Gkglass 1	Nmm^2	1746666667
Gkglass 2	Nmm^2	1746666667
Gkglass 3	Nmm^2	1746666667
Gkcomp	Nmm^2	769313895
GIz,eff	Nmm^2	6009313895
GIz,eff	**kNm^2**	**6.01**
Mcr calculation		
za	mm	100
C1	-	1.130
C2	-	0.460
Mcr	Nmm	17909841
Mcr	**kNm**	**17.91**
Fcr calculation		
P	**kN**	**29.75**
V	**kN**	**59.35**

Source: Author (2019).

6 WALKWAY MODELING

For the design of a walkway, a computational modeling was performed according to the orientations of prEN 16612 (2013). The model was developed on the ©DLUBAL – RFEM 5.16 software with the add-on module RF GLASS. Using the RF-GLASS add-on module it is possible to analyze deformations and stresses of arbitrary shaped and curved glass surfaces and to create all glazing types in the module. In this case, were considered multi-layer laminated glass with PVB interlayers.

The connections between glass elements were not the focus of this dissertation. However, in a complete design it is essential to verify the connections and the critical stresses that can be generated next to them.

6.1 WALKWAY GEOMETRY

According to heading 4.2, the slabs supported on two parallel edges presented admissible overloads below the minimum required by EN 1991-2 (2003), when limiting the stress and deflection to the values recommended by the guidelines. Therefore, it was necessary beams between the adjacent panels, in order to consider slabs supported on four edges.

The walkway model is presented in Figure 6.1 and Figure 6.2. It was designed for a span of 6.4 meters with four square glass slabs of 1.6 x 1.6 meters. The slabs are composed of tempered tri laminated glass with 10 mm of thickness each, glued by PVB interlayer with 1.52 mm thickness each. The longitudinal and transversal beams are 0.5 m high and are composed of the same layers as the slabs. The balustrades are composed of tempered tri laminated glass with 6 mm of thickness each and PVB interlayers of 1.52 mm thickness.

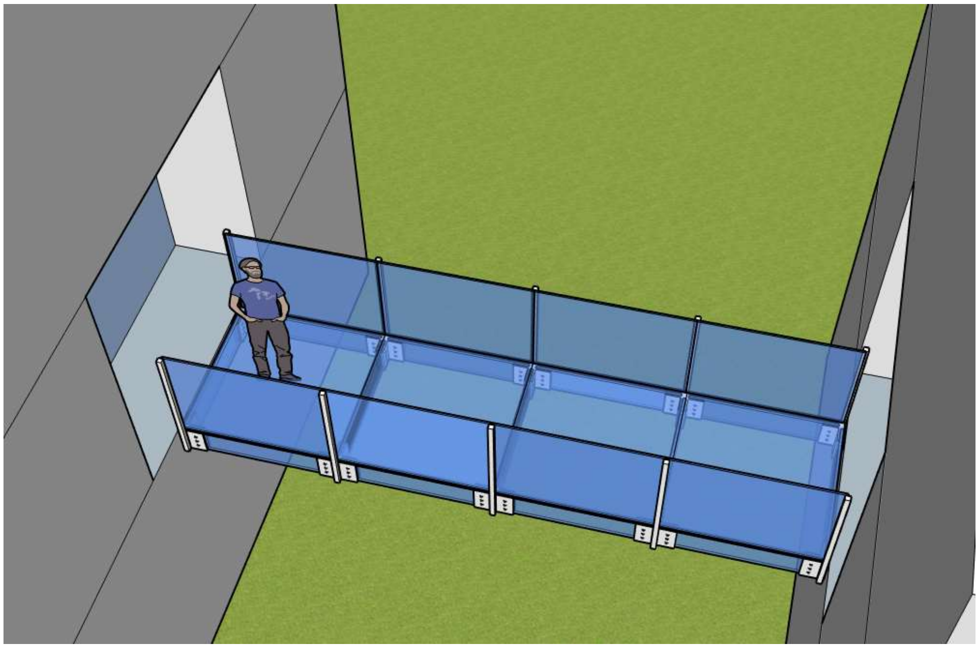


Figure 6.1 – Walkway model – perspective view.
Source: SketchUp - Author (2019).

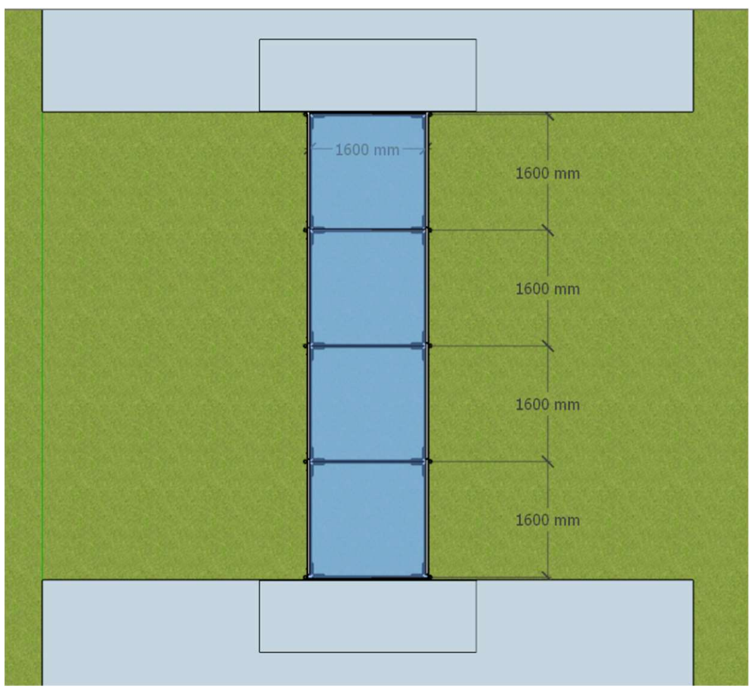


Figure 6.2 – Walkway dimensions – plane view.
Source: SketchUp - Author (2019).

6.2 LOADS

6.2.1 Loads on Slabs

For the walkway slabs were considered the following loads: self-weight and overload.

The nominal thickness of the laminated plate is 30 mm (three times 10mm) and the specific weight of glass is 25 kN/m³. The self-weight (g_{sw}) calculation is presented in equation (6.1).

$$g_{sw} = 0.03 \cdot 25 = 0.750 \text{ kN/m}^2 \tag{6.1}$$

According to EN 1991-2 (2003), should be considered an overload of 5.00 kN/m^2.

6.2.2 Loads on Balustrades

The glass balustrades are laterally fixed each 1.6 m on the longitudinal beams by steel connections. They were designed for pedestrians horizontal loads, wind loads and vertical self-weight.

The self-weight was considered as 0.45 kN/m as a vertical load, as in equation (6.2).

$$g_{sw} = 0.0198 \cdot 25 = 0.495 \text{ kN/m} \tag{6.2}$$

It is recommended on EN 1991-1 (2009) "Eurocode 1 – Action on structures - Part 1: General Actions" that the horizontal load on balustrades should be 0.50 kN/m acting on the top of it. The wind load considered was 1.0 kN/m^2.

6.2.3 Loads on Beams

For the walkway beams were considered its self-weight and the glass balustrades and slabs reactions.

The beams were composed of laminated glass with three plates of 10mm and 500 mm high. The specific weight of glass is 25 kN/m³. The self-weight (g_{sw}) calculation is presented in equation (6.3).

$$g_{sw} = 0.03 \cdot 0.50 \cdot 25 = 0.375 \text{ kN/m} \tag{6.3}$$

It was also considered the wind load of 1.0 kN/m^2.

$$h_{Qy,wind} = 1.00 \cdot 0.50 = 0.50 \text{ kN/m} \tag{6.4}$$

The balustrade reactions were considered as nodal loads on the longitudinal glass beam each 1.60 m, where are located the steel connections. The reactions are presented in equations (6.5) to (6.10).

The vertical load due to self-weight was 0.792 kN.

$$V_{sw} = 0.495 \cdot 1.6 = 0.792 \text{ kN} \tag{6.5}$$

The horizontal load due to pedestrians was 0.80 kN.

$$H_{\text{Qy,pedestrians}} = 0.50 \cdot 1.6 = 0.80\ \text{kN} \tag{6.6}$$

The distance between the top of the balustrade and the center of the steel fixation is 1.30 m, therefore the moment due to horizontal pedestrian load was calculated in equation (6.7).

$$M_{\text{Qx,−pedestrians}} = 0.80 \cdot (1.10 + 0.20) = 1.04\ \text{kNm} \tag{6.7}$$

The horizontal load due to wind was 1.76 kN.

$$h_{\text{Qy,wind}} = 1.00 \cdot 1.10 = 1.10\ \text{kN/m} \tag{6.8}$$

$$H_{\text{Qy,wind}} = 1.10 \cdot 1.60 = 1.76\ \text{kN} \tag{6.9}$$

The distance between the horizontal resultant of wind and the center of the steel fixation is 0.75 m, therefore the moment due to wind load was calculated in equation (6.10).

$$M_{\text{Qx,wind}} = \left(\frac{1.10}{2} + 0.20\right) \cdot 1.76 = 1.32\ \text{kNm} \tag{6.10}$$

6.2.4 Combinations of Loads

According EN 1990 (2009), the load combinations are presented in equations (6.11) and (6.12).

The combinations of loads for ULS is presented in equation (6.11).

$$\sum_{j\geq 1} \gamma_{G,j}\, G_{k,j} + \gamma_P\, P + \gamma_{Q,1}\, Q_{k,1} + \sum_{i>1} \gamma_{Q,i}\, \Psi_{0,i}\, Q_{k,i} \tag{6.11}$$

where,

$\gamma_{G,j}$ is the partial factor for permanent action;

$G_{k,j}$ is the characteristic value of permanent action;

γ_P is the partial factor for prestressing action;

P is the relevant representative value of prestressing action;

$\gamma_{Q,1}$: is the partial factor for the leading variable action 1;

$Q_{k,1}$ is the characteristic value of the leading variable action 1;

$\gamma_{Q,i}$ is the partial factor for variable action;

$\Psi_{0,i}$ is the factor for combination value of a variable action;

$Q_{k,i}$ is the characteristic value of the accompanying variable action i.

The combinations of loads for frequent SLS is presented in equation

$$\sum_{j\geq 1} G_{k,j} + P + \Psi_{1,1}\, Q_{k,1} + \sum_{i>1} \Psi_{2,i}\, Q_{k,i} \tag{6.12}$$

where,

$\Psi_{2,i}$ is the factor for quasi-permanent value of a variable action.

The recommended values of Ψ factors for footbridges are presented in Table 6.1.

Table 6.1–Recommended values of Ψ factors for footbridges.

Action	Symbol	ψ_0	ψ_1	ψ_2
Traffic loads	gr1	0,40	0,40	0
	Q_{fwk}	0	0	0
	gr2	0	0	0
Wind forces	F_{Wk}	0,3	0,2	0
Thermal actions	T_k	0,6 [1)]	0,6	0,5
Snow loads	$Q_{Sn,k}$ (during execution)	0,8	-	0
Construction loads	Q_c	1,0	-	1,0

1) The recommended ψ_0 value for thermal actions may in most cases be reduced to 0 for ultimate limit states EQU, STR and GEO. See also the design Eurocodes.

Source: EN1990 (2002).

The load combinations are presented in Table 6.2.

Table 6.2–Load Combinations

Combination Number	Limit State	Combination Equations
CO1	ULS	1.35 · SW + 1.50 · OL
CO2	SLS	1.00 · SW + 0.40 · OL
CO3	ULS	1.35 · SW + 1.50 · WIND + (1.5 · 0.4) · OL
CO4	ULS	1.35 · SW + 1.50 · OL + (1.5 · 0.3) · WIND
CO5	SLS	1.00 · SW + 0.20 · WIND + 0.0 · OL
CO6	SLS	1.00 · SW + 0.40 · OL + 0.0 · WIND

Source: Author (2019).

Where SW is the self-weight, OL is the overload and WIND is wind.

6.3 STRESSES AND DEFLECTIONS

6.3.1 Stresses and deflections on slabs

The stresses were calculated to the correspondent thickness of 14.14 mm, which was calculated in equation (4.27) and have a maximum value of 29.73 MPa. It occurs at the center of the plate, as shown in Figure 6.3.

The maximum stress on the plate is lower than the design value of stress resistance of 81.15 MPa, which was calculated in equation (4.23). Therefore, the dimensions of the plate are approved regarding stresses.

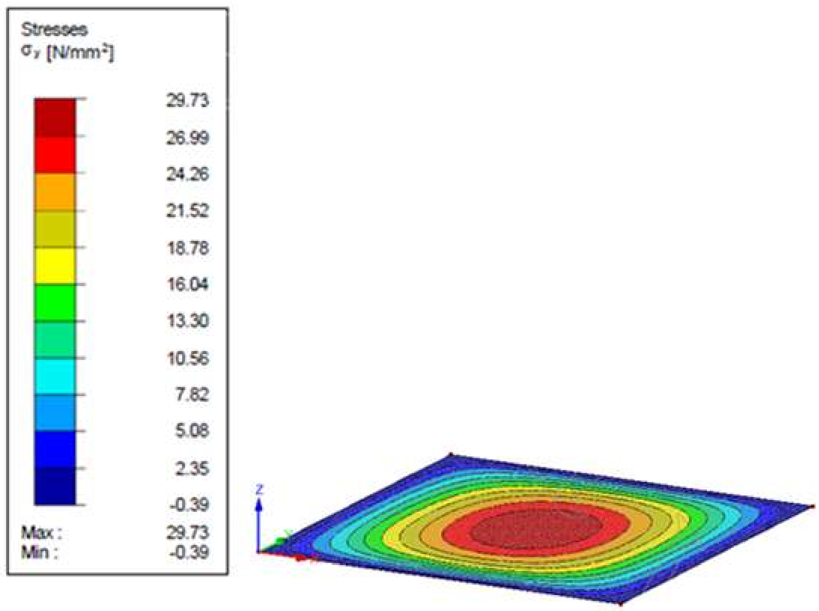


Figure 6.3 – Stresses on the isolated slab due to ULS CO1.
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

The deflections were calculated to the correspondent thickness of 12.60 mm, which was calculated in equation (4.25) and have a maximum value of 6.0 mm. It occurs at the center of the plate, as shown in Figure 6.4.

The German standard, DIN 18008-1 (2010), suggests a maximum deflection of Span/100 and this is limit was adopted on this work. Therefore, the deflection of 6 mm is within the allowed deflection of 16mm.

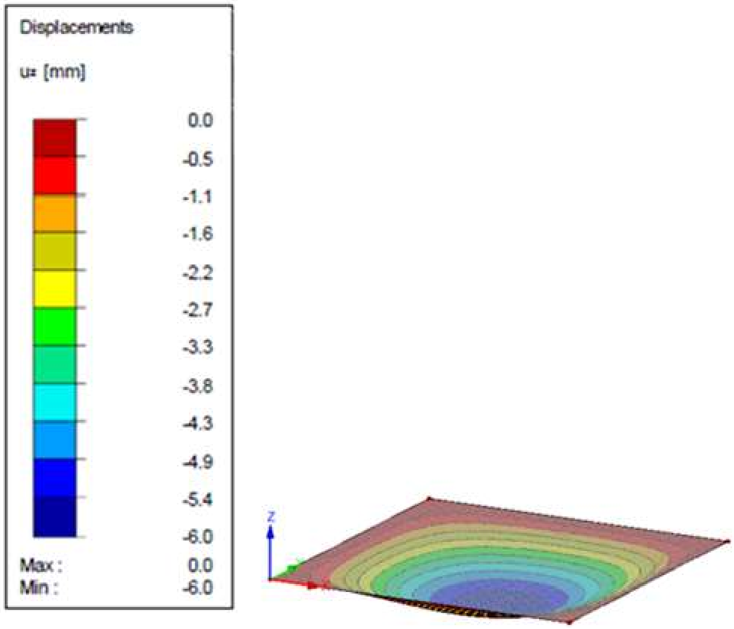


Figure 6.4 – Deflections on the isolated slab due to SLS CO2.
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

The stresses and deflections were also calculated with ©DLUBAL – RFEM 5.16 add-on module RF-GLASS considering the laminated glass assembly of two plates of 10 mm thickness and 1.52 mm of PVB interlayer. The results were the same as the previous models calculated with effective thicknesses, as shown in Figure 6.5. The coupling was not considered to compare the results with the prEN 16612 (2013) effective thickness stresses.

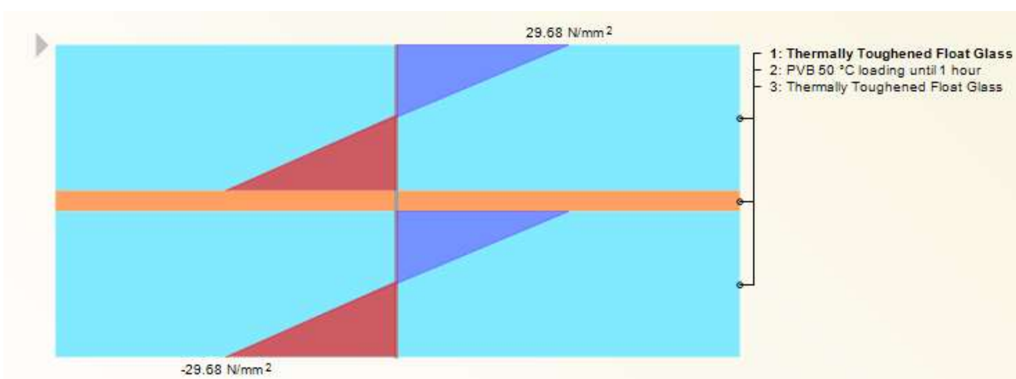


Figure 6.5 – Stresses on laminated glass assembly due to ULS CO1.
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

The slabs were also analyzed with the entire model. The global effects were considered and its results are presented in Figure 6.6 and Figure 6.7.

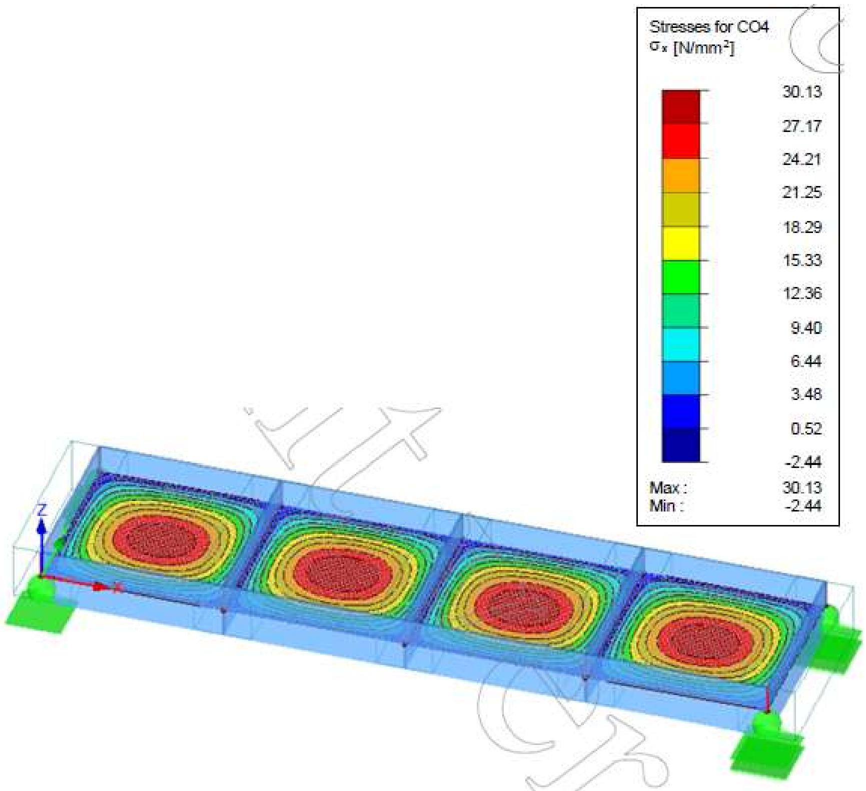


Figure 6.6 – Stresses on the slabs on entire model with global analysis due to ULS CO4.
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

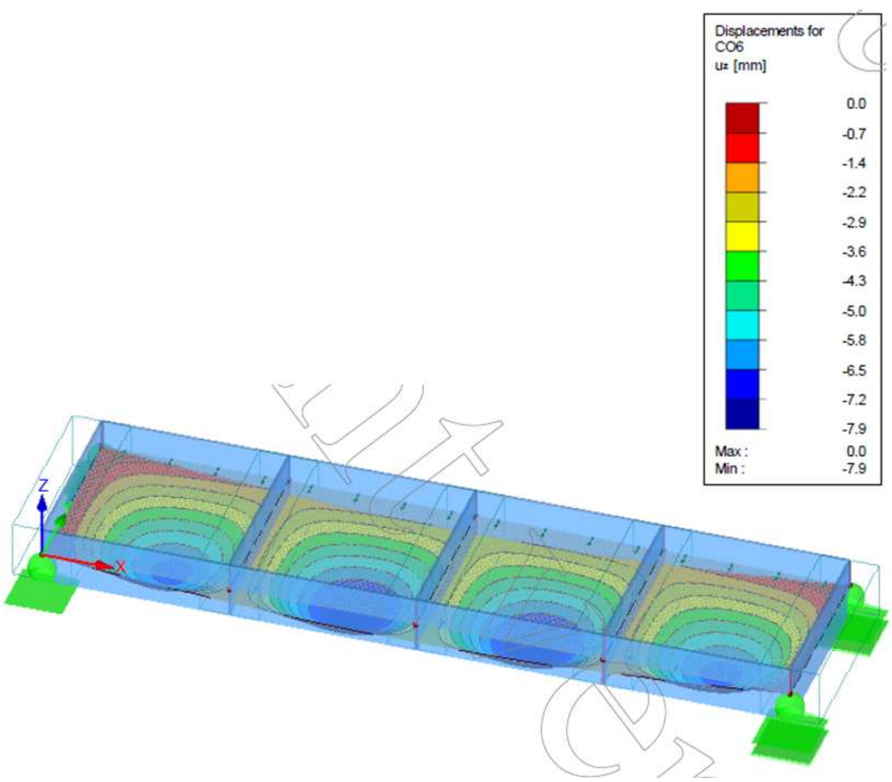


Figure 6.7 – Deflections on the slabs on entire model with global analysis due to SLS CO6.
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

The results of isolated slabs and of the entire model were analyzed and the worst results were considered for checking the design of this structural element.

It was concluded that the plates support the loads required for a walkway with the imposed conditions and proposed dimensions.

6.3.2 Stresses and deflections on balustrades

The stresses and deflections on balustrades were calculated considering the laminated glass assembly of two plates of 6.0 mm thickness and 1.52 mm of PVB interlayer and are presented in Figure 6.8 and Figure 6.9 for the worst combination cases.

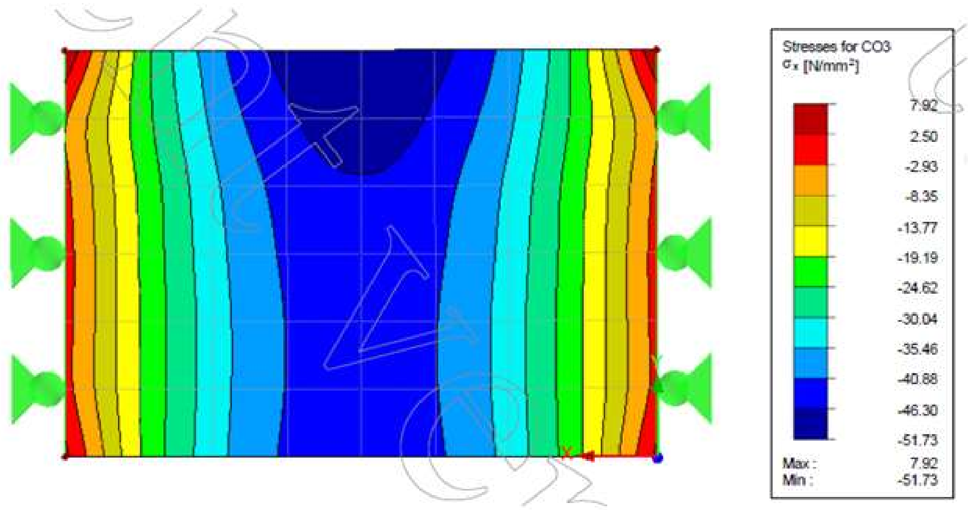


Figure 6.8 – Stresses due to ULS CO3 of loads on balustrades.
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

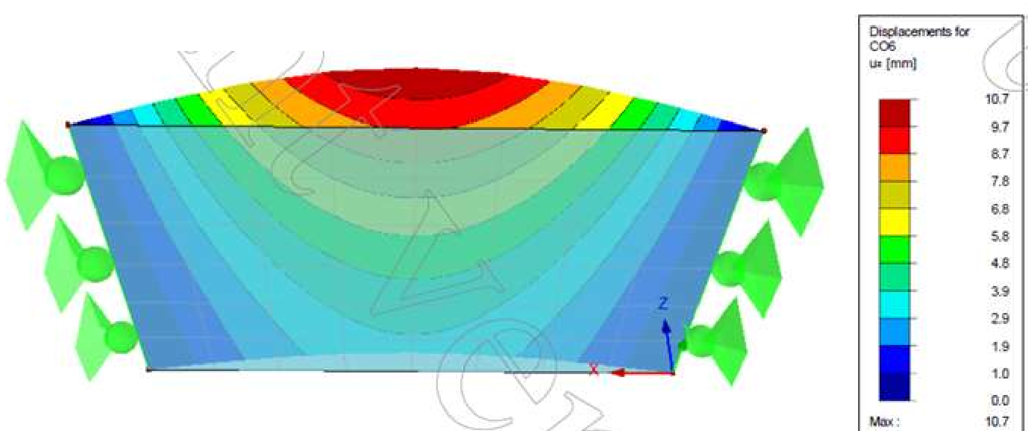


Figure 6.9 – Deflections due to SLS CO6 of loads on balustrades.
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

The maximum stress was 51.73 MPa, which is within the limit of 81.15 MPa. The maximum deflection is 10.7 mm and is also within the limit of 16 mm.

6.3.3 Stresses and deflections on beams

The efforts were calculated in the ©DLUBAL – RFEM 5.16 software for the loads presented on heading 6.2. The maximum moments on the beams, deflections and stresses were generated and are presented in Figure 6.10 to Figure 6.13.

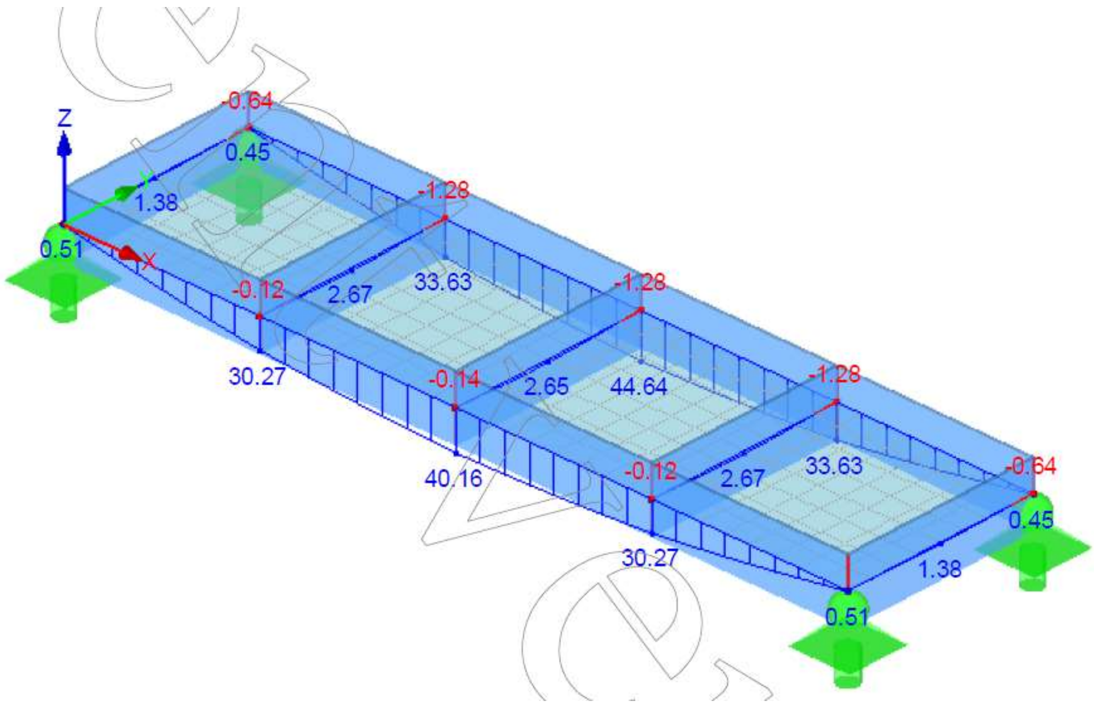


Figure 6.10 – Bending moments due to ULS CO4 of loads on beams (units: kNm).
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

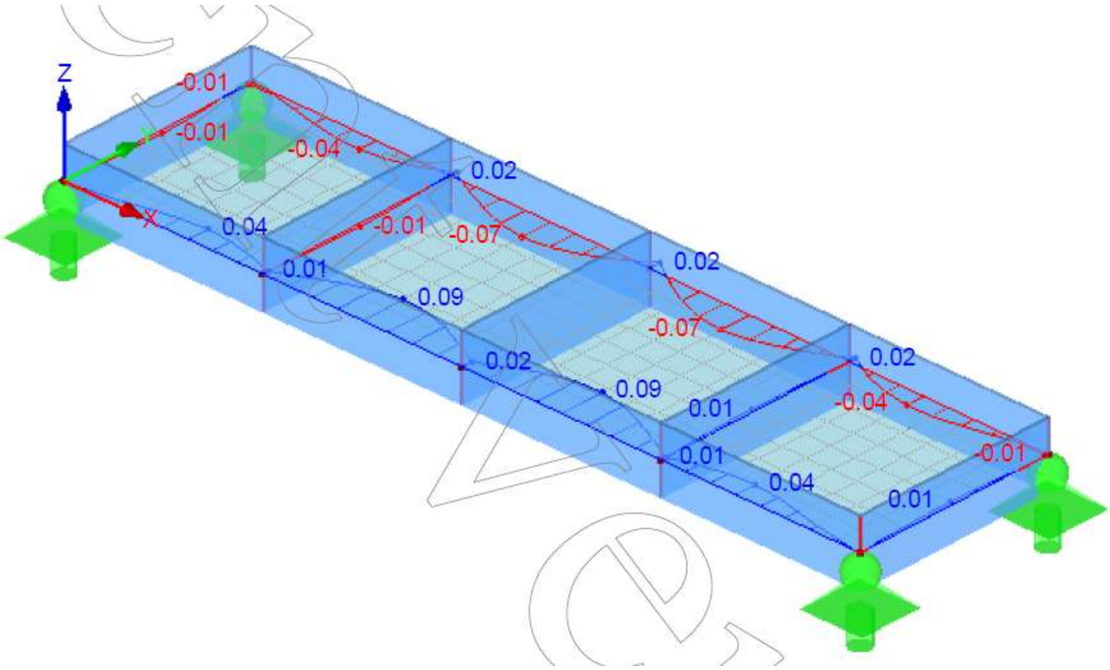


Figure 6.11 – Lateral bending moments due to ULS CO4 of loads on beams (units: kNm).
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

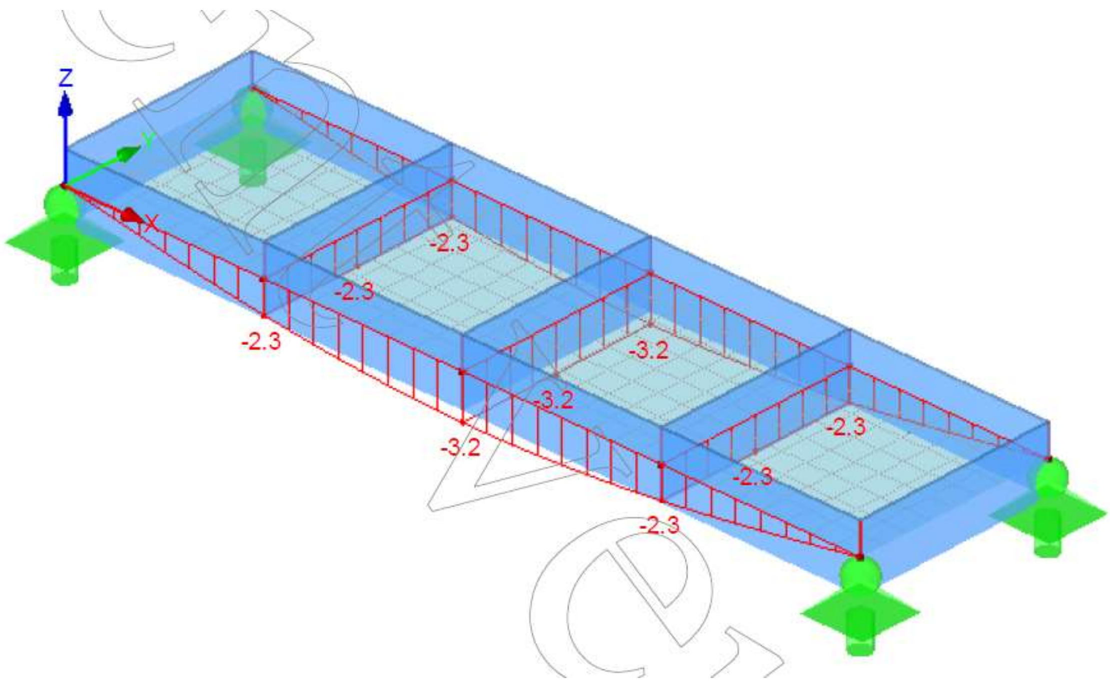


Figure 6.12 – Deflections due to SLS CO6 on beams (units: millimeters).
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

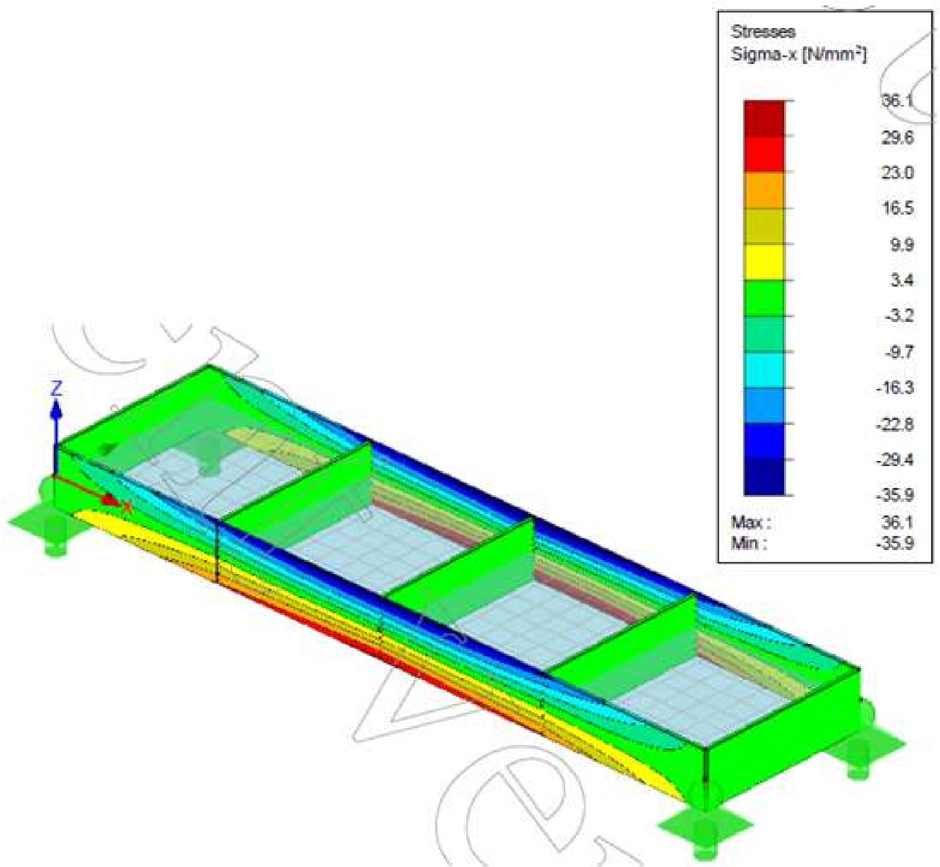


Figure 6.13 – Stresses due to ULS CO4 on beams.
Source: ©DLUBAL – RFEM 5.16 - Author (2019).

The beams are also within the limits regarding stresses and deflections. The moments were verified for lateral torsional buckling on the next section.

6.3.4 Lateral Torsional Buckling Verification

The effect of lateral torsional buckling must be verified due to the slenderness of glass beams. It was considered a length of 1600 mm, as the longitudinal beam is restrained by the transversal beams.

The critical torsional buckling moment was calculated according to the equations from Haldimann et al (2008), presented on heading 3.4. The partial and final calculations are presented in Table 6.3. The shear modulus of the interlayer was considered for a PVB at 50°C and one hour of load duration.

The critical torsional bucking moment is 30.97 kNm. Therefore, the bending moments from the model are over the critical value and the beams are subjected to suffer from this effect.

In accordance with AS 1288 (2006) recommendations, the design moment must be below the value of the M_{cr} divided by a safety coefficient factor of 1.7. In this case, the limit design moment would be 18.22kNm. The maximum design moment for ULS CO4, as presented in Figure 6.10, is 44.64 kN/m. In order to satisfy the limit condition, the critical moment has to be greater than 75.89 kNm. Therefore, should be a transversal beam each 730 mm approximately, as shown in Table 6.4.

Table 6.3– Critical torsional buckling moment calculation for transversal beams each 1600 mm.

	Glass	
h	mm	500
t1	mm	10
t2	mm	10
t3 = t1	mm	10
Llt	mm	1600
E	MPa	70000
G	MPa	26200
	Interlayer	
tint	mm	1.52
Gint	MPa	0.052
	Distances	
z1	mm	11.52
z2	mm	11.52
	Inertias	
I1	mm⁴	41667
I2	mm⁴	41667
I3	mm⁴	41667
Itorção (J)	mm⁴	166667
Iscomp	mm⁴	5308416
	EIz,eff calculation	
Is	mm⁴	1327104
α	-	0.094190
β	-	7.992788
J	mm⁴	166667
EIz,eff	Nmm²	9912878041
EIz,eff	**kNm²**	**9.91**
	GIz,eff calculation	
λ	-	0.000511
Gkglass 1	Nmm²	4366666667
Gkglass 2	Nmm²	4366666667
Gkglass 3	Nmm²	4366666667
Gkcomp	Nmm²	751774357
GIz,eff	Nmm²	13851774357
GIz,eff	**kNm²**	**13.85**
	Mcr calculation	
za	mm	250
C1	-	1.130
C2	-	0.460
Mcr	Nmm	30969713
Mcr	**kNm**	**30.97**

Source: Author (2019).

Table 6.4– Calculation of distance between transversal beams for M_{cr} of 75.89 kNm.

	Glass	
h	mm	500
t1	mm	10
t2	mm	10
t3 = t1	mm	10
Llt	mm	731
E	MPa	70000
G	MPa	26200
	Interlayer	
tint	mm	1.52
Gint	MPa	0.052
	Distances	
z1	mm	11.52
z2	mm	11.52
	Inertias	
I1	mm^4	41667
I2	mm^4	41667
I3	mm^4	41667
Itorção (J)	mm^4	166667
Iscomp	mm^4	5308416
	EIz,eff calculation	
Is	mm^4	1327104
α	-	0.094190
β	-	38.335333
J	mm^4	166667
EIz,eff	Nmm^2	8994882455
EIz,eff	**kNm^2**	**8.99**
	GIz,eff calculation	
λ	-	0.000511
Gkglass 1	Nmm^2	4366666667
Gkglass 2	Nmm^2	4366666667
Gkglass 3	Nmm^2	4366666667
Gkcomp	Nmm^2	751774357
GIz,eff	Nmm^2	13851774357
GIz,eff	**kNm^2**	**13.85**
	Mcr calculation	
za	mm	250
C1	-	1.130
C2	-	0.460
Mcr	Nmm	75889999
Mcr	**kNm**	**75.89**

Source: Author (2019).

7 RESULTS DISCUSSION

7.1 SLAB DESIGN RESULTS

Considering the load resistance determined by ASTM Basic Procedure for the four edges supported plate and applying it for calculating the stresses and deflections based on ASTM Analytical Procedure, on prEN Simplified Method and on AS Design Criteria, it were achieved the results presented on heading 4 and compiled in Table 7.1.

Table 7.1 –Design of a glass slab supported by four edges.

	Self Weight	Overload	Loads Combination for Stress Calculation	Loads Combination for Deflection Calculation	Stress	Stress Limit	Deflection	Deflection Limit
	[kN/m²]	[kN/m²]	[kN/m²]	[kN/m²]	[MPa]	[MPa]	[mm]	[mm]
ASTM Basic Procedure	0.75	21.01	21.76	21.76	-	-	16.00	-
ASTM Analytical Procedure	0.75	21.01	21.76	21.76	86.53	63.00	57.80	16.00
prEN Simplified Method	0.75	21.01	32.53	9.15	113.61	81.15	19.90	16.00
AS Design Criteria	0.75	21.01	32.42	13.36	120.10	82.00	31.70	16.00

Source: Author (2019).

It is possible to conclude that, in this case, the ASTM Basic Procedure is less conservative, since considering the load resistance determined by this method, are generated excessive stresses and deflections on the other three methods.

Comparing the ASTM Analytical Procedure to prEN Simplified Method, it is possible to verify that their guidelines are very similar. The calculation of the effective thickness is practically identical. The difference on effective thickness values were due to the divergent consideration of the shear transference of the interlayer and because ASTM takes in account the minimum thickness of the plate and not the nominal thickness, as prEN 16612 (2013) does. Also, ASTM uses the method of the allowable stresses and prEN 16612 (2013) the method of the limit states.

The Australian standard also uses the limit state method, but it presents a different consideration regarding the thickness. While the American and European standards use the effective thickness, the Australian uses a minimum thickness, which, for laminated glass, is the sum of the glass plates disregarding the interlayer.

It can be noticed that the maximum stress is higher than the allowable limit for all standards. Also, the deflection results present a huge discrepancy (260%) between the values of standards. This can be explained by the fact that the European standard, EN 1990 (2009), reduces the overload by 60% in the serviceability limit state combination and the Australian standard, AS/NZS 1170.0 (2002), reduces it by 40% is SLS.

By limiting the stress to the respective admissible value of each standard, as presented in Table 7.2, it can be noticed that for prEN 16612 (2013), the overload that can be applied is slightly lower (2%) than in ASTM Analytical Procedure. However, prEN 16612 (2013) already fulfill the deflection requirement for the serviceability limit state, while at ASTM the deflection is still much higher (around 162%) than the limit. The overload from AS Design Criteria is the most conservative and the deflection is 37% higher than the limit.

Table 7.2 –Design of a glass slab supported by four edges with limited stresses.

	Self Weight	**Overload**	**Loads Combination for Stress Calculation**	**Loads Combination for Deflection Calculation**	**Stress**	**Stress Limit**	**Deflection**	**Deflection Limit**
	[kN/m²]	**[kN/m²]**	**[kN/m²]**	**[kN/m²]**	**[MPa]**	**[MPa]**	**[mm]**	**[mm]**
ASTM Basic Procedure	0.75	21.01	21.76	21.76	-	-	16.00	-
ASTM Analytical Procedure	0.75	15.09	15.84	15.84	63.00	63.00	42.00	16.00
prEN Simplified Method	0.75	14.81	23.23	6.67	81.15	81.15	14.50	16.00
AS Design Criteria	0.75	14.15	22.13	9.24	82.00	82.00	21.90	16.00

Source: Author (2019).

By limiting the ASTM Analytical Procedure deflection to Span/100, as recommended by DIN 18008(2010), the maximum overload that can be applied on the plate decreases approximately 75%, as presents Table 7.3.

Table 7.3 –Design of a glass slab supported by four edges with limited deflection.

	Self Weight	**Overload**	**Loads Combination for Stress Calculation**	**Loads Combination for Deflection Calculation**	**Stress**	**Stress Limit**	**Deflection**	**Deflection Limit**
	[kN/m²]	**[kN/m²]**	**[kN/m²]**	**[kN/m²]**	**[MPa]**	**[MPa]**	**[mm]**	**[mm]**
ASTM Basic Procedure	0.75	21.01	21.76	21.76	-	-	16.00	-
ASTM Analytical Procedure	0.75	5.28	6.03	6.03	23.98	63.00	16.00	16.00
prEN Simplified Method	0.75	14.81	23.23	6.67	81.15	81.15	14.50	16.00
AS Design Criteria	0.75	10.00	15.90	6.75	58.91	82.00	16.00	16.00

Source: Author (2019).

Therefore, it is possible to conclude that for the analyzed case, the Basic Procedure of the American standard is, somehow, unconservative. When applying the deflection obtained by the Basic Procedure on the Analytical Procedure, the overload is reduced from 21.01 kN/m^2 to 5.28 kN/m^2. The European and

Australian standards lead to an intermediate load capacity. The first presented an overload of 14.81 kN/m^2 limited by the stress and the second an overload of 10.00 kN/m^2 limited by deflection.

In the case of the plate supported on two edges, the maximum allowable loads were calculated restricting the stress values to its limits, which leaded to similar results for the four methods. Nevertheless, there were discrepancies in the deflection generated in each of the methods. On ASTM Basic Procedure and prEN Simplified Method the values presented the same order of magnitude, while in the ASTM Analytical Method, the deflection was double. The AS Design Criteria leads to an intermediate value. Table 7.4 presents the values for loads and deflections for each method.

Table 7.4 –Design of a glass slab supported by two edges with limited stresses.

	Self Weight	Overload	Loads Combination for Stress Calculation	Loads Combination for Deflection Calculation	Stress	Stress Limit	Deflection	Deflection Limit
	[kN/m²]	[kN/m²]	[kN/m²]	[kN/m²]	[MPa]	[MPa]	[mm]	[mm]
ASTM Basic Procedure	0.75	4.75	5.50	5.50	-	-	21.50	-
ASTM Analytical Procedure	0.75	4.97	5.72	5.72	63.00	63.00	51.20	16.00
prEN Simplified Method	0.75	4.95	8.44	2.73	81.15	81.15	19.96	16.00
AS Design Criteria	0.75	4.76	8.04	3.60	82.00	82.00	28.85	16.00

Source: Author (2019).

Analogously to the four edges supported plate, the deflection results present a huge discrepancy (156%) between the values of ASTM Analytical Method and the other three procedures. This can be explained by the fact that the EN 1990 (2009) suggest a reduction of the overload by 60% in the serviceability limit state combination and the Australian standard, AS/NZS 1170.0 (2002), a reduction of it by 40% is SLS.

By limiting the deflection to Span/100, as recommended by DIN 18008(2010), the maximum overload that can be applied on the plate decreases around 58% for the American Analytical Procedure, as presented in Table 7.5. Therefore, it would not be possible to use a slab with those dimensions (span and thickness) on a walkway, due to the recommended overload.

Table 7.5 –Design of a glass slab supported by two edges with limited deflection

	Self Weight	Overload	Loads Combination for Stress Calculation	Loads Combination for Deflection Calculation	Stress	Stress Limit	Deflection	Deflection Limit
	[kN/m²]	[kN/m²]	[kN/m²]	[kN/m²]	[MPa]	[MPa]	[mm]	[mm]
ASTM Basic Procedure	0.75	2.45	3.20	3.20	-	-	16.00	16.00
ASTM Analytical Procedure	0.75	1.03	1.78	1.78	19.48	63.00	16.00	16.00
prEN Simplified Method	0.75	3.59	6.40	2.18	61.58	81.15	16.00	16.00
AS Design Criteria	0.75	2.08	4.02	2.00	82.00	82.00	16.00	16.00

Source: Author (2019).

7.2 SLAB TESTS RESULTS

The heading 5.1 presented the calculations for the estimated load of rupture for each standard guideline and the real load of rupture obtained by the laboratory tests of the glass slabs.

The estimated loads were calculated for 3 seconds and 10 minutes of load duration for ASTM Analytical Method, prEN Simplified Method and AS Design Criteria, to estimate the creep effect. The values are presented in Table 7.6.

Table 7.6 –Expected Rupture Values from Standards.

	SLAB 3 seconds			SLAB 10 minutes		
	V	**Stress**	**Deflection**	**V**	**Stress**	**Deflection**
	[kN]	**[MPa]**	**[mm]**	**[kN]**	**[MPa]**	**[mm]**
ASTM Analytical Procedure	4.55	73.00	34.42	4.05	65.30	30.87
prEN Simplified Method	7.69	120.00	56.63	6.91	108.30	51.11
AS Design Criteria	17.62	95.34	15.45	7.37	122.40	59.55

Source: Author (2019).

The real rupture values were obtained from the laboratory tests. As presented in Table 7.7, the real rupture loads were well above expected, which demonstrates that the interlayer efficiently transferred the shear.

Table 7.7 –Real Rupture Values from Laboratory Tests.

	Load Speed	**Real Rupture Load**	**Real Rupture Deflection**
	[N/s]	**[kN]**	**[mm]**
SLAB 1	7.00	28.00	17.89
SLAB 2	47.70	34.00	20.44
SLAB 3	47.70	32.00	18.65

Source: Author (2019).

In order to estimate the rupture stresses and deflections, the effective thicknesses were recalculated for a full transfer of the shear by the interlayer. The effective thickness of deflection is 32.66 mm and the effective thickness for stress is 32.48 mm. Considering that the Young's Modulus is 70000 MPa, the tensile rupture unitary deformation was calculated. The results are presented in Table 7.8.

Table 7.8 –Estimated stresses and deflections based on effective thickness and laboratory tests loads.

	Stresses	Deflection	εu
	[MPa]	[mm]	[‰]
SLAB 1	122.13	17.62	1.74
SLAB 2	146.46	21.09	2.09
SLAB 3	135.84	19.58	1.94

Source: Author (2019).

Comparing the V rupture expected loads from Table 7.6 with the real rupture loads in Table 7.7, it is possible to notice that the real loads have higher values, at least 59% above it. That shows that all the studied standards are in favor of safety.

It was observed that the first slab, which was submitted to 10 minutes of load duration, ruptured with a stress of 122.13 MPa. The other two slabs, however, broke with an average stress of 141.15 MPa. The stresses of the last two slabs were greater than the first one and this can be explained by the creep effect. On this case, it represented a stress reduction of 14% approximately on the stress. To measure this effect with accuracy, tests with more samples should be performed and with different load duration.

Regarding the deflection, the calculated values considering the full shear transfer by the interlayer, leads to values quite similar to the real rupture values obtained from the laboratory tests.

7.3 BEAM TESTS RESULTS

The heading 5.2 presented the calculations for the estimated load of rupture for each standard guideline and the real load of rupture obtained by the laboratory tests of the glass beams.

The estimated loads were calculated for 3 seconds and 10 minutes of load duration for ASTM Analytical Method, prEN Simplified Method and AS Design Criteria. The values are presented in Table 7.9.

Table 7.9 –Expected Beam Rupture Values from Standards.

	BEAM 3 seconds				BEAM 10 minutes			
	P	V	Stress	Deflection	P	V	Stress	Deflection
	[kN]	[kN]	[MPa]	[mm]	[kN]	[kN]	[MPa]	[mm]
ASTM Analytical Procedure	24.23	48.31	73.00	3.60	21.67	43.19	65.30	3.22
prEN Simplified Method	39.90	79.65	120.00	5.91	36.00	71.85	108.30	5.33
AS Design Criteria	31.68	63.21	95.34	4.69	31.68	63.21	95.34	9.35

Source: Author (2019).

The beams ruptures occurred under oblique bending effect. This effect might be caused by the fact that the machine has a kneecap and any eccentricity is amplified with the movement of the kneecap. During the test, it was possible to notice the gradual increase of the eccentricity.

The result of critical torsional buckling moment obtained on heading 5.2.6 proved that the beams rupture on the laboratory test most likely occurred not only due to the eccentricity of the load caused by the kneecap but also due to lateral buckling effect influence.

The load applied on the beams were, in average, 70.50 kN, which is 19% above the critical calculated load. Therefore, the guideline for determining this effect is in favor of safety.

All the plates broke, and the dust remained glued on the interlayer, except on the points of the load application and on the lower part of the beam, which suffered the higher tensile stresses.

The rupture, as presented in Table 7.10, occurred with a load above the expected value for simple bending effect considering the values from American and Australian standards. Taking in account the European standard, the rupture value was slightly under the expected, with 98% of the predicted load, even under oblique bending effect.

Table 7.10 –Real Beam Rupture Values from Laboratory Tests.

	Load Speed	**Real Rupture Load**	**Real Rupture Deflection**
	[N/s]	**[kN]**	**[mm]**
BEAM 1	120.00	70.41	18.02
BEAM 2	120.00	70.60	17.37

Source: Author (2019).

The rupture stresses and deflections were estimated from the test data and the results are presented in Table 7.11.

Table 7.11 –Estimated Stresses and Deflections from Beams Laboratory Tests Loads.

	Stresses	**Deflection**	ε_u
	[MPa]	**[mm]**	**[‰]**
BEAM 1	105.53	5.23	1.51
BEAM 2	105.82	5.24	1.51

Source: Author (2019).

7.4 WALKWAY MODELING RESULTS

The design of the walkway was made considering the recommended overload of 5 kN/m^2 and slabs supported on four edges with beams between the adjacent panels. Considering these conditions, it was able to conclude the safety of the slab on the walkway.

The results of isolated slabs were compared to the global analysis of this structural element. On the global analysis it presented similar stresses values, however, presented higher deflections due to the deformation of the beams.

It was concluded that the plates support the loads required for a walkway with the imposed conditions and proposed dimensions.

The stresses and deflections on balustrades were within the limits.

The longitudinal beams presented stresses for simple bending moments and deflections within the limits recommended by the International Standards. However, when analyzed for critical lateral torsional buckling moment, it was concluded that the design was not satisfactory. One possible solution would be to add transversal beams each 730 mm.

8 CONCLUSION

Glass is a material that has recently started to be used as a structural element. The advantages of this material are aesthetics and sustainability. Glass is a 100% recyclable material, it allows the passage of sunlight and it is produced in factories, ensuring the reduction of waste in the work sites.

There are several types of glass and the most suitable for structural elements is laminated glass, which is a safety glass. It is composed of glass plates, which can be tempered, to gain more strength, and an adherent material as PVB.

The studied standards present criteria for the design of glasses with structural application. However, they present some limitations and, sometimes, it is necessary to combine the standards to develop a complete design.

Glass is a fragile material and have few specific standards for structural applications, such as for floors. Thus, it is recommended, when possible, to make laboratory tests to analyze its behavior.

The design of a glass slab demonstrated that the ASTM Basic Procedure is the least conservative method and it is limited by the charts geometries and supports conditions. Therefore, it should be used only to make a pre-dimensioning. For the final dimensioning of a glass structural element it is recommended to use the other methods presented, which use engineering mechanics formulas and the Finite Element Method, that leads to more reliable results.

The results of the computational modeling of the walkway demonstrated that glass is a material that presents enough strength for use on walkway floors. It also demonstrated that special attention should be given to the beams due to lateral torsional buckling.

The laboratory tests showed that the loads supported by the material are larger than those foreseen by the standards, demonstrating that the guidelines have been developed in favor of safety, because even without the coefficients of safety, their maximum loads to be applied, are lower than the loads of rupture of the material.

On the tests, the creep effect represented a stress reduction of 14% approximately on the stress. To measure this effect with accuracy, tests with more samples should be performed and with different load duration.

The deflections presented discrepant values between the ASTM Analytical Procedure and prEN Basic Procedure guidelines. This can be explained by the fact that the European and Australian standards reduce the overloads in the SLS calculation. In the laboratory calculations the reductions were not performed because the overload would be applied throughout the test. Even so, the deflections generated were below the value and therefore both guidelines are in favor of safety.

The study of the connections was not subject of this work, but it is an important aspect to be considered. Depending on their arrangement, it can generate local critical stresses.

There are still several details to be studied on structural glass due to the lack of standards on this subject. Some recommendations for future work are the study of other standards such as French and German guidelines; the study of the creep effect for several load durations and with larger numbers of samples and study of connections.

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