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Comparison of various design methods in glass construction (European standards and ASTM E1300-16)

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Kurzfassung

Während die Ausarbeitung des neuen Eurocodes für Glas fortschreitet, sind Standardisierung bzw. die Bemessungsmethoden häufig Themen der aktuellen wissenschaftlichen Publikationen. Bis zu diesem Zeitpunkt ist der Entwurf von Glaskonstruktionen nur durch Normen auf der nationalen Ebene verfügbar. Diese Normen sind in vielen Fällen signifikant unterschiedlich in Bezug auf die vorgeschlagenen Bemessungsansätze. Ein Überblick und Vergleich dieser Dimensionierungsansätze helfen, die oben genannten Publikationen und auch die konstruktionsbezogenen Vorschläge für den kommenden Eurocode, zu verstehen.

Diese Diplomarbeit zielt darauf ab, die in Europa derzeit verwendeten nationalen Standards mit der amerikanischen Norm, die ASTM E1300-16 zu vergleichen. Mit einer relativ langen Geschichte hat der amerikanische Code eine große Bedeutung im Glasdesign und dient als gute Basis für den Vergleich. Die besprochenen europäischen Dokumente werden zum Vergleich wegen ihrer grundlegenden Rolle in der europäischen Industrie und der Entwicklung der harmonisierten Norm ausgewählt.

Die Arbeit wird mit Kapitel 1 vorgestellt, das die Motivation für die Normung und den Umfang der Arbeit weiter veranschaulicht. Es folgt eine kurze Präsentation von zwei innovativen Glasstrukturen in Kapitel 2, um die Potenziale von Glas als primäres Strukturmaterial zu zeigen. Das Kapitel enthält auch einen kurzen Überblick über den aktuellen Stand der Normung. Die zum Vergleich ausgewählten Normen sind im Kapitel 3 dargestellt.

Der Hauptteil der Arbeit, der Vergleich der vorgenannten Entwurfsunterlagen, wird in den Kapiteln 4, 5 und 6 erarbeitet. Kapitel 4 erörtert die wichtigsten Merkmale der Normen und gibt einen kurzen Überblick über den grundlegenden wissenschaftlichen Hintergrund. Die Dokumente werden anhand ihres Anwendungsbereiches, des Sicherheitskonzepts und des allgemeinen Verifikationsverfahrens verglichen; sowie anhand ihrer Methode zur Handhabung von Lastdauer, Verbundglas und Isolierglas. Im Kapitel 5 werden spezielle Themen diskutiert, wie Stabilitätsverlust von Glaselementen und Design in seismischen Bereichen. Da dieser Bereich noch standardisiert werden soll, kann ein Vergleich zwischen den amerikanischen und europäischen Dokumenten nicht gezogen werden; dieses Kapitel stellt daher nur einen Ausblick auf die Designmethoden für den kommenden Eurocode dar. Im Kapitel 6 werden einige der verschiedenen Bemessungsansätze anhand einfacher Berechnungen dargestellt. Das erste Beispiel zeigt die verschiedenen Methoden zur Dimensionierung von Verbundglas; es folgt die Präsentation der verschiedenen Ansätze für das Design von Isolierglas. Das Kapitel wird mit vier kurzen Beispielen abgeschlossen, um die Methoden für Stabilitätsnachweis vorzustellen, die voraussichtlich in den neuen Eurocode aufgenommen werden.

Schließlich fasst Kapitel 7 die Schlussfolgerungen der Arbeit zusammen und gibt einen Ausblick auf die zukünftige Standardisierung im Bereich Glasbau.

Abstract

As the development of the new Eurocode for glass design progresses, standardization and verification methods are frequent subjects of the recent scientific publications. Up to this date, only national standards are available in the field of structural glass; in many cases significantly differing in regard to the proposed design approaches. An overview and comparison of these dimensioning approaches help to understand the above-mentioned publications, as well as the design related proposals for the upcoming Eurocode.

This thesis intends to presents a comparison of the national design standards currently used in Europe, with the American glass standard, the ASTM E1300-16. Having a relatively long history, the American code has a significant importance in glass design and serves as an adequate basis for comparison. The discussed European documents are selected for comparison based on their fundamental role in the European industry and the development of the harmonized standard.

The thesis is introduced with chapter 1, which further illustrates the motivation for standardization and the scope of the work. It is followed by a brief presentation of two innovative glass structures in chapter 2, aiming to show the potentials of glass as a primary structural material. The chapter includes a brief overview of the present state of standardization as well. The design documents chosen for comparison are presented in chapter 3.

The main part of the thesis, the comparison of the before-mentioned design documents, is elaborated in chapters 4, 5 and 6. Chapter 4 discusses the main characteristics of the standards, providing a brief overview of the basic scientific background as well. The documents are compared based on their scope of application, safety concept, and general verification procedure; as well as based on their method for handling load duration, laminated glass and insulating units. Chapter 5 discusses special design issues, such as stability failure modes of glass members and design in seismic areas. As this field is still to be standardized, a comparison between the American and European documents cannot be drawn; this chapter represents only an outlook on the design methods for the upcoming Eurocode. Chapter 6 further illustrates some of the different design approaches by means of exemplary calculations. The first example shows the different methods for dimensioning laminated glass; it is followed by the presentation of the different approaches for the design of insulating units. The chapter is concluded with four short examples, aiming to present the verification methods for stability failure modes, expected to be included in the new Eurocode standard.

Finally, chapter 7 summarizes the conclusions of the thesis and gives an outlook on the future standardization in the field of glass design.

Contents

List of symbols and abbreviations

$(.)_{d}$	Design value of (.);
$(.)_{k}$	Characteristic value of (.);
d	Thickness of glass ply;
$f_{(.)}$	Material strength;
g_{k}	Characteristic value of self-weight;
h	Thickness of glass ply;
$h_{ef,w}$	Deflection effective thickness;
$h_{ef,\sigma}$	Stress effective thickness;
h_{int}	Thickness of interlayer;
k_{mod}	Load duration factor;
k_{σ}	Stability coefficient for buckling of plates under compression load;
k_{τ}	Stability coefficient for buckling of plates under shear load;
l	Relevant span of a single-span element;
q_{k}	Characteristic value of live load;
s_{k}	Characteristic value of snow load;
t	Time;
$w_{(.)}$	Deflection;
w_{k}	Characteristic value of wind load;
$A_{(.)}$	Generic area;
D	Bending stiffness of plates;
E	Young’s modulus of elasticity;
G	Shear modulus of glass;
G_{int}	Shear modulus of interlayer;
$I_{(.)}$	Moment of inertia;
$M_{b.Rd}$	Critical buckling moment of beam (lateral-torsional stability);
M_{cr}	Critical Euler moment for lateral-torsional stability;
$N_{b.Rd}$	Resistant design load for compressed Euler beam;
N_{cr}	Critical load for Euler beam;
$V_{b.Rd}$	Critical resisting shear stress in stability of panels;
V_{cr}	Critical Euler shear stress of a panel;
$W_{(.)}$	Elastic resistant modulus of cross section;
AN	Annealed glass;
FT	Fully tempered glass;
GTF	Glass type factor;
HS	Heat-strengthened glass;
LR	Load resistance;
LSF	Load share factor;
NFL	Non-factored load;

$\alpha_{(.)}$	Factor for stability analysis;
$\gamma_{(.)}$	Partial safety factor;
γ_{global}	Global safety factor;
η	Generic shear transfer coefficient – Italian Recommendations;
σ_{allow}	Permissible stress;
σ_{max}	Maximum principal stress;
$\tau_{(.)}$	Shear stress, shear strength;
$\psi_{(.)}$	Combination factor;
ω	Shear transfer coefficient – European standards;

Φ	Parameter for buckling verifications;
χ	Reduction factor for stability analysis;
Γ	Shear transfer coefficient – American Standard;
$\bar{\lambda}$	Normalized slenderness.

1. Introduction and scope of the work

Over the last few decades, developments in the production and construction technology have enabled a great expansion in the application range of architectural glass. The progress is astonishing: from a simple glass pane covering a wall opening to glazing elements carrying wind, snow and traffic loads, functioning as anti-fall guards or even as primary structural elements of self-supporting facades. The new, structural applications raise the question of the general reliability of the constructions, design methods and standardization.

To satisfy the need for structural verification and a guaranteed level of safety, design documents have been developed. Starting with simple technical recommendations, tables and handbooks, nowadays a wide range of standards support engineers during the design of glass constructions. Despite the rapid development in this field and the large amount of research data, the standards discussing the structural use of glass are still incomplete.

The scope of the thesis is to compare the design methods of the most commonly used standards in Europe with the American code, the ASTM E1300-16 [2]. The discussion is restricted to the design documents in the field of structural glass; product and execution standards will not be discussed.

In the first part of this work, in chapter 2 and 3, two recently built glass constructions are presented, illustrating the potentials of architectural glass and serving as motivation for further discussions. It is followed by a brief overview of the present state of standardization, as well as a presentation of the design documents, which are later discussed in the thesis.

Chapter 4 presents the basic design related issues discussed by most documents, followed by the comparison of the standardized verification methods. This part discusses the scopes of application, the general verification procedures, the proposed methods for handling the problem of load duration, as well as the design of laminated and insulating glass. Applications, which are not yet included in the standards, are presented in chapter 5. The chapter discusses the structural use of glass, referred to as special design: including the verification of stability failure, and a brief overview of the design in seismic areas.

To make the differences easier to grasp, chapter 6 presents some simple, exemplary calculations. The examples cover the design methods of laminated and insulating glass, as well as the verification procedures for stability failure modes.

At last, chapter 7 summarizes the results of the thesis, and gives an outlook on the upcoming developments in the field of glass standardization.

2. Structural glass and the current state of the standardization

2.1 Motivation

Glass, being a transparent material, has a wide variety of applications in modern architecture. Elements, which in the past had only in-fill or decorative purpose, are nowadays used as facade, roof or floor panels, railings and structural members, such as glass fins or walls. There is an increasing need for more complex glass structures, either to create architectural landmarks, expand the boundaries of engineering, or to simply design more economical buildings by using multifunctional elements.

With increasing functionality comes the need for a reliable load bearing capacity as well as a confirmable level of safety, which leads to the development of design standards. As glass can be used as self-supporting structures or even as primary structural members, the elements must undergo similar design procedures as other materials used in construction works. Taking into account some additional aspects related to the brittle behaviour of the material, with standardized design methods the same reliability can be achieved, as for structures built of traditional materials like steel or concrete [3].

The development of design approaches and scientific research, in general, are motivated by construction projects, which challenge the state of the art and exceed the actual engineering know-how. In the following, two building projects are briefly presented, as motivation for the future standardisation of the structural use of glass.

Apple Store – 5th Avenue, New York

Apple, besides delivering many influential products in the field of information technology, is famous for its architecturally ingenious store buildings. To demonstrate the company's commitment to innovation, in 2011 Apple has opened its second retail store in New York, presenting a highlight in terms of glass technology and architecture. After years of research and development, the second cube, being even more transparent, minimalistic and innovative than the first one, is acknowledged worldwide as an iconic glass construction [51].

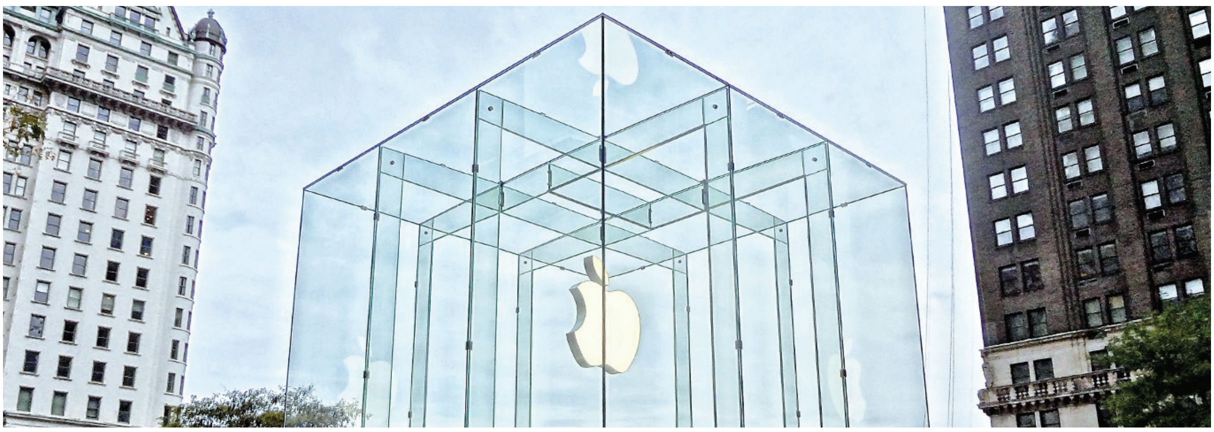


Fig. 2.1: Glass cube of the Apple Store – 5th Avenue, New York [51]

Since the completion of the first cube in 2006, the German company responsible for the general design of the project - Seele - has redefined the boundaries of the technically feasible structural glazing. In order to make the glass enclosure as transparent as possible, the walls of the cube are now realized with only three glass elements each, using five-ply laminated safety glass panes with the astonishing dimensions of 10.30m x 3.30m. The panes are connected to the vertical fins with titanium fittings laminated into the panes, making the connection barely visible [51].

Under the cube, a self-supporting spiral staircase made entirely of glass provides access to the actual store area, the underground main level. The glass cylinder in the middle functions as the shaft of the elevator situated in it, and also as load bearing element for the entire staircase. The treads of the staircase are on the inner side connected to the glass cylinder, on the other side to the outer stringer. The stringer elements are supported by cantilever glass fins.

Fig. 2.2: Glass staircase in the Apple Store – 5^{th} Avenue, New York [50]

The staircase, in addition to the obvious structural function, had to fulfil two special requirements: firstly, the elevator inside the glass cylinder causes a dynamic loading on the whole structure; secondly, as the area is located in an earthquake zone, the structure had to be verified for seismic loads as well [51].

Etihad Museum, Dubai

The Etihad Museum is a museum complex in Dubai, built for the 45th anniversary of the founding of the United Arab Emirates. The credit for the engineering design and the execution should be given to the Austrian company Waagner-Biro, who realised the project in an extremely short period of time: from design to complete handover in barely more than a year [58]. The most spectacular part of the complex is the so-called pavilion building; its glass fin facade is the first in the world ever to be built in this size and load bearing system.

Fig. 2.3: Pavilion Building, Etihad Museum, Dubai [58]

The glass fin facade of the pavilion covers three sides of the building, the most complex part of which is the facade on the main entrance elevation. This part consists of 26 fins, each composed of a 4 ply laminate with 600 mm width and up to 12,8 m length. The facade is without any structural steel, the load transfer takes place directly between the glass elements. The main structure of the building, including the 21 steel columns carrying the roof, is inclined at 21 degrees to the vertical; the layout of the fin facade follows this pattern.

As a consequence, the sideways tilted glass panes transfer a horizontal load to the neighbouring panes. In addition to that, the weight of the upper elements is carried by the lower ones. It all results in a significant compression in the panes, the value of which increases towards the direction of the tilt. As the corner is also designed without any steel connection, the last glass in the row has to withstand the entire horizontal load resulting from the inclination. The manufacturing of this unit with over 5,0 m x 2,0 m dimensions and 86 mm thickness, shows great engineering know-how [58].

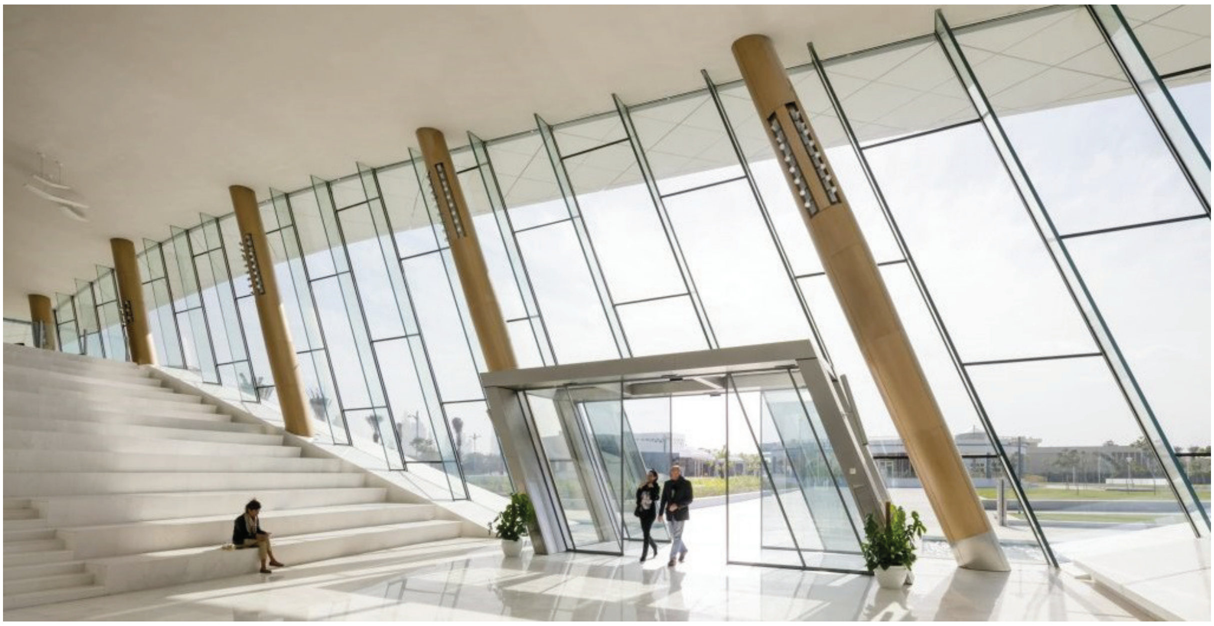


Fig. 2.4: The atrium of the Pavilion Building, Etihad Museum, Dubai [52]

An additional interesting consequence of this load bearing system is the complexity of glass exchange. In case of glass failure, the elements have enough post-breakage capacity to transfer compression forces, maintaining the overall integrity of the structure. If however, a glass is removed, the necessity of a temporary support structure has to be examined. Depending on the location of the broken glass, the removal of a pane would leave the upper elements without vertical support; in addition, due to the lack of horizontal support, the fins would be subjected to torsion [58].

2.2 Present state of standardization

Although both the need for a uniform level of safety and the scientific knowledge of the structural behaviour are present, a harmonized standard for structural glass is yet to be developed. The today existing codes are national standards, naturally different in regard to safety level, which creates a difficulty when it comes to the free trading of glazing elements. Furthermore, despite the large amount of research data prepared in the last decades, the scope of these existing national codes is mostly limited to the secondary applications of glass, barely discussing primary structural functions.

Concerning the standardization on the European level, the Technical Committee of CEN (European Committee for Standardization), the TC250 is currently engaged in the development of design rules for glass. In order to provide a harmonized level of safety, ensuring free trading of prefabricated structural glass elements in Europe, as well as to provide design techniques representing the latest research, the European Commission has established a stepwise plan for developing a harmonized design standard for the structural use of glass [27].

To carry out the development procedure of the European Standard, a Working Group has been established as part of the Technical Committee. The first document to be published was the PrEN 13474 draft standard [13], followed by the second issue in 2013, the PrEN 16612 [14]; both aiming to provide a basis for discussion with engineers and the industry. The drafts proposed methods for the design of glass structures; the structural application is, however, not covered. The documents were followed by the Scientific and Policy Report [27] in 2014, presenting scientific background for the design of glass and providing an overview of the verification methods used in the relevant national codes and regulations. The Report includes proposals for the future European Standard as well.

Concerning the ASTM E1300 series, its current state of development is similar to the European documents. The standard applications of glass are relatively well covered by the code; however, regulations concerning structural glass are not included. The publishing organization, the American Society for Testing and Materials, has plans to further develop the document, but the structural applications are planned to be included in an other code, elaborated under the title "New Guide for Structural Use of Glass in Buildings" [45].

At present, the verification of structural reliability is carried out based on national standards and regulations. As to which documents are used for the design, is usually project-specific. The most relevant national standards in the field of glass design are briefly presented in the next chapter.

3. Relevant standards in the field of structural glass dimensioning

This chapter gives a general overview of the standards discussed in this thesis, briefly presenting their origin and contents. The design documents, which are chosen to be compared with the American ASTM E1300-16 [2], are The German Technical Regulations [16] [17] [19], the German DIN 18008 standard [5], the Austrian ÖNORM B 3716 standard [12], the European draft designated as PrEN 16612 [14], and the Italian Technical Recommendations [3].

The German standard, being the most influential document in the European standardization, is evidently selected for comparison. As it was developed mostly based on the German Technical Regulations, these documents, although rather briefly, are also presented. The Austrian national standard is chosen since this thesis is written with the support of the Austrian University TU Wien. The last two documents, the draft standard PrEN 16612 and the Italian Technical Recommendations are chosen because of their significance in glass design: the first represents a draft for the harmonized European Standard currently being developed; the second covers special topics, which are not discussed in other design standards.

3.1 The German Technical Regulations[1]

The German Technical Regulations [16] [17] [19] can be considered as the preceding documents for the today used DIN 18008 standard [5]. They were published by the Centre of Competence for Construction in Germany (Deutsches Institut für Bautechnik – DIBt) and served as a basis of glass design for many years in Europe. Altogether three documents were published, which were to cover the design of glazing elements with linear and point-wise supports, as well as glass parapets. Although the documents have already been replaced by the new DIN standard, they are still often referenced and used as a basis of design.

The regulations were often referred to by the acronym TRXV, indicating the titles of the different parts; this designation will be used in the following part of this thesis, in case it is referred to generally all three documents.

Technical Regulations for the Use of Glazing with Linear Supports [19] –
„*Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen*“

> The document was first published in 1998, after DIBt has merged two of its preceding regulations for vertical [20] and overhead [18] glazings. The TRLV applied for glazing elements with continuous, linear supports along at least two opposite edges. It proposed glass types and compositions, which could be used depending on glass size and location. Regarding loads TRLV referred to DIN 1055 [4]; in addition, it defined the climatic load for insulation glazing. The document included recommendations

[1]It should be noted, that the English titles of the Technical Regulations used in this thesis are not the official designations, as these documents are only available in German.

concerning structural analysis, as well as values of permissible stresses and a method for the calculation of insulation glass elements [19].

Technical Regulations for Anti-fall Glazing [17] –
„Technische Regeln für die Verwendung von absturzsichernden Verglasungen"

Published in 2003, the TRAV discussed the design of various glass elements functioning as an anti-fall barrier (e.g. vertical glazing with an additional function, balustrades, glass parapets). The document classified these glazing elements in three categories, defined their service conditions and proposed design loads, as well as a method for the calculation structural capacity [17].

Technical Regulations for Point-wise Supported Glazing [16] –
„Technische Regeln für die Bemessung und die Ausführung punktförmig gelagerter Verglasungen"

The TRPV, published in 2006, covered the design of point-wise supported vertical and overhead glazings. Its scope was limited, however, by the dimensions of the glass elements to a maximum of 2500 x 3000 mm, as well as by their relative altitude above ground to 20 m. The document discussed the layout and the applicable types of point-wise supports; as well as the composition of the laminate in case of laminated glass [16].

3.2 The German Standard - DIN 18008

The DIN 18008 [5], one of the most often referenced documents in the field of structural glass, is published by the German Institute for Standardization (DIN – Deutsches Institut für Normung). The Institute is a national organization in Germany, aiming to develop national standards in cooperation with representatives from the industry, research groups and public authorities; as well as to contribute to the European and international standardization [53].

In Germany, the technical rules, which have been introduced by the Supreme Building Authorities through official publication, are to be followed in each federal state. It is the responsibility of DIBt, that these technical rules for construction products and types of constructions are compiled and published to the federal states. On behalf of the federal states, DIBt also publishes the Model List of Technical Building Rules ("Liste der Technischen Baubestimmungen"), which contains technical rules for the design and building of construction works and their parts. In 2014 the DIN 18008 parts 1 to 5 were added to the MLTB. Consequently, the Technical Regulations (TRXV) and the standard DIN 18516-4 were removed from MLTB [53].

The standard provides design and construction rules for glazed structures, as well as specifications of experiments required for determining the suitability of glazing elements for their intended purpose. The “DIN 18008: Glass in Building – Design and construction rules” consists of the following parts [47]:

Part 1: Terms and general bases, 2010-12
Part 2: Linearly supported glazings, 2011-04
Part 3: Point fixed glazings, 2013-07
Part 4: Additional requirements for fall-secured glazings, 2013-07
Part 5: Additional requirements for walkable glazings, 2013-07
Part 6: Additional requirements for glazings accessible for cleaning and maintenance measures, 2015-02 (draft)
Part 7: Special structures (withdrawn)

3.3 The Austrian Standard - ÖNORM B 3716

The ÖNORM B 3716 [12] is a national standard, published by Austrian Standards. Austrian Standards is a non-profit service organization, founded in 1920. It started its activity in the field of standardization in 1921 by publishing the first ÖNORM standard, governing metric threads. Austrian Standards is a member of the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) [46].

The standard “ÖNORM B 3716: Glass in building – Structural glass construction”, regarding its composition and contents, resembles the German DIN standard. It consists of the following parts[2] [46]:

Part 1: Basic principles, 2016-06
Part 2: Linear glazings, 2013-04
Part 3: Vertical glazings with protective function against fall, 2015-01
Part 4: Accessible, walkable and trafficable glazings, 2009-11
Part 5: Point fixed glazing and special structures, 2013-04
Part 7: Applications for glass, 2014-09

3.4 The European Draft Standard - PrEN 16612

As an addition to the existing Eurocodes, a design standard for glass structures is currently in development by the CEN/TC 250 (Technical Committee 250 in the Committee for European Standardization) and is planned to be designated as Eurocode 11. The new Eurocode is prepared and published in several steps [36]:

- Development of a technical report
- Development of a technical specification
- Development of a draft standard
- Development of the harmonised standard

[2] Part 6, which was intended to discuss the design of structural sealant glazings, is cancelled and thus omitted from this list.

Of the steps listed above, the first has already been finished: a technical report was published in 2014 under the title Guidance for European Structural Design of Glass Components [27]. The Report reviews, among others, the most important aspects of glass design, presenting the scientific background and the design approaches proposed in the currently available standards as well. The document also proposes design methods, which shall be included in the Eurocode 11.

Parallel to the development of the Report, two draft standards are prepared, the latest of which was published in 2017. After the release of the draft standard PrEN 13474 in 2009, as it needed considerable revision, the new draft was published with the designation PrEN 16612. Both drafts have been drawn up by the Technical Committee CEN/TC 129. The purpose of these documents is to provide a base for discussion with the industry and designers. Being only draft documents, they cannot be referred to as European standards; they are only distributed for review and will be a subject of later revision. The PrEN 16612 fits in the normative background laid down in the governing document, which is in this case the standard EN 1990: Basis of structural design [7].

3.5 The Italian Technical Recommendations - CNR DT-210

The CNR DT-210 [3] is published by the National Research Council of Italy, with the title “Guide for the Design, Construction and Control of Buildings with Structural Glass Elements”. The National Research Council (CNR – Consiglio Nazionale delle Ricerche) is the largest public research institution in Italy, its mission is to inspire and coordinate research activities in the different areas of science since 1924 [54].

The purpose of the document is to give technical recommendations for engineers regarding various problems in the field of glass design. Compared to other European standards, it is relatively self-contained, discussing most of the essential glass related subjects: mechanical properties, design principles, actions, verification methods, as well as testing procedures. The document is in accordance with semi-probabilistic limit state method of the EN 1990 [7]; however, it is not a legally binding standard. In the rest of this thesis, the Italian Technical Recommendations - CNR-DT 210, for the sake of simplicity, will be referred to as the “Italian Recommendations”.

3.6 The American Standard - ASTM E1300-16

The ASTM E1300-16 [2] is a code commonly used in the United States as well as in parts of Canada. It is globally recognized as an influential standard in the field of structural glass design and often referenced in the corresponding literature and regulations. The document itself is published and updated by the ASTM International (American Society for Testing and Materials), an association founded in 1898 by Charles B. Dudley [44].

The first version of the standard was released in 1989. This issue discussed only annealed monolithic glass panes with a rectangular shape, simply supported on all four edges, bearing a lateral load with a duration of 60 seconds [21]. After years of development and numerous revisions, the latest version of the standard covers many of the glazing types offered today: monolithic, annealed, fully tempered, heat-strengthened, laminated and insulating glass panes, with various support conditions and load duration.

The standard stems from the dimensioning charts of the 1960's, which were based on empirical data and covered only annealed glass panes. These charts showed the maximum load capability in relation to the area of the glass for each conventional thickness, with the probability of breakage of eight lites per 1000. In order to fulfil the needs of the industry and cover new glass products, further charts were developed and introduced, among others by PPG Industries Inc. The most significant research was presented by Beason in his work "Glass failure prediction model" [22], where based on the statistical prediction method of Weibull [41] a new design method was developed. The ASTM E1300-89 and the later versions are based on this research [28].

4. Comparison of standards

This chapter presents a comparison of the design documents mentioned above. Several aspects are discussed, including safety concept, general verification procedure, handling the topic of load duration, as well as the design of laminated and insulating units. The topic of special design is discussed separately in chapter 5, as no reasonable comparison can be made between the American and European standards in this regard. To further explain certain differences of the design approaches, a reference is made here to the exemplary calculations in chapter 6.

4.1 Scope of application

Although the scope of the latest design standards has been significantly developed in the recent years, there are still numerous technical solutions, for which design methods are yet to be standardized. The reason for it is not the lack of scientific research, but rather the duration of the standardisation process, which incorporates the results of these works into the codes. The topics covered by the discussed design standards are briefly summarized in Table 4.1. A more detailed description of the scopes follows below.

Table 4.1: Scopes of the discussed design standards

	TRXV	DIN 18008	ÖNORM B 3716	PrEN 16612	CNR-DT 210	ASTM E1300-16
Linearly supported glass plates	✓	✓	✓	✓	✓	✓
Point-wise supported glass plates	✓	✓	✓	✓	✓	
Glass parapets	✓	✓	✓	✓	✓	
Glass floors with maintenance load		✓	✓	✓	✓	
Glass floors with traffic load		✓	✓	✓	✓	
Special design					✓	

4.1.1 European standards

The German Standard, DIN 18008 is composed of 7 parts, as already mentioned in section 3.2. These discuss linearly supported and point fixed glass elements, as well as fall-barriers and walkable glazings. Generally, the standard is not applicable to individual panes of nominal glass thicknesses of less than 3 mm and greater than 19 mm. The scope is further limited by the following conditions:

- linearly supported elements have to be flat, mechanically fixed and supported at least along two opposite edges,
- point-wise supported elements can be fixed exclusively by mechanical fasteners, the holes in the glass must go through its whole thickness,
- barrier glazings must be vertical or inclined with a max. angle of 10 degrees towards the secured side,
- walkable glazing can only be subjected to a regular traffic load of 5 kN/m^2, whereas the section covering walkable elements does not apply to glazings with vehicle loads.

Two parts, the 6th and the 7th are yet to be finalized and published; Part 6 will provide additional requirements for walkable glazing used for maintenance works, Part 7 is planned to cover special structures.

The composition of Austrian Standard ÖNORM B 3716 [12] follows the one defined in the DIN standard, and thus its scope is also similar to the German code. ÖNORM B 3716 covers the design of glazing elements supported along the edges, elements used for fall-through barriers, point-wise supported facades and glass floors. Regarding the latter, the standard distinguishes between floors which are only accessible during maintenance, ones which are used regularly as public walking areas, and floors fit for traffic loads. The standard does not cover curved glazing; however, it is applicable to glass elements used as a fire barrier. The part discussing the point-wise supported glass can be applied to elements, which are also used as stiffeners or bracings [12].

The European Draft Standard does not define its scope explicitly. Given, that the PrEN 16612 is only a draft, its scope cannot be considered as finalized. For the sake of completeness, it should be mentioned that the draft briefly discusses linearly and point-wise supported flat glazing elements and fall-barriers, as well as laminated and insulating units. It also gives recommendations for the testing of glass elements.

The scope of the Italian Recommendations, given the novelty of the document, is not presented in detail here. It is however clear, that of all the discussed standards the CNR-DT 210 has the widest applicability, as it covers not only the regular glazing elements, but also gives recommendations for glass parts used as primary structures.

4.1.2 American Standard

The first issue of the American standard, the ASTM E 1300-89 only covered rectangular, monolithic glass elements supported linearly on all four edges, with thickness between 2.5 and 25 mm, subjected to a lateral load with a duration of 60 seconds [28]. Since then, the code has undergone a major development and its scope has been significantly expanded. The ASTM E1300-16 describes procedures to determine the load resistance of not only monolithic, but also of laminated and insulation glass elements. It applies to vertical and sloped glazing in buildings, supported along from one to four edges, subjected to lateral loads (wind, snow and self-weight) not exceeding 15 kPa. The standard specifies a method for handling different load durations as well, however, balustrades, floor panels and primary structural members are not covered [2].

4.2 Safety concept

The main purpose of standardisation is among others to harmonize the safety level of civil engineering structures. During the history of standardisation several safety concepts were developed, all aiming to limit the risk of structural failure and at the same time to provide a method for economic design. These verification procedures are based on probability models, defining some of the engineering input, such as load intensity or material resistance, as probabilistic variables. As to which extent is the variation of these values is considered, depends on the consequences of the eventual failure of the structure, and the complexity of the probabilistic method. In the field of glass design, two of these concepts are used in the discussed standards: the one based on permissible stresses and the limit state design method [26].

4.2.1 Permissible stresses

The method of permissible stresses, or as it is usually referred to in the US, allowable stress method[3], is based on the comparison of the so-called existing stresses with the allowable stresses. Concerning the design documents discussed in this thesis, only the American ASTM E1300 and the German Technical Regulations are based on this method. However, while the American Standard continues to exist on this basis, the latter was superseded by the German DIN 18008 [5], which is based on the limit state design method.

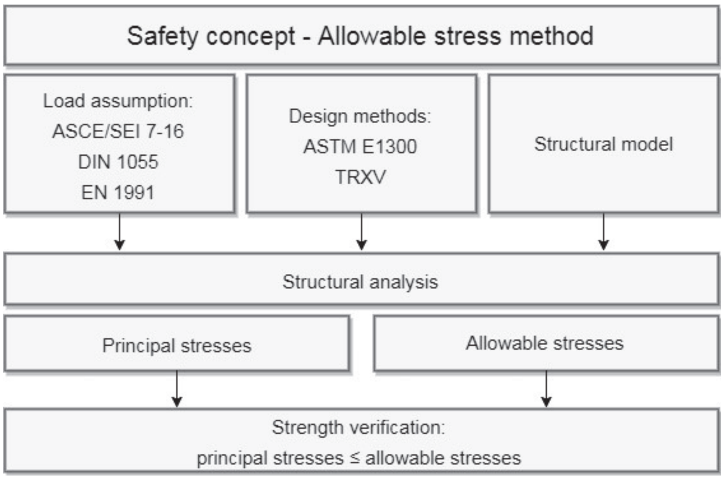


Fig. 4.1: General procedure for strength verification, based on the allowable stress method (Self-made fig. based on [40])

Fig. 4.1 shows the general procedure of the strength verification based on this method. The existing stresses are derived from the characteristic values of the loads, which are usually assumed using the American ASCE/SEI 7 Standard [1], the German DIN 1055 [4] or the

[3] The expression „permissible stress” is mostly used in European literature. Since in the case of this thesis the American Standard ASTM E1300 is more relevant, in the following the expression „allowable stress” will be used.

Eurocode 1 [8]. The allowable stresses result from the material strength divided by a global safety factor, which represents the probabilistic variation of all the design values. It is to be noted that the global safety factor has different values depending glass type. The deformations, deflections of the glazing elements are calculated with the load combination used for the stress analysis [40].

The verification scheme is presented with the following formula [40]:

$$\sigma_{\mathrm{max}} = \sigma_{\mathrm{max}}\left(g_{\mathrm{k}} \pm s_{\mathrm{k}} \pm w_{\mathrm{k}} \pm \sum q_{\mathrm{k}}\right) \leq \frac{\sigma_{\mathrm{breakage}}}{\gamma_{\mathrm{global}}} = \sigma_{\mathrm{allow}}$$

where σ_{max} stands for the maximal principal stress, derived from the combination of the characteristic values of dead loads, snow, wind and any other loads acting on the structure (g_{k}, s_{k}, w_k and q_{k} respectively). In most cases, given the brittle behaviour of glass, the principal tensile stresses have to be verified.

4.2.2 Limit state design method

The limit state design method is based on the research of Prof. N.S. Streletski and was first introduced in the USSR Building Regulations in 1955 [25]. In Europe, it was first incorporated by the German standard for structural steelwork design, the DIN 18800-1 [6]. The European design standards currently used in construction engineering are based on this method.

The method is based on the verification of so-called limit states, each representing a mode of failure of the structure. Failure in this aspect does not necessarily mean collapse, but exceeding a limit, beyond which the structure cannot fulfil its function. Such limit states are the so-called Ultimate Limit State (ULS) and Serviceability Limit State (SLS). The first covers design situations endangering human or structural safety, the latter sums up situations compromising the comfort of the people inside, or the normal functioning and appearance of the structure.

Table 4.2: ULS and SLS according to EN 1990 [7]

Ultimate Limit States:	Serviceability Limit States
EQU – Equilibrium: Loss of static equilibrium as a rigid body **STR** – Structural: Internal failure or excessive deformation of the structure **GEO** – Geotechnical: Failure or excessive deformation of the ground **FAT** – Fatigue: Fatigue failure of the structure **UPL** – Uplift: Loss of equilibrium resulting of water pressure or other or other vertical action **HYD** – Hydraulic Heave: internal erosion and piping of ground caused by hydraulic gradients	Limitation of: ▪ Deformations ▪ Vibrations ▪ Stresses ▪ Damage effecting appearance, durability or function of the structure

According to EN 1990, “it shall be verified that no limit state is exceeded when relevant design values for actions, material properties, or product properties, and geometrical data are used...” [7]. The relevant design values are calculated using safety factors, which represent the uncertainties of the different design variables. These factors are divided and assigned to both the load and the resistance side.

This safety concept is incorporated in the latest civil engineering design standards. The national standards for glass design, such as the German and Austrian Standards and the Italian Recommendations refer to the EN 1990 as a basis, and use the method of the limit states.

The general formula for strength verification of an element in the ultimate limit state, with the notation used in DIN 1055 and EN 1990, is the following [40]:

$$\sigma_{\mathrm{max,d}} = \sigma_{\mathrm{max}}\left(\gamma_{\mathrm{G}} g_{\mathrm{k}} \pm \gamma_{\mathrm{Q,1}} q_{\mathrm{k,1}} \pm \sum \gamma_{\mathrm{Q,i}} \psi_{\mathrm{0,i}} q_{\mathrm{k,i}}\right) \quad \leq \quad \frac{f_{\mathrm{k}}}{\gamma_{\mathrm{M}}} = f_{\mathrm{d}}\,,$$

whereas the left side represents the stresses estimated from the most relevant load combination. The right side shows the resistance, which, in glass design, usually includes several factors depending on material characteristics, glass type or load duration.

In the case of the serviceability limit state, the partial factors are set to 1,0. For example, the verification of deflections is based on the following formula [40]:

$$w_{\mathrm{max,d}} = w_{\mathrm{max}}\left(g_{\mathrm{k}} \pm q_{\mathrm{k,1}} \pm \sum \psi_{\mathrm{0,i}} q_{\mathrm{k,i}}\right) \quad \leq \quad C_{\mathrm{d}}\,.$$

In comparison, a clear advantage of the permissible stress method is its simplicity; the idea of the global safety factor is easy to grasp. The disadvantage, however, stems also from the same characteristic: the variation of the design values is taken into consideration simplified on the resistance side. This straightforward approach can lead to less economical results than more detailed design methods. Additionally, if the designed construction includes materials, which are to be verified according to the limit state method, designing glass elements based on the permissible stress approach requires additional calculations [40].

Opposed to that, the limit state method considers the variation of design values exactly where they arise, providing a more economical approach. A design standard for glass based on this method also helps to avoid unnecessary calculations and conversions of load combinations.

4.3 General verification procedure

The general verification procedure is different in the American and European standards. All of them propose an analytical method, which is based on the comparison of the estimated principal stresses with the normative material strength. However, the main concept in the American ASTM code is considerably different from the verification method used in the European standards. The following sections briefly present the different approaches.

4.3.1 European standards

According to the approach of the discussed European standards, the strength of glass structures is verified on the level of stresses. Consequently, the calculation of the principal stresses is necessary for the structural verification. For glass, this has to be carried out using a linear-elastic material model; for interlayers, a material model taking into consideration the temperature and load duration. It is not specified in the standards, how the stresses should be estimated; only that it has to be carried out with a sufficient accuracy, considering local stress concentrations. The geometric nonlinearity (e.g. membrane effect of glass plates) has to be taken into consideration depending on its favourability.

The structural analysis is carried out considering the above mentioned, assuming all the actions, which may act during the lifespan of the structure. The estimated stresses are compared with the design strength of the material. This value is derived from characteristic strength values given in the standard, considering several modification factors as well as the partial safety factor of the material, glass type and load duration respectively.

The structural calculation in most cases, according to this approach, requires the support of a FE-software.

4.3.2 American standard

The primary verification procedure of the ASTM code is the glass charts method. The charts define the value of the “non-factored load” (NFL) for conventional glazing products, based on empirical data. The non-factored load is defined as the “three second duration uniform load associated with the probability of breakage less than or equal to 8 lites per 1000 for monolithic AN glass“ [2]. Fig. 4.2 shows the general procedure of the verification with glass charts.

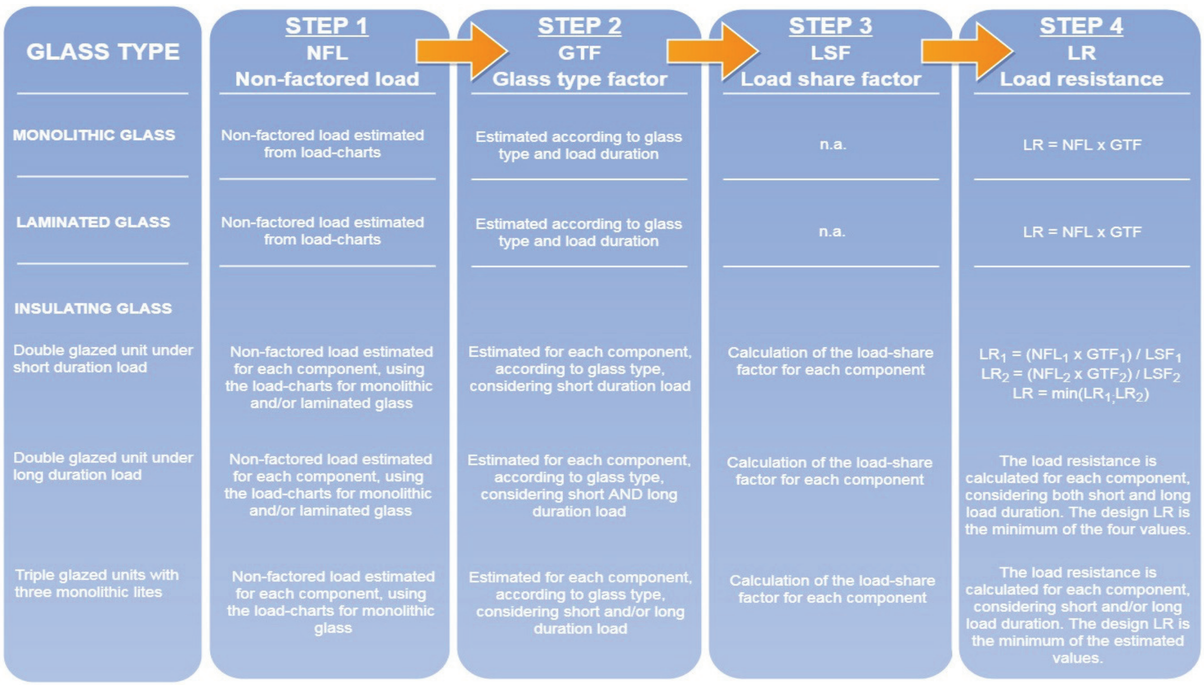


Fig. 4.2: Flow chart of the verification procedure with glass charts (Self-made fig. based on [2])

The value given by the charts is modified according to the glass type and the duration of the load. The final result of the calculation is the load resistance (LR), which is defined as "the uniform lateral load which the glass construction can sustain based upon a given probability of breakage and load duration" [2]. The value is estimated as the non-factored load modified with the glass type factor, and in the case of insulation units, modified with the so-called load-share factor (LSF).

The method is presented with the following simple example: Fig. 4.3 shows the non-factored load (NFL) of a 10 mm thick, monolithic, annealed glass lite with outer dimensions of 4000 x 2000 mm, under short duration load. According to the chart given in the standard, the NFL is estimated to be approximately 1,15 kN/m^2. The glass type factor (GTF), considering the heat-strengthening and the short load duration, is defined as 2.0, given in Table 1. [2]. The load resistance (LR) is then estimated as follows:

$$LR = NLF \cdot GTF = 1.15\ \frac{\mathrm{kN}}{\mathrm{m}^2} \cdot 2.0 = \ 2{,}30\ \frac{\mathrm{kN}}{\mathrm{m}^2}$$

The deflection in the glass centre, corresponding to the 2,30 kN/m^2 load, is shown in Fig. 4.4. In the chart, the AR curves designate the side length ratio of the element, in this case 2,0; the horizontal axis defines the sum of the acting load multiplied by the glass surface area:

$$2{,}30\ \frac{\mathrm{kN}}{\mathrm{m}^2} \cdot\ (2\ \mathrm{m} \cdot 4\ \mathrm{m})^2 = 147{,}2\ \mathrm{kNm}^2.$$

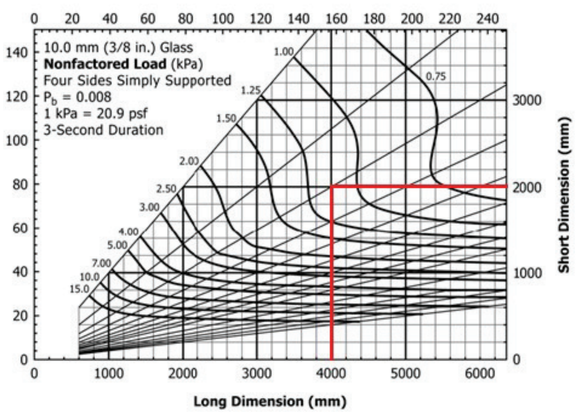


Fig. 4.3: NFL chart for a 10 mm thick monolithic glass lite [2]

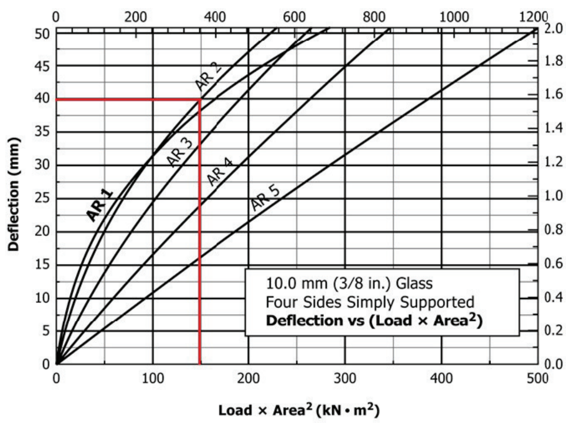


Fig. 4.4: Deflection chart for a 10 mm thick monolithic glass lite [2]

The American Standard also proposes an alternative procedure for the verification of glass strength. The purpose of the method proposed in the Appendix X6 of the code is to provide a conservative technique for estimating the maximum allowable surface stress, depending on the area of the glass pane, the load duration and the probability of breakage. The method can be used for the calculation of lites with various shapes and supported along all edges. This way, elements, which are not covered by the charts, can be calculated. However, the strength values, estimated with this procedure, are conservative in comparison to the charts; and the verification requires the direct calculation of the stresses with means of a FE-software or other methods.

Fig. 4.5 shows the stress analysis of the 4000 x 2000 mm pane, subjected to a 2,30 kN/m^2 load; the corresponding deflections are shown in Fig. 4.6. The calculation is carried out with the FE software SJ MEPLA. The maximum principal stress is estimated to be 55,5 MPa, the corresponding maximum deflection is 59 mm. For comparison, the maximum allowable surface stress of heat strengthened glass subjected to short duration load is 46,6 MPa, as defined by the Appendix X6 in the American Standard.

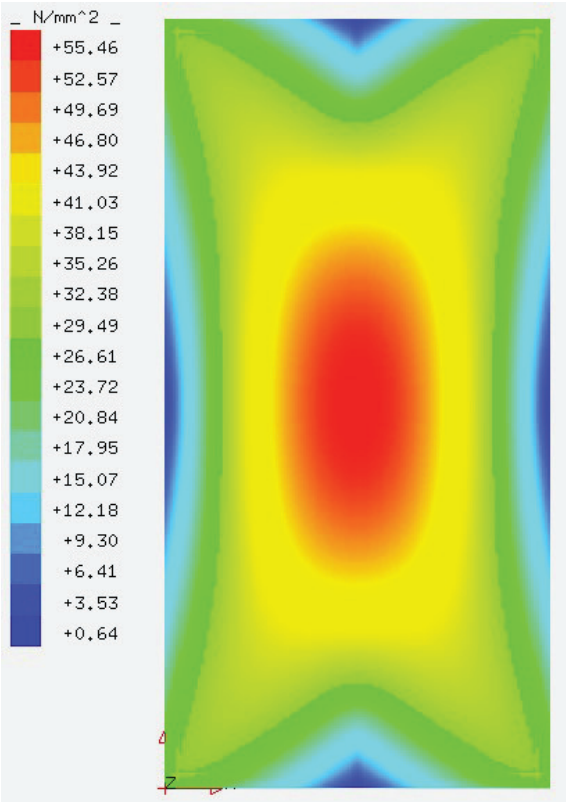


Fig. 4.5: FE-analysis of the pane under 2.30 kN/m^2 load – principal stresses

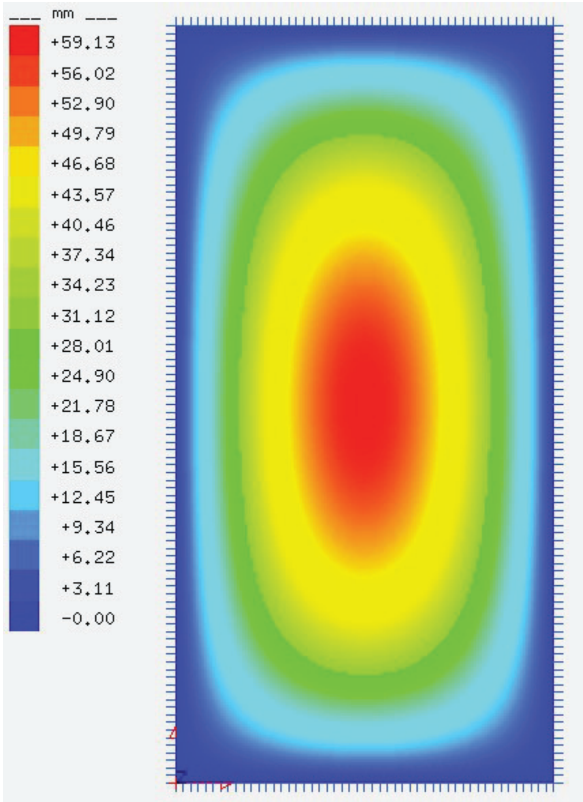


Fig. 4.6: FE-analysis of the pane under 2.30 kN/m^2 load – deflections

The glass chart method of the American Standard represents an approach, which suits very well for the preliminary design of glass panes, without the necessity of stress estimation. In comparison to the European standards, the chart method offers a more simple verification procedure for rectangular panes, regarding load bearing capacity or the maximum glass dimensions for a given load intensity. The general procedure of ASTM and the European standards however, provide a more complex, but generally applicable method, whereas the estimation of stresses is necessary in all cases, usually by means of a FE-software or engineering tables like in [42].

4.4 Load duration

It is well known, that the strength of silicate glass is considerably affected by the duration of the applied load. Depending on factors like temperature, humidity or glass composition, surface flaws in glass grow over time, even when they are below the critical size. This phenomenon, which eventually leads to the failure of the material, is usually referred to as stress corrosion, static fatigue or subcritical crack growth [33]. Design standards take this effect into consideration by defining a lower bending strength value for annealed glass subjected to long-term loads.

4.4.1 Load duration in the European standards

In the discussed European standards, the effect of the load duration is taken into account by a modification factor k_{mod}, which defines the ratio of the material strength in a current loading environment compared to the reference strength. The latter is evaluated in a testing environment, using a reference load duration. The standards either give values for the different load types, such as permanent, intermediate or short duration loads; or propose a formula for the estimation of the k_{mod} factor. In the latter case, the designer has to approximate the duration of the actions. It is important to note, that the reduction factor only applies to annealed glass.

The calculation method of the modification factor in the different standards is summarized in Table 4.3.

Table 4.3: Calculation of the k_{mod} factor

DIN 18008	With predefined values for different load types
ÖNORM B 3716	With predefined values for different load types
PrEN 16612	With the formula: $k_{\mathrm{mod}} = 0{,}663 \cdot t^{-\frac{1}{16}}$
CNR DT-210	With the formula: $k_{\mathrm{mod}} = 0{,}585 \cdot t^{-\frac{1}{16}}$

Both the German and the Austrian standards take the load duration into account with predefined modification factors. It has the advantage of not having to know the duration of typical load cases, such as snow or wind load; but the method is consequently less flexible as the calculation with formulas. The values given by the two standards are significantly different; the comparison is shown in Table 4.4.

Table 4.4: The k_{mod} factor in DIN 18008 and ÖNORM B 3716

		DIN 18008	ÖNORM B 3716
Permanent loads	Dead load, difference in altitude	0,25	0,60
Intermediate loads	Snow, temperature change, barometric pressure change	0,40	0,60
Short duration loads	Wind, horizontal line load	0,70	1,00

The European draft standard, the PrEN 16612 gives both predefined values for typical loads and a formula for the exact estimation of the k_{mod} factor for any load duration. The duration of the reference load used for the estimation is 5 sec. For ordinary structures, the factor should be at least 0,25 and maximum 1,0. For exceptionally short duration loads, such as explosions, the duration can be reduced down to 20 ms, allowing the consideration of a k_{mod} factor greater than one.

The formula given in the Italian Recommendations is derived from the so-called Linear-Elastic Fracture Mechanics Model [3]. Compared to the European draft standard, it gives slightly lower factors, thus a more conservative result. In addition to the formula above, the document defines nominal load duration values for typical load cases, which proves to be useful for approximating the duration of simple actions, such as wind gust or daily temperature variations. The values are summarized in Table 4.5.

Table 4.5: Nominal value of load duration for typical load cases (Self-made table based on [3])

Type of action	Load spectrum: Characteristic reference value	Load spectrum: Type	Time *t* equivalent to the integral of the spectrum
Wind load	Averaged over 3 seconds	Maximum pressure peak	5 sec
	Averaged over 10 minutes	Repeated pressure peaks	15 minutes
Snow load	Annual maximum		3 month
Live operating load	Brief	Single load peak	30 seconds
Crowd-induced load	Brief	Single load peak	30 seconds
Temperature variation (daily)	Maximum daily difference	Duration of maximum peak	11 hours
Self-weight and other dead loads	Permanent	Invariable load over time	Nominal lifetime

An important aspect of the design is the combination of load cases with different durations. As the approach above proposes different bending strength values for different load cases, it should also be defined, which strength value is definitive in a case of load combination composed of load cases with different durations. It can occur that load combinations not resulting in the maximum stress may still be relevant, if the corresponding strength value is relatively low.

The discussed European standards handle the question in the same way. Each possible load combination has to be examined, whereas the corresponding bending strength depends only on the action with the shortest duration. Consequently, the more load cases act on an element, the more calculation will be required in order to determine the most relevant case. An exception from the above is the German Technical Regulations [16] [17] [19], which defines neither load duration factors, nor a design method for handling load cases with different durations.

4.4.2 Load duration in the American Standard

The design approach of the American standard, the ASTM E1300-16 is slightly different from the ones presented above. The code defines so-called glass type factors (GTF), which, similar to the k_{mod} factor, consider the effect of stress fatigue. However, these factors only refer to short (3 sec) and long duration loads (30 days). Additionally, these factors depend not only on the load duration, but also on the glass type and composition. The standard distinguishes between monolithic, laminated and insulating glazing units, as well as annealed, heat-strengthened and fully tempered glass lites. As for annealed glass, the glass type factor is always smaller than 1.0. However, unlike in the European standards, this factor can have a value up to 4.0, for instance in the case of a monolithic fully-tempered glass unit subjected to a 3 sec duration load.

Table 4.6: Glass type factors (GTF) for a single lite of monolithic or laminated glass - Table 1, [2]

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

The standard defines additional load duration factors in its Appendix X4, which allows the designer to convert the load resistance of an element subjected to a 3 sec load to a duration by choice. Although an exact formula is not given in the standard, using the concept of the European draft standard, the load duration values can be approximated as:

$$k_{\mathrm{mod}} = 0{,}64 \cdot t^{-\frac{1}{16}},$$

whereas t designates the load duration in hours. The load duration factors of the Appendix X4 are shown in Table 4.7.

Table 4.7: Load duration factors – Table X4.1 in [2]
Calculated to 8/1000 lites probability of breakage

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

Regarding the combination of loads with different durations, ASTM proposes a different method from the European standards. Instead of only considering the load case with the shortest duration and use that as the basis of calculation, the American Standard defines an equivalent 3-s duration design load, considering all the load cases with their corresponding duration. The formula is the following:

$$q_3 = \sum_{i=1}^{i=j} q_i \cdot \left[\frac{d_i}{3}\right]^{1/n} \tag{4.1}$$

where q_3 is the magnitude of the 3-s duration design load, q_i is the magnitude of the i^{th} load case with the duration of d_i given in seconds. The value of n is 16 for annealed glass [2].

In comparison, the values given by ASTM are slightly higher than the ones in the Italian Recommendations, but more conservative than the values proposed in the European draft standard. The k_{mod} factors defined in these three standards are shown on a logarithmic scale in Fig. 4.7.

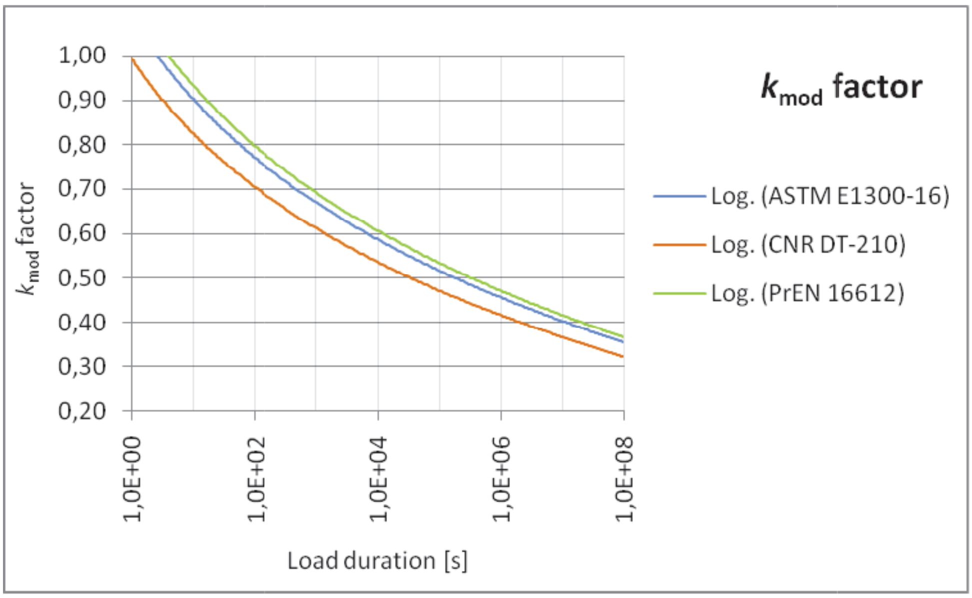


Fig. 4.7: Comparison of the values of the k_{mod} factor estimated with different formulas

4.5 Laminated glass

Laminated glass consists of two or more monolithic glass panes bonded together with an interlayer. Regarding its material, the most commonly used interlayers for architectural purposes are made of polymers. In normal loading conditions, the interlayer transfers shear stresses between the bonded glass plies, thus it constrains their sliding relative to each other.

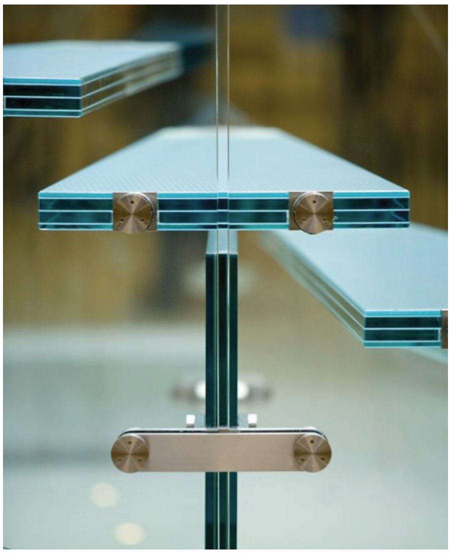


Fig. 4.8: Laminated tread of a glass stair, Apple Store, New York [49]

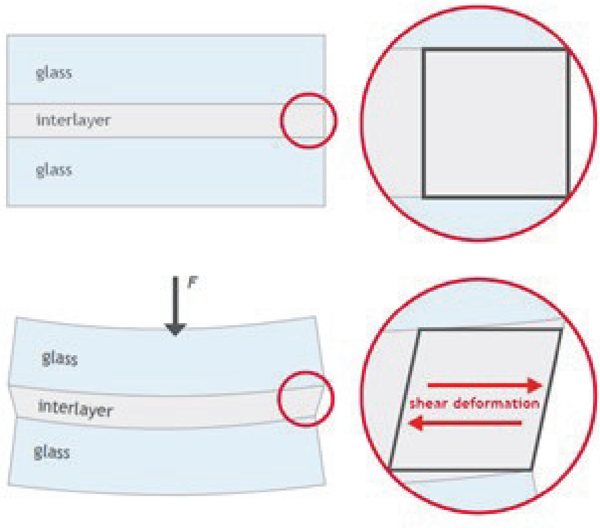


Fig. 4.9: Laminate under bending [56]

After breakage, the purpose of the interlayer is to retain fragments in the event of the glass failing [32]. Considering that glass, unlike other, commonly used building materials, has a brittle behaviour, design methods follow the so-called fail-safe approach. It means that even in case of failure of a glazing element, the risk of any injury should be minimized. This requires glass structures, depending on their function and location, to have a certain amount of residual load-bearing capacity after the breakage of glass.

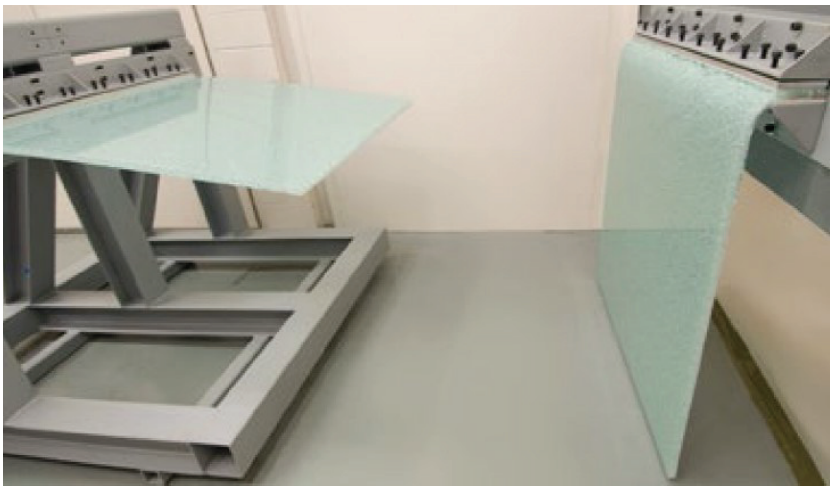


Fig. 4.10: Post-breakage behaviour of cantilevering laminates with SentryGlas (left) and PVB interlayer (right) [57]

The most commonly used polymeric interlayer is the PVB (Polyvinyl butyral) foil. Its optical clarity and good adhesion to glass surfaces, as well as its toughness and flexibility, have made it to be the dominantly used architectural safety glass interlayer [55].

Also frequently used is the so-called SentryGlasPlus (SGP) ionoplast interlayer, which was originally developed to provide a higher resistance for glass laminates against flying debris, in case of strong winds or hurricane. Compared to the conventionally used interlayer materials, SGP has a higher strength and stiffness, which effectively increases the mechanical resistance of SG-laminated glass panels. The enhanced performance is widely used in architecture as well, for instance as vandalism- or burglary-resistant glass laminates or structural glass elements [37].

During structural design and the estimation of load bearing capacity or deflections, the stiffness of the laminated glass, thus the shear interaction between the single panes plays a significant role. In the literature two marginal situations are usually referred to: the case of a perfect shear coupling as “monolithic limit” and the zero shear connection as “layered limit” [3]. The distribution of the normal stress along the cross-section due to bending is shown in Fig. 4.11.

Fig. 4.11: Normal stress due to bending: in monolithic limit (left), layered limit (right), and with viscoelastic interlayer [34]

As the mechanical behaviour of the polymer is viscoelastic, nonlinear and temperature dependent, a precise calculation of the laminate requires complex numerical analysis [32]. Thus, most standards propose simplified methods for dimensioning laminated glass elements and estimate the degree of shear coupling.

4.5.1 Laminated glass in the European standards

The German national standard, DIN 18008 [5] discusses laminated glass rather briefly. The only given instruction is that favourable shear interaction between the individual panes shall not be taken into consideration; whereas a full shear connection should be assumed, if it results in greater stresses or deflections. The code does not specify the interlayer material.

The standard ÖNORM B 3716 [12] handles the issue similarly. According to the Austrian code, a full shear interaction shall be assumed, if it is unfavourable, and the same assumption can be made in case of an impact loading. For vertical glasses under short duration loads a shear modulus of 0,4 N/mm^2 can be applied, in other cases the evaluation of the shear interaction is the designer’s responsibility. However, only PVB interlayers shall be used, which meet the minimum criteria specified in the standard.

The draft standard PrEN 16612 proposes, that if „shear stress is developed in laminated glass parallel with the interlayer, the interlayer can be considered as having some shear resistance" [14]. The viscoelastic behaviour of the material and its temperature dependent mechanical properties shall be taken into consideration during the design. As an alternative to a complex calculation, the standard describes a simplified method, using the so-called effective thickness. The effective thickness is defined as the thickness of a monolith pane equivalent to the laminate in terms of deflection and stress [32].

The simplified method is unaltered compared to the one presented in the preceding document of the draft standard, the PrEN 13474 [13]. The effective thickness is derived using the thickness of the single glass plies and a coefficient ω, which represents the degree of shear coupling. The coefficient varies between 0 (layered limit) and 1 (monolithic limit), whereas the designer shall define its exact value on the basis of the interlayer stiffness families defined in Table 11 in the standard [14]. The formulas (4.1) and (4.2) below show the calculation of the deflection-effective and stress-effective thickness:

$$h_{\mathrm{ef,w}} = \sqrt[3]{\sum_k h_{\mathrm{k}}^{\,3} + 12\omega\left(\sum_k h_{\mathrm{k}} h_{\mathrm{m,k}}^{\,2}\right)} \tag{4.1}$$

$$h_{\mathrm{ef},\sigma,\mathrm{j}} = \sqrt{\frac{h_{\mathrm{ef,w}}^{\,3}}{h_{\mathrm{j}} + 2\omega h_{\mathrm{m,j}}}} \tag{4.2}$$

Whereas ω is the shear transfer coefficient, h_{k} and h_{j} are the thicknesses of the glass plies, $h_{\mathrm{m,k}}$ and $h_{\mathrm{m,j}}$ are the distances of the mid-plane of the single plies from the mid-plane of the laminate.

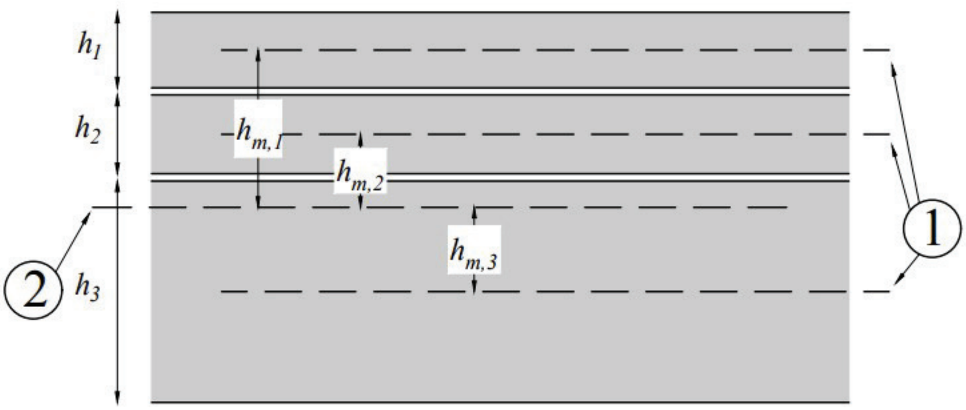


Fig. 4.12: Laminated glass thickness dimensions.
No. 1 designates the mid-plane of each ply, no. 2 the mid-plane of the laminate. (Self-made fig. based on [14])

It should be noted here, that the reliability of this method is questioned among others in [32]. The degree of shear coupling in glass laminates depends on many factors, such as the size of the glazing element, the support conditions, the type of loading and the temperature [3]. The simplified method estimates the effective thickness using a beam model and does not consider the shape and size of the glass or its boundary conditions. The results estimated with the formulas above can significantly differ from reality. In case of very slender laminates, as it is shown in [32], the results are too conservative. Whereas, applied for small elements with continuous constraints the method is not always on the safe side.

The Italian Recommendations, the CNR-DT 210 [3] presents a recently proposed design method, the Enhanced Effective Thickness approach. The method is based on finding the best approximation for the mechanical response of the laminate through the minimization of the strain energy functional. The assumptions are the following: the interlayer has only shear stiffness, both the shear deformation of the laminate and geometrical non-linearities can be neglected and all materials are linear-elastic [32]. Values of the deflection-effective and stress-effective thickness are given as in shown in (4.3) and (4.4) [3]:

$$h_{\mathrm{ef,w}} = \sqrt[3]{\frac{1}{\frac{\eta}{\sum_{i=1}^{N} h_{\mathrm{i}}^{3} + 12\sum_{i=1}^{N}(h_{\mathrm{i}} d_{\mathrm{i}}^{2})} + \frac{(1-\eta)}{\sum_{i=1}^{N} h_{\mathrm{i}}^{3}}}} \tag{4.3}$$

$$h_{\mathrm{ef},\sigma,\mathrm{i}} = \sqrt{\frac{1}{\frac{2\eta|d_{\mathrm{i}}|}{\sum_{i=1}^{N} h_{\mathrm{i}}^{3} + 12\sum_{i=1}^{N}(h_{\mathrm{i}} d_{\mathrm{i}}^{2})} + \frac{h_{\mathrm{i}}}{h_{\mathrm{w}}^{3}}}} \tag{4.4}$$

where η is a non-dimensional coefficient varying from 0 (layered limit) to 1,0 (monolith limit). The coefficient is calculated, as mentioned above, based on the stress energy of the laminate. It considers not only the material characteristics and the size effect, but with the factor ψ also the loading and support conditions [3]. To make the practical design simpler, pre-calculated values for the factor ψ are given in the Italian Recommendations and also in other literature [30].

4.5.2 Laminated glass in the American Standard

ASTM proposes non-factored load charts also for laminated glass panes. The code covers laminates consisting of two glass lites with the same thickness from 5 mm up to 19 mm, with different support conditions. It is to be noted, that the charts can only be used in case of a PVB interlayer. If the designer intends to use an other type of material, its equivalency has to be verified, based on the shear modulus and viscoelastic behaviour of the interlayer [2].

An alternative method is proposed in the appendix of the standard, allowing the designer to perform the analysis of laminated glass for cases not covered by the non-factored load charts. The method is similar to the one presented in the draft standard [14]; it defines the equivalent thickness of the glazing element, however, only for two-ply laminates. This approach is based on the work by Wölfel [43] and Bennison [24]; it corresponds to a simply supported beam under a uniform load. The standard defines a shear transfer coefficient Γ, which takes the shear coupling between the glass plies into consideration. It should be noted, that although this method considers the size of the glass element, it may give incorrect results in case of different support or loading conditions [32]. However, in case of simply supported beams subjected to uniformly distributed loads, the procedure is very accurate [31].

The shear transfer coefficient, the deflection effective and stress effective thickness are calculated as shown in (4.5), (4.6) and (4.7):

$$\Gamma = \frac{1}{1 + 9{,}6\,\frac{E \cdot I_{\mathrm{s}} \cdot h_{\mathrm{int}}}{G_{\mathrm{int}} \cdot {h_{\mathrm{s}}}^{2} \cdot a^{2}}} \tag{4.5}$$

$$h_{\mathrm{ef,w}} = \sqrt[3]{{h_1}^3 + {h_2}^3 + 12 \cdot \Gamma \cdot I_{\mathrm{s}}} \tag{4.6}$$

$$h_{1,\mathrm{ef},\sigma} = \sqrt{\frac{{h_{\mathrm{ef,w}}}^3}{h_1 + 2\Gamma \cdot h_{\mathrm{s},2}}}\,,\; h_{2,ef,\sigma} = \sqrt{\frac{{h_{\mathrm{ef,w}}}^3}{h_2 + 2\Gamma \cdot h_{\mathrm{s},1}}} \tag{4.7}$$

where E is the Young’s modulus of the glass, G_{int} is the shear modulus of the interlayer, I_{s} and h_{s} are values depending on the glass composition, h_i is the thickness of the i^th^ glass ply and h_{int} is the thickness of the interlayer.

As shown above, the discussed standards propose rather different design approaches and calculation procedures of the effective thickness. This aspect of the standards is of special importance, since the effective thickness directly affects the calculated stiffness of the glass pane. As to which extent do the values estimated with the presented methods differ, is briefly shown in section 6.1.

4.6 Insulating glass units

Insulating glass units consist of two or more glass plies with an enclosed air cavity in between them. The component plies, which can be either monolithic or laminated, are connected by a spacer and sealing along the edges. The purpose of the air cavity is to enhance the insulating capacity of the glazing unit, while the sealing impedes air exchange with the external environment. In order to achieve better thermal insulation values, inert gases may be used in the air cavity [3].

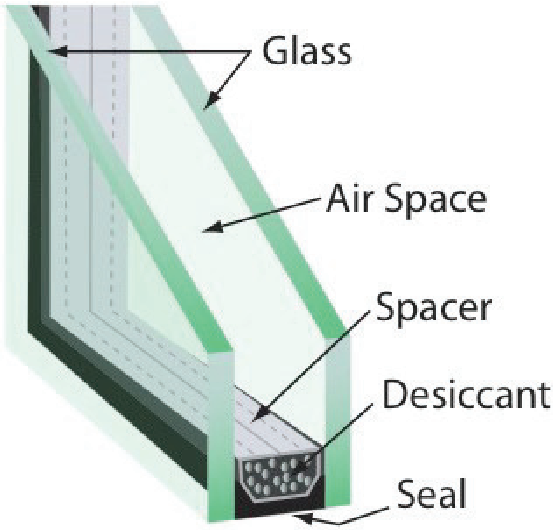


Fig. 4.13: Composition of a simple insulating unit [48]

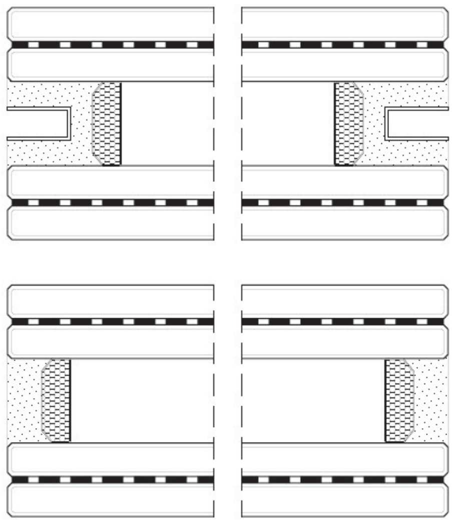


Fig. 4.14: Sections of insulating units with spacer (bottom) and additional C-channel for mechanical fixing (top) – Self-made fig.

The hermetically sealed cavity, and thus the fixed quantity of gas result in peculiarities, which need to be considered by the standardized design approaches. These are briefly listed below:

- The presence of the fixed quantity of gas causes a phenomenon called load sharing or coupling effect: actions, which are applied on one pane, have effects on all of the composing panes. This means that external loads like wind, snow or live loads are acting on the whole insulating unit, whereas the load distribution depends on the stiffness of the single panes [27].

- Difference between the ambient pressure and the pressure of the gas enclosed in the cavity causes an additional load on each pane. This load, acting as an inner load on the glazing unit, is referred to as climatic load. The pressure difference can be the result of a change in temperature, barometric pressure or difference of altitude in relation to the place of production [27].

- The effect of the climatic load depends on the overall stiffness of the glazing unit: the higher the deformability, the lower are the stresses due to the pressure change. In the case of larger glass panels, the climatic load is not predominant compared to wind and snow loads, whereas for the design of small glazing units, it becomes relevant [27]. It is thereby important, that in the case of insulating units composed of glass laminates, both the “monolithic limit” and the “layered limit” cases are investigated.

The standards discussed in this thesis propose a detailed method for the design of insulating units. The procedure is generally the same in all the codes. In the first step, the loads acting on the unit are estimated, including the climatic load. The next step is to assign a certain part of the load to each composing pane, load share factors respectively. At last, the maximum stresses are calculated and compared with the material strength defined by the standard.

As both the climatic loading and the load sharing are general phenomena, they are defined mostly alike by the standards. The differences concern the handling the different durations of load cases and how the stiffness of laminated glass, being a part of the insulating unit, is estimated.

4.6.1 Insulating glass in the American Standard

The ASTM E1300-16 proposes two procedures for the structural verification of insulating glass units. The general procedure is the glass chart method, presented in 4.3.2. The steps of the verification according to the glass chart method, as also shown in Fig. 4.1, are the following [2]:

1. The non-factored loads (NFL) are estimated for each pane of the insulating unit, using the corresponding charts of the standard.
2. The glass type factors (GTF) are defined in the code, glass type (annealed glass, heat-strengthened or fully tempered glass) and load duration respectively.
3. The load share factors (LSF) are estimated for each pane.
4. The load resistance (LR) - the uniformly distributed load perpendicular to the glass surface, which corresponds with a probability of breakage of 0.008 – is calculated for each pane as follows:
$$LR_\mathrm{i} = \frac{NFL_\mathrm{i} \cdot GTF_\mathrm{i}}{LSF_\mathrm{i}}$$
5. The load resistance of the whole unit is the smallest of the calculated LR_i values.

The code also proposes a more general procedure, which can be applied to insulating units with shapes or support conditions not covered by the charts. This method requires the calculation of the principal stresses directly, which can be carried out with a FE-software. The stresses in each pane are compared with the allowable stresses defined in the standard.

An example of the dimensioning with the glass chart method is shown in 6.2.

4.6.2 Insulating glass in the European standards

Concerning insulation glass units, the discussed European documents can be divided into two groups. The first would include only the German Technical Regulations (TRXV), whereas the second includes the German, the Austrian and the European draft standard, as well as the Italian Recommendations. The general verification procedure of the mentioned standards is summarized as follows.

<table>
<tr><th>TRXV</th><th>DIN 18008, ÖNORM B 3716, PrEN 16612, CNR-DT 210</th></tr>
<tr><td colspan="2">Load estimation, including climatic loads</td></tr>
<tr><td>Defining load combinations, without consideration to the different load durations</td><td>Defining load combinations, taking into consideration the different duration of the load cases</td></tr>
<tr><td colspan="2">Estimation of the load share factors for each ply</td></tr>
<tr><td colspan="2">Estimation of the principal stresses for each ply and load combination</td></tr>
<tr><td>Comparison of the estimated stresses with the material strength:
▪ The material strength is independent from the load duration
▪ The separation of the load combinations is not required
▪ The principal stresses are compared with the permissible stresses</td><td>Comparison of the estimated stresses with the material strength:
▪ The material strength is dependent on the load duration
▪ The separation of the load combinations is required, the load duration respectively
▪ The principal stresses are compared with the design strength</td></tr>
</table>

The standards also differ in one other important aspect. In case the insulating unit includes laminated glass, the effective thickness of the laminate has to be estimated. The European standards, as shown in 4.5.1, propose different methods for the estimation of the effective thickness, leading to rather different results. To illustrate the effect of this difference, a simple calculation is shown in 6.2.

5. Special design

As already mentioned in the previous chapters, glass elements can be used as primary structural members as well, if the brittle behaviour of the material is taken into consideration. As a result of scientific research and the general developments of the industry in the latest years, this potential of the material is being more and more utilized. The title of this chapter, the term “special design” is the designation used in the JRC Scientific Report [27]; referring to applications, where glass elements are used as primary structural members.

The national standards as of today have only incorporated very few of the results of the research data regarding the structural use of glass. Concerning the documents discussed in this thesis, only the Italian Technical Recommendations [3] presents design approaches regarding special design. Since in this case a comparison of the standards is, due to the lack of design methods, not reasonable, this chapter is restricted only to the verification procedures presented in the Italian document.

5.1 Structural use of glass – Buckling

Buckling is a failure mode of slender elements under compression, whereas the failure is characterised by the sudden increase of the deflections normal to the beam axis. The buckling phenomena of glass members is influenced among others by the support conditions, loading eccentricity, manufacturing and installation tolerances, as well as the material behaviour of glass and the interlayer [3]. A possible deflection mode and a set-up of a buckling test are shown in Fig. 5.1 and Fig. 5.2.

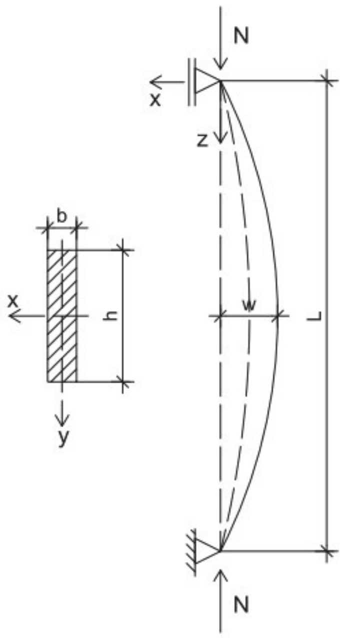


Fig. 5.1: Deflected shape of an Euler-beam under axial loading - Self-made fig. based on [3]

Fig. 5.2: Test set-up: Laminate under axial compression [36]

As mentioned earlier, the standards discussed in this thesis, with the exception of the Italian Recommendations, do not propose design methods for the verification of buckling failure. Concerning the ASTM E1300, the scope of the document is not planned to be extended in this regard. However, a so-called Work Item is being prepared under the name of “ASTM WK37764: New Guide for Structural Use of Glass in Buildings”, which shall describe methods for the verification of stability as well [45]. As far as the European standards are concerned, the new Eurocode is planned to cover primary structural members of glass [27].

The buckling failure of structural members of steel and concrete is very well covered in the Eurocodes [9] [10]. The same verification approach is adopted by the Italian Recommendations: calibrated buckling curves are proposed for the stability check of compressed members. It is generally to verify, that the compressing force does not exceed the buckling strength of the member, see Eq. (5.1) [23]. The equations from (5.2) to (5.6) [3] briefly show the verification procedure.

$$N_{\mathrm{Ed}} \leq N_{\mathrm{b,Rd}} \tag{5.1}$$

$$N_{\mathrm{b,Rd}} = \chi \cdot A \cdot f_{\mathrm{g,d}} \tag{5.2}$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \tag{5.3}$$

$$\phi = 0{,}5 \cdot \left[1 + \alpha^*\left(\bar{\lambda} - \alpha_0\right) + \bar{\lambda}^2\right] \tag{5.4}$$

$$\bar{\lambda} = \sqrt{\frac{A \cdot f_{\mathrm{g,k,st}}}{{N_{\mathrm{cr}}}^{(\mathrm{E})}}} \tag{5.5}$$

$${N_{\mathrm{cr}}}^{(\mathrm{E})} = \frac{\pi^2 EI}{l^2} \tag{5.6}$$

The buckling resistance of the structural member is calculated as the compressive strength of the cross-section reduced by the factor χ (5.2). The reduction factor is derived from the normalised slenderness of the member (5.5) and from the coefficient ϕ (5.4), whereas the latter includes the α^* and α_0 imperfection factors. The value $f_{\mathrm{g,d}}$ in (5.2) and $f_{\mathrm{g,k,st}}$ in (5.5) are the design tensile strength and characteristic strength of glass for the checking of buckling, respectively [23].

The verification of laminated glass is based on the same procedure, but the stiffness of the compressed member in (5.6), is calculated using the deflection effective thickness of the laminate. The effective thickness is estimated with the Wölfel-Bennison model (see 4.5.2), described in the American standard [2]. Interestingly, the document proposes this more simple procedure instead of the EET-method, but as mentioned in section 4.5.1, in the case of beam-like members under uniformly distributed loads, the accuracy of the Wölfel-Bennison model is sufficient.

The design of insulating units can be carried out using the same procedure. In this case, the load share factors are estimated using the compression stiffness of the glass elements; the buckling strength of each ply has to be verified [3]:

$$N_{\mathrm{Ed,i}} = N_{\mathrm{Ed}} \cdot \frac{A_{\mathrm{i}}}{A_{\mathrm{tot}}} \leq N_{\mathrm{b,Rd,i}}$$

5.2 Structural use of glass – Lateral-torsional buckling

Beam-like elements subjected to bending moment may exhibit lateral-torsional instability. The deformation of this failure mode, shown in Fig. 5.3, is characterised by lateral deflection normal to the plane of the bending moment as well as torsional rotation of the cross-section [3].

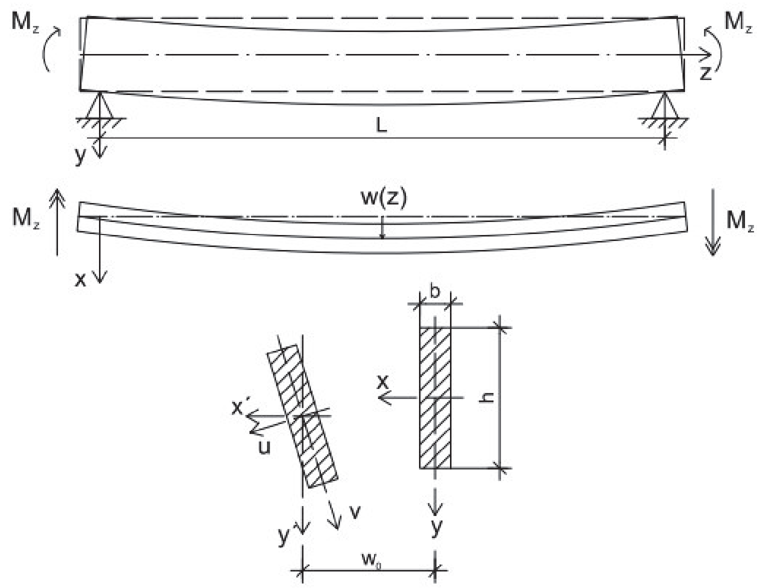


Fig. 5.3: Flexural-torsional deformation of a beam element under bending – Self-made fig. based on [3]

Fig. 5.4: Sideways inclined fins supporting a vertical glass facade – Etihad Museum, Dubai [52]

Lateral-torsional buckling failure is especially typical for glass fins and beams. As the purpose of glass fins is to provide stiffness to facades normal to their plane, the bending moment is mostly due to wind loads, or in case of inclined fins, due to the self-weight. In beam members, bending moment mostly occurs due to live loads.

Regarding standardization, also lateral-torsional buckling is yet to be incorporated in the design codes. As mentioned in the previous section, verification methods also for this failure mode are in development: in the Work Item WK37764 by ASTM [45] and for the new Eurocode by the European Committee for Standardization. Until the publication of these standards, the most detailed method for the design of glass fins and beams is provided by the Italian Recommendations [3].

The proposed approach is analogous to the buckling verification: it needs to be shown that the bending moment in the structural member does not exceed the beam buckling strength (5.7). The buckling strength is calculated as it is in (5.8), whereas W_x designates the elastic section modulus of the cross section, $f_{g,d}$ the design value of the tensile strength and χ_{LT} is the reduction factor for lateral-torsional stability. The reduction factor is dependent on the normalised slenderness (λ_{LT}) of the beam, calculated using formulas analogous to (5.3) and (5.4) [3].

$$M_{\mathrm{Ed}} \leq M_{\mathrm{b,Rd}} \tag{5.7}$$

$$M_{\mathrm{b,Rd}} = \chi_{\mathrm{LT}} \cdot M_{\mathrm{Rd}} = \chi_{\mathrm{LT}} \cdot W_{\mathrm{x}} \cdot f_{\mathrm{g,d}} \tag{5.8}$$

$$\bar{\lambda} = \bar{\lambda}_{\mathrm{LT}} = \sqrt{\frac{W_{\mathrm{x}} \cdot f_{\mathrm{g,k,st}}}{M_{\mathrm{cr}}{}^{(\mathrm{E})}}} \tag{5.9}$$

$$M_{\mathrm{cr}}{}^{(\mathrm{E})} = C_1 \frac{\pi}{l} \cdot \sqrt{EI_{\mathrm{y}} \cdot GI_{\mathrm{t}}} \tag{5.10}$$

$M_{cr}{}^{(E)}$ in (5.10) defines the critical moment for lateral-torsional buckling, taking into consideration the bending moment distribution with the coefficient C_1, as well as the bending (EI_y) and torsional stiffness (GI_t) of the cross-section.

Lateral-torsional buckling of laminated glass, similarly to the compressed elements, can be verified using the effective thickness method. In this case, the stiffness values in (5.10) are calculated with the deflection effective thickness of the laminate, taking into consideration the appropriate shear coupling provided by the interlayer [3].

5.3 Structural use of glass – Glass plates under in-plane compression

Buckling of plates under in-plane compression is a typical failure mode of slender glass walls, whereas the elements are usually tall and thin, subjected to their own self-weight and indirectly to live or snow loads as well. The buckling effect is aggravated by loads acting perpendicular to the glass plane, such as wind or live loads; as well as by manufacturing or installation tolerances and load eccentricity.

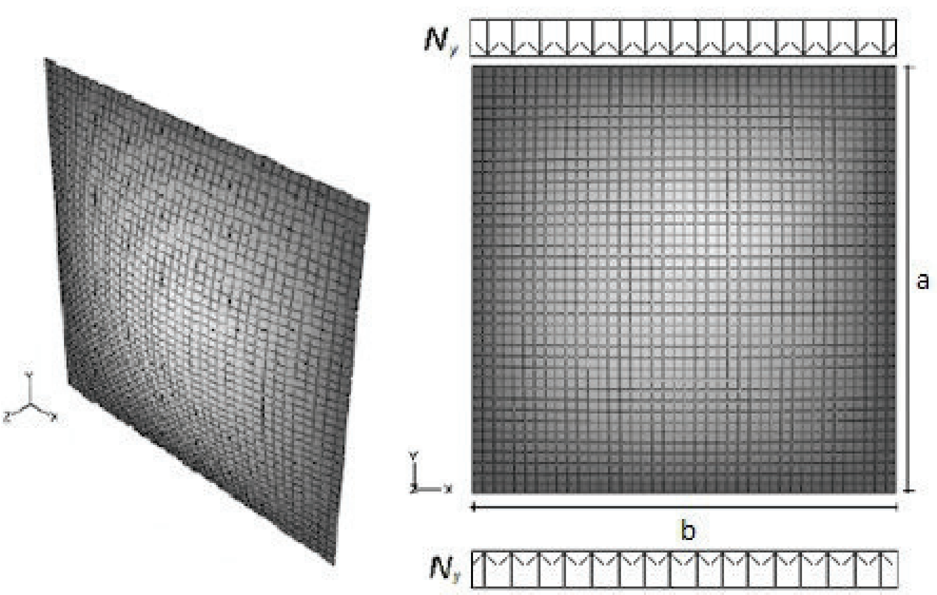


Fig. 5.5: Panel simply supported along the edges subjected to in-plane compression – Self-made fig. based on [3]

The Italian Recommendations proposes a verification method for monolithic, laminated and insulating units as well. The design approach is analogous to the stability checks presented above: it has to be verified, that the compression force does not exceed the buckling strength of the ply (see Eq. (5.1)). The Euler critical load is estimated as:

$$N_{\mathrm{cr}}{}^{(\mathrm{E})} = \left(\frac{mb}{a} + \frac{a}{mb}\right)^2 \cdot \frac{\pi^2 \cdot D}{b^2} = k_\sigma \frac{\pi^2 \cdot D}{b^2} \qquad (5.11),$$

where D is the flexural stiffness of the element, per unit of length, calculated as

$$D = \frac{Eh^3}{12(1-\upsilon^2)} \qquad (5.12),$$

and k_σ is a stability coefficient,

$$k_\sigma = \left(\frac{mb}{a} + \frac{a}{mb}\right)^2 \qquad (5.13).$$

The support conditions of the glazing element are taken into consideration with the stability coefficient: the variable m designated the number of semi-waves in the direction of the load, assumed according to the minimum buckling load. The buckling strength is estimated in the same way as presented in the previous sections; the compression resistance is reduced by a reduction factor dependent on the slenderness of the element [3].

5.4 Structural use of glass – Glass plates under in-plane shear stress

The buckling phenomenon of glass plates under in-plane shear stress is a subject to many recent studies (see e.g. [29] [35]); however, just as in the case of the other stability failure modes, a verification method is still to be standardized. Buckling due to in-plane shear is a typical failure mode of facade elements, if the glazing is utilized, additionally to its primary function, as a bracing system of the overall structure as well. This sort of multifunctionality is becoming a requirement in today's innovative architecture.

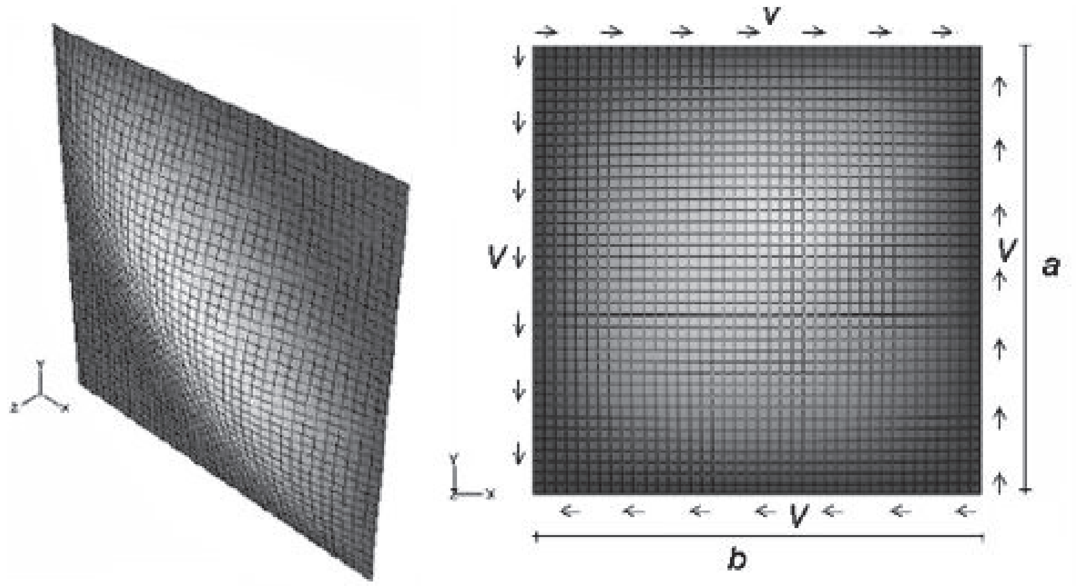


Fig. 5.6: Panel supported along its edges and subjected to in-plane shear forces – Self-made fig. based on [3]

Just as for the previous failure modes, the CNR-DT 210 proposes a verification method for monolithic, laminated and insulating glass under shear-stress as well. Analogous to the general procedure of the Eurocode stability checks, the method is as follows [3].

The buckling verification has to be carried out by the means of Eq. (5.14), whereas V_{Ed} is the design shear force per unit length and $V_{\mathrm{b,Ed}}$ designates the elastic resisting shear force per unit length of the panel.

$$V_{\mathrm{Ed}} \leq V_{\mathrm{b,Rd}} \tag{5.14}$$

The latter is calculated as in (5.15); whereas χ designated the usual reduction factor calculated as in (5.3) with corresponding imperfection factors, and $\tau_{\mathrm{g,d}}$ is the design shear strength of the material.

$$V_{\mathrm{b,Rd}} = = \chi \cdot A \cdot \tau_{\mathrm{g,d}} \tag{5.15}$$

In order to calculate the reduction factor χ, the normalised slenderness has to be estimated, as defined in (5.16). In the formula, $\tau_{g,k,st}$ is the characteristic shear strength of the material; and $V_{cr}{}^{(E)}$ designates the Euler critical shear stress in the element.

$$\bar{\lambda} = \sqrt{\frac{A \cdot \tau_{g,k,st}}{V_{cr}{}^{(E)}}} \tag{5.16}$$

The Euler critical shear stress is defined by the Eq. (5.17), taking into consideration the effect of the side length ratios with the factor κ^{τ}. The value D designates the flexural stiffness of the element, as defined in (5.12).

$$V_{cr}{}^{(E)} = \frac{\pi^2 \cdot D}{b^2} \kappa^{\tau} \tag{5.17}$$

The design procedure is applicable to laminated glass and insulating units as well. In case of laminates, the effective thickness method can be used; whereas in case of insulating units, each ply has to be verified with a method corresponding to its composition.

5.5 Design in seismic areas

Regarding their behaviour in seismic perspective, glass parts can be, in most cases, considered as secondary elements, since their strength and stiffness usually does not influence the overall response of the construction. Most glass parts are either designed with adequate joints and connections to isolate them from the main structure, or are assumed to shatter in case of an earthquake. If the glass part is designed as a primary structural element, special studies need to be carried out. In this case, the element must be designed taking into account the high consequences of the structural failure [3].

As far as the seismic action is concerned, both the American and European standards are well prepared. On European level, the Eurocode 8 [11] discusses the standard seismic load for buildings; the same is specified in the ASCE Standard [1] for the American standards.

Regarding a verification approach for glass, neither the ASTM E1300-16, nor the European draft standard proposes considerations for the design in seismic area. As for the American documents, the only reference regarding glass under seismic load is made in the ASCE Standard, which defines a so-called design clearance: the size of the joint around an element, aiming to isolate the glass pane and allowing it to move rigidly during seismic action [1]. Among the discussed European documents, only the Italian Recommendations [3] and the Glass Design Report [27] mentions the seismic design.

The Italian Recommendations, similarly to the Eurocode 8, defines the seismic action in accordance with the importance class and the design life span of the construction, as well as the limit state that needs to be considered. The design life span, during the structure fulfils its purpose, can be assumed as 50 years for glass structures. The reference period of the seismic action is derived from the design life span, using a factor depending on the importance class. The importance class is chosen in accordance with EN 1990 [7]: from Class I. to IV., depending on the function of the construction. The document also specifies four limit states, which can be considered for the verification of the glazing element: operability limit state, damage limit state, limit state for the safeguard of human life and collapse prevention limit state [3].

The above-mentioned Glass Design Report [27] does not propose any specific design method, however, it provides recommendations, which shall be included in the future Eurocode for glass. According to the document, the verification of primary members has to be based on linear analysis, considering no energy dissipation and no ductility. The verification of connection shall consider both relative displacements and internal actions, and it has to be carried out in a limit state associated with the no-collapse requirement. Regarding secondary elements, a special attention should be given to the contribution of such members to the overall stiffness of the structure [27].

It is expected, that the new Eurocode for glass will give rules for the design of secondary and primary members in seismic areas, which comply with the existing Eurocode 8. Regarding the American standards, up to this date ASTM has announced no document in preparation, which would cover seismic design.

6. Exemplary calculations

This chapter aims to illustrate the design approaches presented in the previous parts of the thesis. The peculiarities of the dimensioning methods are shown by means of simple, exemplary calculations; and where it is relevant, the results are compared at the end of each section.

The glazing elements shown here are chosen only to highlight the relevant differences between the standards; regarding post-breakage behaviour or building physics, they are not necessarily fit for construction. The calculations should not be considered as complete, as loads and structural behaviour are simplified.

6.1 Laminated glass

In this section, three methods will be briefly presented for the evaluation of the effective thickness, using an example of a rectangular glass laminate. The three methods are the following: the Wölfel-Bennison [43] approach proposed in the American standard, the method presented in the European draft standard and the Enhanced Effective Thickness method [31].

The exemplary glazing element is a 2000x1500 mm laminate, simply supported along its four edges and exposed to a short duration load perpendicular to its surface. The element is composed of two glass plies, both with 8 mm thickness, bonded together with a 0,76 mm thick, Trosifol BG type PVB interlayer. Its geometry is shown in Fig. 6.1, the material characteristics are listed below.

Young's modulus of glass:	$E = 70000$ MPa
Shear modulus of the interlayer *(for a 3 sec duration load in 50 °C environment):*	$G_{\text{int}} = 0{,}44$ MPa
Thickness of each glass ply:	$h_1 = h_2 = 8$ mm
Thickness of the interlayer	$h_{int} = 0{,}76$ mm
Length of the shorter edge:	$a = 1500$ mm
Length of the longer edge:	$b = 2000$ mm

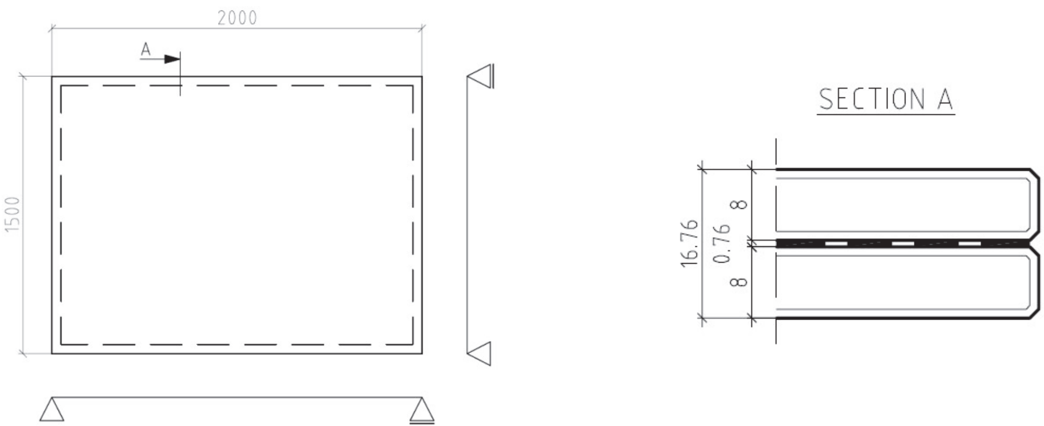


Fig. 6.1: Overview of the exemplary glazing element

6.1.1 Effective thickness according to ASTM E1300-16

Stiffness related values:

$$h_s = 0{,}5 \cdot (h_1 + h_2) + h_{int} = 0{,}5 \cdot (8 + 8) + 0{,}76 = 8{,}76 \text{ mm}$$

$$h_{s,1} = \frac{h_s h_1}{h_1 + h_2} = \frac{8{,}76 \cdot 8}{8 + 8} = 4{,}38 \text{ mm}$$

$$h_{s,2} = \frac{h_s h_2}{h_1 + h_2} = \frac{8{,}76 \cdot 8}{8 + 8} = 4{,}38 \text{ mm}$$

$$I_s = h_1 \cdot {h_{s,2}}^2 + h_2 \cdot {h_{s,1}}^2 = 8 \cdot 4{,}38^2 + 8 \cdot 4{,}38^2 = 307{,}0 \text{ mm}^3$$

The shear transfer coefficient (as in (4.5)):

$$\Gamma = \frac{1}{1 + 9{,}6 \frac{E \cdot I_s \cdot h_{int}}{G_{int} \cdot {h_s}^2 \cdot a^2}} = \frac{1}{1 + 9{,}6 \frac{70000 \cdot 307{,}0 \cdot 0{,}76}{440 \cdot 8{,}76^2 \cdot 1500^2}} = 0{,}326$$

Deflection effective thickness (as in (4.6)):

$$h_{ef,w} = \sqrt[3]{{h_1}^3 + {h_2}^3 + 12 \cdot \Gamma \cdot I_s} = \sqrt[3]{8^3 + 8^3 + 12 \cdot 0{,}326 \cdot 307{,}0} = 13{,}06 \text{ mm}$$

Stress effective thickness (as in (4.7)):

$$h_{1,ef,\sigma} = h_{2,ef,\sigma} = \sqrt{\frac{{h_{ef,w}}^3}{h_1 + 2\Gamma \cdot h_{s,2}}} = \sqrt{\frac{13{,}06}{8 + 2 \cdot 0{,}326 \cdot 4{,}38}} = 14{,}32 \text{ mm}$$

It should be noted, that according to the American standard, the effective thickness is calculated using the minimum thickness of the glass panes, not the nominal. Thus, in case of 8 mm glass layers, the calculation should take 7,42 mm thick plies into consideration. In order to compare the values with the ones estimated with other methods, the calculation is carried out using the nominal thickness.

6.1.2 Effective thickness according to PrEN 16612

According to the draft standard, the shear coupling is given by a ω factor, depending on the stiffness family of the interlayer. The test procedures of the interlayers, as well as their classification into stiffness families, are defined by an other draft standard, the PrEN 16613 [15]. As to which family should be considered, depends on the Young's modulus of the interlayer material at a specified temperature range.

In interlayer used in this example, as per its mechanical properties, belongs to the stiffness family 3. According to the Table 11 in PrEN 16612 [14], the shear transfer coefficient is defined as 0,3 for intermediate duration loads.

Shear transfer coefficient: $\omega = 0{,}3$

Deflection effective thickness (as given in (4.1))

$$h_{\mathrm{ef,w}} = \sqrt[3]{\sum_{\mathrm{k}} h_{\mathrm{k}}^{3} + 12\omega\left(\sum_{\mathrm{k}} h_{\mathrm{k}} h_{\mathrm{m,k}}^{2}\right)} = \sqrt[3]{8^3 + 8^3 + 12 \cdot 0{,}3 \cdot 2 \cdot 8 \cdot 4{,}38^2} = 12{,}86\ \mathrm{mm}$$

Stress effective thickness for both plies (as given in (4.2) and (4.1))

$$h_{\mathrm{ef},\sigma,1} = h_{\mathrm{ef},\sigma,2} = \sqrt{\frac{h_{\mathrm{ef,w}}^{3}}{h_{\mathrm{j}} + 2\omega h_{\mathrm{m,j}}}} = \sqrt{\frac{12{,}86^3}{8 + 2 \cdot 0{,}3 \cdot 4{,}38}} = 14{,}15\ \mathrm{mm}$$

6.1.3 Effective thickness according to CNR-DT 210

Stiffness related values:

$$d = h_s = 0{,}5 \cdot (h_1 + h_2) + h_{\text{int}} = 0{,}5 \cdot (8+8) + 0{,}76 = 8{,}76\ \text{mm}$$

$$d_1 = h_{s,1} = \frac{d \cdot h_2}{h_1 + h_2} = \frac{8{,}76 \cdot 8}{8+8} = 4{,}38\ \text{mm}$$

$$d_2 = h_{s,2} = \frac{d \cdot h_1}{h_1 + h_2} = \frac{8{,}76 \cdot 8}{8+8} = 4{,}38\ \text{mm}$$

$$I_s = \frac{h_1 h_2}{h_1 + h_2} \cdot \mathrm{d}^2 = \frac{8 \cdot 8}{8+8} \cdot 8{,}76^2 = 307{,}0\ \text{mm}^3$$

Flexural stiffness in the case of layered limit:

$$D_{\text{abs}} = \sum_{\mathrm{i}=1}^{2} \frac{E h_{\mathrm{i}}{}^3}{12(1-\nu^2)} = \frac{70000 \cdot 8^3}{12(1-0{,}22^2)} \cdot 2 = 6\,277\,147\ \text{Nmm}$$

Flexural stiffness in the case of monolith limit:

$$D_{\text{full}} = D_{\text{abs}} + \frac{E}{1-\nu^2} \frac{h_1 h_2}{h_1 + h_2} d^2 = 6277147 + \frac{70000}{1-0{,}22^2} \cdot \frac{8 \cdot 8}{8+8} 8{,}76^2$$

$$D_{\text{full}} = 28\,856\,517\ \text{Nmm}$$

Non-dimensional shear transfer coefficient:

$$\eta_{2\mathrm{D}} = \frac{1}{1 + \frac{h_{\text{int}} \cdot E}{G_{\text{int}} \cdot (1-\nu^2)} \cdot \frac{D_{\text{abs}}}{D_{\text{full}}} \cdot \frac{h_1 h_2}{h_1 + h_2} \cdot \psi} = \frac{1}{1 + \frac{0{,}76 \cdot 70000}{0{,}44 \cdot (1-0{,}22^2)} \cdot \frac{6277147}{28856517} \cdot \frac{8 \cdot 8}{8+8} 6{,}969 \cdot 10^{-6}}$$

$$\eta_{2\mathrm{D}} = 0{,}565$$

Ψ designates the coefficient taking the support and load conditions, as well as the size of the laminate, into consideration; defined in Table 6.4 in [3]:

$$\psi = 6{,}969 \cdot 10^{-6} \text{mm}^{-2}$$

Deflection effective thickness:

$$h_{\mathrm{w}} = \sqrt[3]{\frac{1}{\frac{\eta}{h_1{}^3 + h_2{}^3 + 12 \cdot I_s} + \frac{1-\eta}{h_1{}^3 + h_2{}^3}}} = \sqrt[3]{\frac{1}{\frac{0{,}565}{8^3+8^3+12 \cdot 307{,}0} + \frac{1-0{,}565}{8^3+8^3}}} = 12{,}24\ \text{mm}$$

Stress effective thickness:

$$h_{1,\sigma} = h_{2,\sigma} = \sqrt{\frac{1}{\frac{2\eta |d_1|}{h_1{}^3 + h_2{}^3 + 12 \cdot I_s} + \frac{h_1}{h_{\mathrm{w}}{}^3}}} = \sqrt{\frac{1}{\frac{2 \cdot 0{,}565 \cdot 4{,}38}{8^3+8^3+12 \cdot 307{,}0} + \frac{8}{12{,}24^3}}} = 13{,}60\ \text{mm}$$

6.1.4 Comparison

The deflection effective and stress effective thickness values are calculated with three different methods. The values are summarized in Table 6.1.

Table 6.1: Summary of the estimated values for the effective thickness

	Deflection effective thickness	Stress effective thickness
ASTM E1300-16	13,06 mm	14,32 mm
PrEN 16612	12,86 mm	14,15 mm
CNR-DT 210	12,24 mm	13,60 mm

According to the literature ([3] [32]), the most accurate approximation of the effective thickness can be given by using the Enhanced Effective Thickness (EET) method, proposed also in the Italian Recommendations. The difference in the results is mostly due to the fact, that the geometry and size of the element are not considered accurately enough, or as in the case of the draft standard, not considered at all. To show the effect of this difference in the calculation methods, the effective thickness values are calculated for a 10.10.2[4] rectangular laminate, with one varying side length and one fixed side with a length of 5000 mm. The results are shown in Fig. 6.2. For the sake of comparison, the values given by the American and the European draft standard are converted into relative values, using the EET method as reference. The details of these calculations can be found in the Appendix.

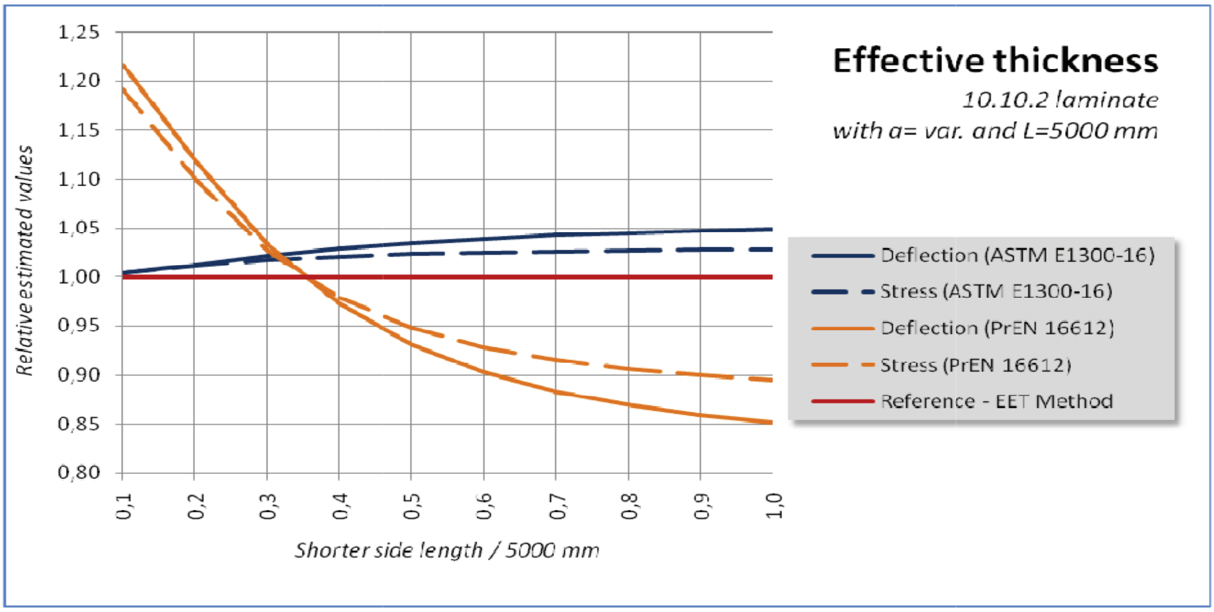


Fig. 6.2: Estimated effective thickness values relative to the results of the EET-method for a 10.10.2 laminate with various side dimensions

As it is clearly shown above, the Wölfel-Bennison model delivers result very close to the EET-method. The American code is especially accurate in case of beam-like members;

[4] The laminates are referred to as follows: the composition is given by three numbers separated by dots, whereas the first two numbers represent the thickness of the two glass plies; and the third figure denotes the proportion of the interlayer's thickness to 0,38 mm.

whereas applied for square elements, the evaluated effective thickness values are higher than the ones proposed by the Italian Recommendations.

The effective thickness values are estimated for two further exemplary elements, one with dimensions of 2000 x 1500 mm and one with 2000 x 2000 mm. In both cases, several laminate compositions are examined. The results are shown in Fig 6.3 and Fig 6.4.

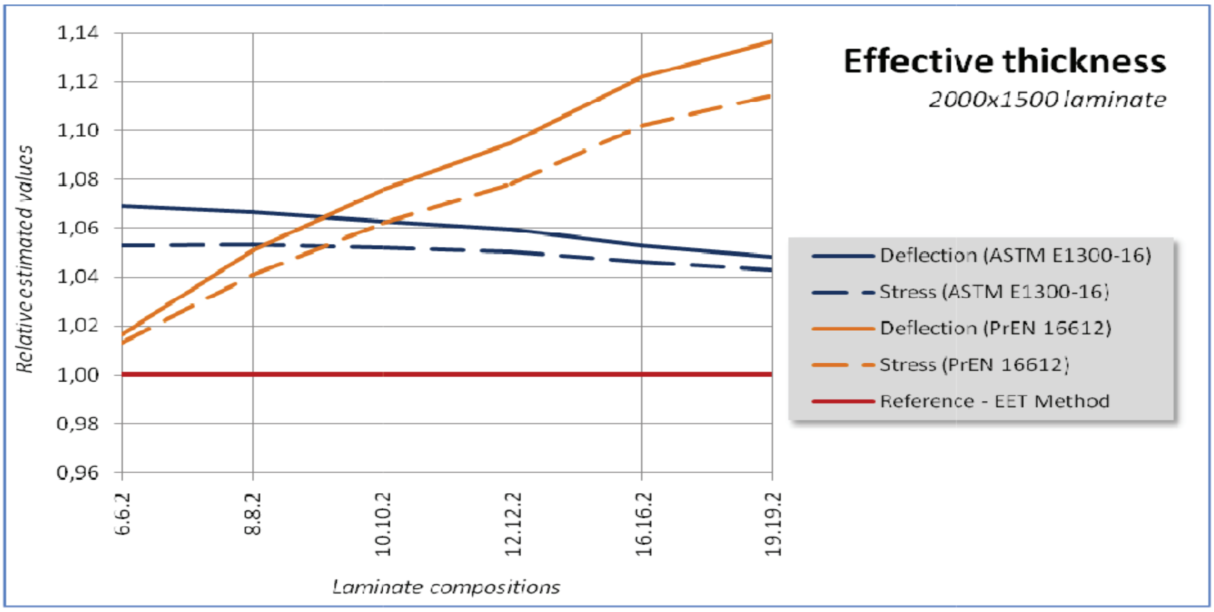


Fig. 6.3: Estimated effective thickness values relative to the results of the EET-method for various compositions – Laminate size 2000x1500 mm

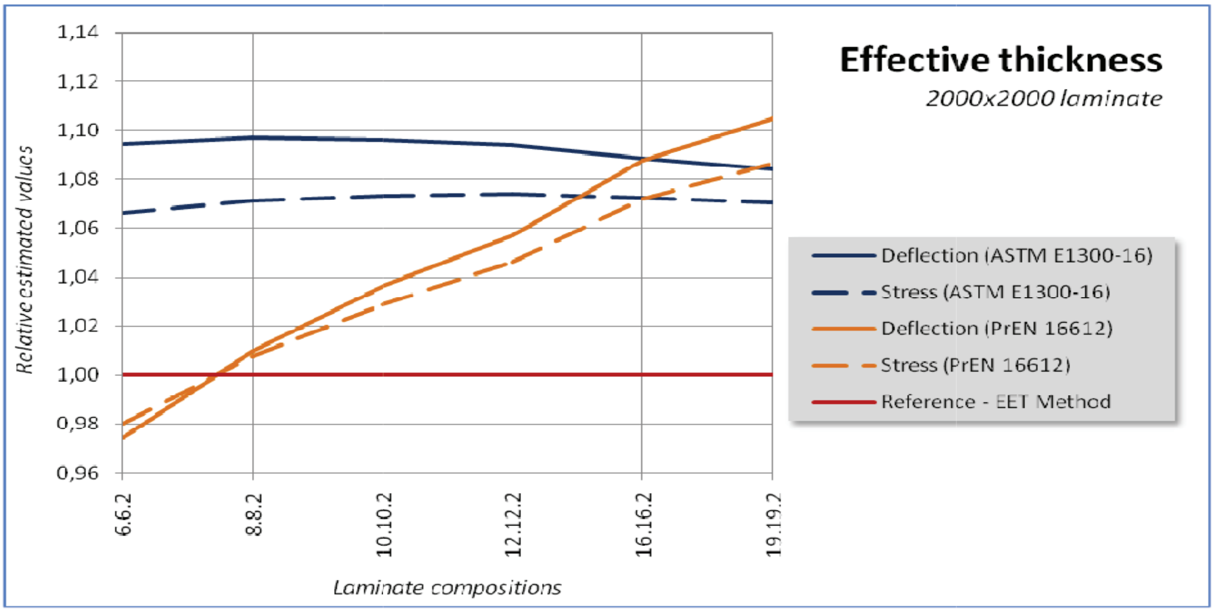


Fig. 6.4: Estimated effective thickness values relative to the results of the EET-method for various compositions – Laminate size 2000 x 2000 mm

As the figures above show, both the American code and the European draft standard give higher values for the effective thickness of the laminate than the EET method. Assuming, that the values estimated by the latter are correct, the other two methods deliver results, which are - in most design cases - not on the safe side. While the proportion of the values given by ASTM and the EET method is almost independent of the glass composition, the draft standard errs more if the thickness of the laminate is increased.

6.2 Insulation glass

The following chapter presents the calculation of two simple insulating units. Section 6.2.1 illustrates the different ways of handling the effect of load duration, whereas the calculated element is a unit consisting of two monolithic plies. Section 6.2.2 presents a glazing element consisting of a monolithic ply and a laminate; aiming to present, how the estimated effective thickness influences the load sharing between the glass components

6.2.1 Double glazed unit with monolithic plies

This example of a rather simple glass composition should illustrate the complexity of the different design methods proposed in the American code and the European documents. It is not intended to present the differences in the level of safety; consequently, and to keep the calculation short, the stress verification is not shown here.

The exemplary glazing unit, shown in Fig. 6.5, is supported along all edges, consists of an 8 mm thick heat-strengthened and a 12 mm thick annealed glass ply, both with dimensions of 3000x1500 mm, separated by a 16 mm cavity. The unit is positioned horizontal, with its 8 mm ply on the top.

The glazing is subjected to the following loads:

- Dead load (permanent duration): estimated with 2500 kg/m^3 density,
- Wind suction (short duration): $w_k = 0{,}40$ kN/m^2,
- Snow load (long duration): $s_k = 1.2$ kN/m^2,
- Climatic loading (intermediate duration): $p_0 = +16$ kPa in summer, $p_0 = -16$ kPa in winter [19].

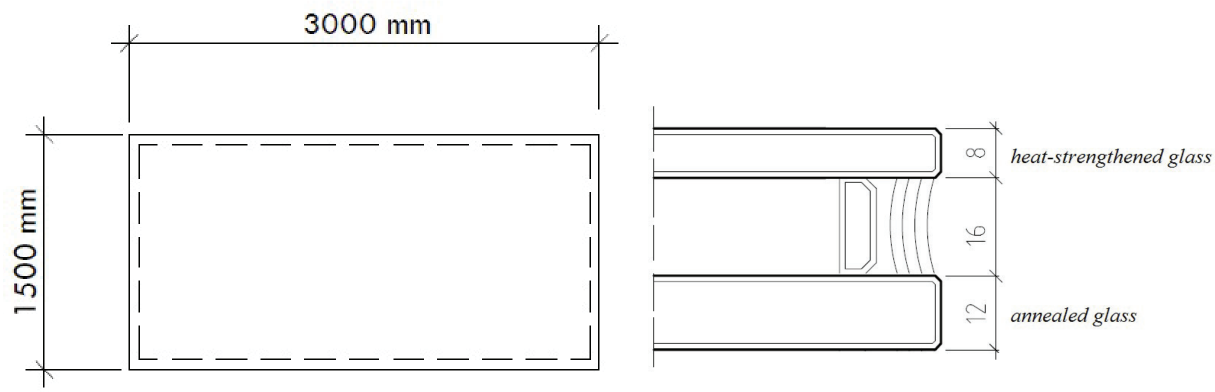


Fig. 6.5: Double glazed insulating unit

6.2.1.1 Calculation according to ASTM E1300-16

In the first step, the load resistance of the glazing unit is estimated with the glass chart method proposed in the American code, as presented in 4.3.2. The charts for the two monolithic plies are shown in Fig. 6.6.

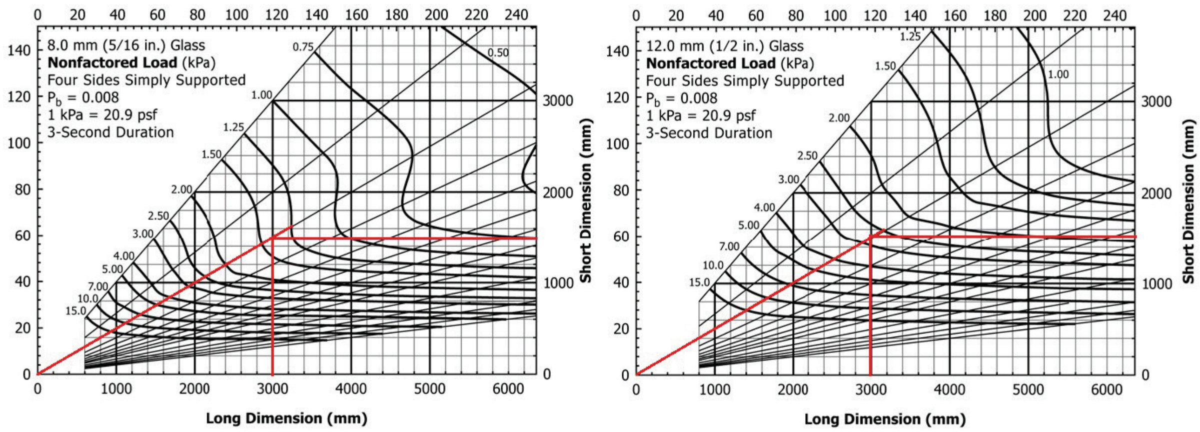


Fig. 6.6: Charts for 8 mm and 12 mm thick glass plies ([2], A1.8 and A1.10)

Non-factored load for the 8 mm ply (HS glass): $NFL_1 = 1{,}35$ kN/m^2

Non-factored load for the 12 mm ply (AN glass): $NFL_2 = 2{,}75$ kN/m^2

Glass type factors for 3 sec. duration loads ([2], Table 2.): $GTF_{1,S} = 1{,}9$ $GTF_{2,S} = 1{,}0$

Load share factors ([2], Table 5.): $LSF_1 = 0{,}195$ $LSF_2 = 0{,}805$

Load resistance for a 3 sec. duration load:

8 mm pane (HS glass): $$LR_{1,S} = \frac{NFL_{1,} \cdot GTF_{1,S}}{LSF_1} = \frac{1{,}35 \cdot 1{,}9}{0{,}195} = 13{,}2\ \mathrm{kN/m^2}$$

12 mm pane (AN glass): $$LR_{2,S} = \frac{NFL_2 \cdot GTF_{2,S}}{LSF_2} = \frac{2{,}75 \cdot 1{,}0}{0{,}805} = 3{,}4\ \mathrm{kN/m^2}$$

Load resistance of the glazing unit: $LR = 3{,}4\ \mathrm{kN/m^2}$

As next step, the loads are distributed between the glass plies, using the load share factors estimated above. Since neither the ASTM E1300-16, nor the American load standard [1] defines the intensity of climatic load, the values given in the German Technical Regulations (TRXV) will be used in this example. For the distribution of the climatic load, the following factors are required:

Characteristic edge length: $$a^* = 28{,}9 \cdot \sqrt[4]{\frac{d_{\mathrm{SZR}} \cdot {d_\mathrm{a}}^3 \cdot {d_\mathrm{i}}^3}{\left({d_\mathrm{a}}^3 + {d_\mathrm{i}}^3\right) \cdot B_\mathrm{V}}}$$

$$a^* = 28{,}9 \cdot \sqrt[4]{\frac{16 \cdot 8^3 \cdot 12^3}{(8^3 + 12^3) \cdot 0{,}0501}} = 545 \text{ mm}$$

Insulating glass factor:

$$\varphi = \frac{1}{1 + \left(\frac{a}{a^*}\right)^4} = \frac{1}{1 + \left(\frac{1500}{545}\right)^4} = 0{,}017$$

The TRLV [19] defines the value of climatic load as ±16 kPa, whereas the positive load occurs in summer, causing an excess pressure in the cavity, and the negative load occurs in winter, resulting in a lower internal pressure. The climatic load is distributed equally between the plies:

$$p_1 = p_2 = \pm\varphi \cdot p_0 = \pm 0{,}017 \cdot 16 \text{ kPa} = 0{,}27 \text{ kN/m}^2$$

The other load cases, distributed between the plies, are summarized below. Positive values represent loads pointing downwards.

	Share on the 8 mm ply	Share on the 12 mm ply	Duration
Dead load	+ 0,20 kN/m^2	+ 0,30 kN/m^2	50 years
Wind load	- 0,08 kN/m^2	- 0,32 kN/m^2	15 minutes
Snow load	+ 0,23 kN/m^2	+ 0,97 kN/m^2	3 months
Climatic load	± 0,27 kN/m^2	± 0,27 kN/m^2	12 hours

Using the values above, an equivalent design load with a duration of 3 sec is calculated, with the means of Eq. (4.1) given in 4.4.2. The load combinations to be inspected are summarized below, showing the design load values with bold letters. The fact, that snow load usually does not occur simultaneously with "summer" climatic action is in this case disregarded; the intention is to show all load combinations.

Equivalent, 3 sec. combined load	Share on the 8 mm ply	Share on the 12 mm ply	Duration
Self-weight + snow + climatic load winter	**+ 1,73 kN/m^2**	+ 2,84 kN/m^2	3 sec
Self-weight + snow + climatic load summer	+ 0,75 kN/m^2	**+ 3,82 kN/m^2**	3 sec
Self-weight - wind + climatic load winter	+ 1,08 kN/m^2	+ 0,10 kN/m^2	3 sec
Self-weight - wind + climatic load summer	+ 0,10 kN/m^2	+ 1,09 kN/m^2	3 sec

At last, the estimated design load values are compared with the load resistance of the glazing unit: in this case, the load bearing capacity of the element is not sufficient.

6.2.1.2 Calculation according to TRLV

Regarding the consideration of the load duration, the design approach presented in the German Technical Regulation [19] is similar to the American method. The method does not require the breakdown of the climatic load into intermediate and short duration parts: in this regard, the method is simplified compared to the one proposed in the DIN Standard.

The characteristic edge length and the insulating glass factor are calculated as shown in 6.2.1.1. Regarding the load share factors, the values are defined differently in the American code and TRLV, resulting in a 3,4 % difference.

Load share factors: $\delta_{8\text{mm}} = \frac{8^3}{8^3+12^3} = 0{,}229$ $\delta_{12\text{mm}} = \frac{12^3}{8^3+12^3} = 0{,}771$

Characteristic edge length: $a^* = 545\ mm$, see 6.2.1.1

Insulating glass factor: $\varphi = 0{,}017$, see 6.2.1.1

The distribution of the load cases, shown with formulas and the actual values, is summarized below. As it is noted in the tables, the duration of the single load cases is not relevant for the verification.

	Share on the 8 mm ply	Share on the 12 mm ply	Duration
Dead load	calculated as in 6.2.1.1		not relevant
Wind load	$(\delta_a+\varphi\delta_i)\cdot w_a$	$(1-\varphi)\ \delta_i\cdot w_a$	not relevant
Snow load	$(\delta_a+\varphi\delta_i)\cdot s$	$(1-\varphi)\ \delta_i\cdot s$	not relevant
Climatic load	calculated as in 6.2.1.1		not relevant

	Share on the 8 mm ply	Share on the 12 mm ply	Duration
Dead load	+ 0,20 kN/m^2	+ 0,300 kN/m^2	not relevant
Wind load	- 0,10 kN/m^2	- 0,30 kN/m^2	not relevant
Snow load	+ 0,29 kN/m^2	+ 0,91 kN/m^2	not relevant
Climatic load	± 0,27 kN/m^2	± 0,27 kN/m^2	not relevant

The load combinations for the verification of the two plies, acc. to TRLV:

Load combination	Share on the 8 mm ply	Share on the 12 mm ply	Duration
Self-weight + snow + climatic load winter	**+ 0,76 kN/m^2**	+ 0,94 kN/m^2	not relevant
Self-weight + snow + climatic load summer	+ 0,22 kN/m^2	**+ 1,48 kN/m^2**	not relevant
Self-weight - wind - climatic load winter	+ 0,37 kN/m^2	- 0,27 kN/m^2	not relevant
Self-weight - wind - climatic load summer	- 0,17 kN/m^2	+ 0,27 kN/m^2	not relevant

With the help of a FE-Software or engineering tables (e.g. [42]) the principal stresses can be estimated and compared with the permissible stress values defined in TRLV.

6.2.1.3 Calculation according to DIN/ÖNORM/PrEN

The German DIN 18008 [5], as well as the Austrian national standard [12] and the European draft [14] define the load share factors, the characteristic edge length and the insulating glass factors the same way, as the TRLV.

Load share factors: $\delta_{8\text{mm}} = \frac{8^3}{8^3+12^3} = 0{,}229$ $\delta_{12\text{mm}} = \frac{12^3}{8^3+12^3} = 0{,}771$

Characteristic edge length: $a^* = 545\ mm$, see 6.2.1.1

Insulating glass factor: $\varphi = 0{,}017$, see 6.2.1.1

Opposed to the German Regulations, the load duration of the single load cases becomes relevant in the European national and draft standards. The duration is taken into consideration with the k_{mod} factor, presented in chapter 4.4. The standards defined these factors for permanent loads, as well as for actions with short and intermediate duration.

As a consequence of the consideration of the load duration, the German Standard requires the breakdown of the climatic load. The pressure difference in the air cavity has to be divided into permanent part, caused by the altitude difference, and into intermediate duration part, caused by temperature changes. The DIN 18008 defines the climatic load, considering the partition, as follows:

$$p_{0,\text{summer}} = p_{0,\text{summer,perm}} + p_{0,\text{summer,interm}} = 7{,}2\text{ kPa} + 8{,}8\text{ kPa} = +16{,}0\text{ kPa}$$

$$p_{0,\text{winter}} = p_{0,\text{winter,perm}} + p_{0,\text{winter,interm}} = -3{,}6\text{ kPa} - 12{,}5\text{ kPa} = -16{,}1\text{ kPa}$$

The distribution of the load cases, including their duration and considering the above definition of the climatic load, is shown below.

	Share on the 8 mm ply	Share on the 12 mm ply	Duration
Dead load	calculated as in 6.2.1.1		permanent
Wind load	$(\delta_a+\varphi\delta_i)\cdot w_a$	15 minutes	short
Snow load	$(\delta_a+\varphi\delta_i)\cdot s$	3 months	intermediate
Climatic load winter	$-\varphi\cdot p_{0,\text{winter,perm}}$	$+\varphi\cdot p_{0,\text{winter,perm}}$	permanent
Climatic load winter	$-\varphi\cdot p_{0,\text{winter,interm}}$	$+\varphi\cdot p_{0,\text{winter,interm}}$	intermediate
Climatic load summer	$+\varphi\cdot p_{0,\text{summer,perm}}$	$-\varphi\cdot p_{0,\text{summer,perm}}$	permanent
Climatic load summer	$+\varphi\cdot p_{0,\text{summer,interm}}$	$-\varphi\cdot p_{0,\text{summer,interm}}$	intermediate

Using the actual load intensity values:

	Share on the 8 mm ply	Share on the 12 mm ply	Duration
Dead load	+ 0,20 kN/m^2	+ 0,300 kN/m^2	permanent
Wind load	- 0,10 kN/m^2	- 0,30 kN/m^2	short
Snow load	+ 0,29 kN/m^2	+ 0,91 kN/m^2	intermediate
Climatic load winter	- 0,12 kN/m^2	+ 0,12 kN/m^2	permanent
Climatic load winter	- 0,15 kN/m^2	+ 0,15 kN/m^2	intermediate
Climatic load summer	+ 0,06 kN/m^2	- 0,06 kN/m^2	permanent
Climatic load summer	+ 0,21 kN/m^2	- 0,21 kN/m^2	intermediate

The peculiarity of the European standard is that the effect of the load duration is taken into consideration by the k_{mod} factor; meaning, that the design strength of annealed glass can be different, load combination respectively. As discussed in chapter 4.4, the modifying factor depends on the load duration: in the case of a combination of actions, the load case with the shortest duration is governing. This results in a calculation method, which requires the verification of significantly more load combinations, than the American Standard. The load combinations to be taken into consideration are listed below, whereas G designates the self-weight, S the snow, W the wind and CL the climatic load. As in the calculation according to the American Standard, all combinations are listed here as well, disregarding the fact that snow load and "summer" climatic load usually do not occur simultaneously. For the sake of simplicity, the actual values of the combined design loads are not estimated here.

Nr.	**Permanent action x 1,35**	**Governing load x 1,5**	**Additional loads x 1,5 x 0,6**	**k_{mod} factor acc. to**
LC1	G + $CL_{winter,perm}$	S	-	Snow load
LC2	G + $CL_{winter,perm}$	S	W	Wind load
LC3	G + $CL_{winter,perm}$	S	$CL_{winter,interm}$	Climatic load
LC4	G + $CL_{winter,perm}$	S	W + $CL_{winter,interm}$	Wind load
LC5	G + $CL_{winter,perm}$	W	-	Wind load
LC6	G + $CL_{winter,perm}$	W	S	Wind load
LC7	G + $CL_{winter,perm}$	W	$CL_{winter,interm}$	Wind load
LC8	G + $CL_{winter,perm}$	W	S + $CL_{winter,interm}$	Wind load
LC9	G + $CL_{winter,perm}$	$CL_{winter,interm}$	-	Climatic load
LC10	G + $CL_{winter,perm}$	$CL_{winter,interm}$	S	Climatic load
LC11	G + $CL_{winter,perm}$	$CL_{winter,interm}$	W	Wind load
LC12	G + $CL_{winter,perm}$	$CL_{winter,interm}$	S + W	Wind load

Nr.	Permanent action x 1,35	Governing load x 1,5	Additional loads x 1,5 x 0,6	k_{mod} factor acc. to
LC13	G + $CL_{summer,perm}$	S	-	Snow load
LC14	G + $CL_{summer,perm}$	S	W	Wind load
LC15	G + $CL_{summer,perm}$	S	$CL_{summer,interm}$	Climatic load
LC16	G + $CL_{summer,perm}$	S	W + $CL_{summer,interm}$	Wind load
LC17	G + $CL_{summer,perm}$	W	-	Wind load
LC18	G + $CL_{summer,perm}$	W	S	Wind load
LC19	G + $CL_{summer,perm}$	W	$CL_{summer,interm}$	Wind load
LC20	G + $CL_{summer,perm}$	W	S + $CL_{summer,interm}$	Wind load
LC21	G + $CL_{summer,perm}$	$CL_{summer,interm}$	-	Climatic load
LC22	G + $CL_{summer,perm}$	$CL_{summer,interm}$	S	Climatic load
LC23	G + $CL_{summer,perm}$	$CL_{summer,interm}$	W	Wind load
LC24	G + $CL_{summer,perm}$	$CL_{summer,interm}$	S + W	Climatic load

The strength verification would be completed with the estimation of the design strength, considering the relevant modifying factors, and the calculation of the design values of the principal stress.

6.2.1.4 Comparison

The purpose of the calculation example was to illustrate, how the consideration of the k_{mod} factor changes the verification process, making the design more complex. The schematic calculation of a simple insulating unit was carried out with the American Standard, the German Technical Regulations and the method proposed in the latest European standards.

As it is clear from the example above, the American Standard provides a simple method; the glass charts would suffice perfectly for the verification of simple rectangular elements. However, since the climatic loading is not defined in the document, the design method cannot be considered complete.

The approach proposed in the German Technical Regulations provides an equally simple solution, defining the climatic loading as well. However, it requires the estimation of the principal stresses, and it does not consider the effect of the load duration, when actions with different durations are combined.

In contrast, the method used in the latest national standards in Europe provides a definition for the climatic loading, and consider the effect of the load duration as well. This, however, results in a more time-consuming procedure, requiring the consideration of load combinations, than the other approaches.

6.2.2 Double glazed unit with monolithic and laminated plies

The purpose of this example is to illustrate the variation of the load share factors in insulating units composed of laminated glass. As presented in chapter **Hiba! A hivatkozási forrás nem található.**, the design standards propose various definitions for the effective thickness of glass laminates; consequently, the load share factors show a variety as well. This results in differences between the estimated values of load resistance.

As shown in chapter 6.1, the results of the different design procedures vary the most, if the laminate is beam shaped and is composed of relatively thick plies. The exemplary glazing unit, shown in Fig. 6.7, is composed of a 19 mm thick monolithic ply and a glass laminate of two 19 mm plies with a 1.52 mm thick PVB interlayer. The insulating unit is supported along four edges, has the outer dimensions of 5000x1000 mm. The width of the air cavity is 16 mm. The material characteristics used for the calculation of the effective thickness are the following:

Modulus of elasticity for glass:	70000 MPa
Interlayer shear modulus:	0,44 MPa

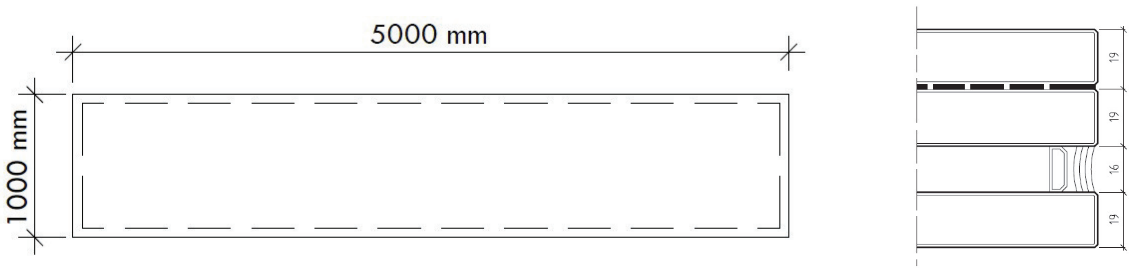


Fig. 6.7: Double glazed insulating unit with glass laminate

The calculation of a laminate, as mentioned in chapter 4.5, is usually carried out in the two limit states. In the first case, the effective thickness of the laminate is estimated assuming a rigid shear connection between the single plies (referred to as “monolith limit”). The factors for long duration loading are calculated taking a so-called “layered limit” into consideration; the shear connection between the laminate plies is in this case neglected. These two limit states are estimated in the same way in all the discussed design documents. Consequently, this comparison will concentrate on standards, which propose a method for the consideration of a partial shear coupling, namely the American code, the Italian Recommendations and the European draft standard.

6.2.2.1 Load share factors in layered and monolithic limit

The American code defines the load share factors for insulating units with glass laminates in two tables: for short duration loads in Table 5, for long duration loads in Table 6. The values represent the monolithic and the layered limit, load duration respectively.

The European standards approach the problem similarly: two limit states are verified, considering fully rigid shear coupling or none at all. The load share factor for a glass ply is estimated with the following formula in each design document:

$$LSF_{\mathrm{i}} = \frac{{d_{\mathrm{i}}}^3}{\sum {d_{\mathrm{j}}}^3} \tag{6.1),}$$

whereas d_i and d_j designate the thickness of the glass plies. The load share factors in the two limit states are as follows:

- Considering monolithic limit, for short duration loads:

  For the monolith 19 mm ply: $LSF_{19\mathrm{ply}} = \frac{19^3}{19^3+38^3} = 0{,}111$

  For the laminate: $LSF_{\mathrm{lam}} = \frac{38^3}{19^3+38^3} = 0{,}889$

- Considering layered limit, for long duration loads:

  For the monolith 19 mm ply: $LSF_{19\mathrm{ply}} = \frac{19^3}{19^3+19^3+19^3} = 0{,}333$

  For the laminate: $LSF_{\mathrm{lam}} = \frac{19^3+1\ \ ^3}{19^3+19^3+1\ \ ^3} = 0{,}666$

6.2.2.2 Load share factors according to ASTM E1600-16

As mentioned before in 4.5.2, the effective thickness of the laminate pane can also be estimated with the method proposed in the appendix X.9 of the standard. In this case, the deflection effective thickness is estimated as:

$h_{\mathrm{ef,w}} = 25{,}09\ mm$ (The calculation is carried out as in 6.1.1)

The load share factors of the monolithic pane and the laminate are then estimated with Eq. (6.1) as follows:

For the monolith 19 mm ply: $LSF_{19\mathrm{ply}} = \frac{19^3}{19^3+2\ \ ,09^3} = 0{,}303$

For the laminate: $LSF_{\mathrm{lam}} = \frac{25{,}09^3}{19^3+25{,}09^3} = 0{,}697$

6.2.2.3 Load share factors according to CNR-DT 210

As shown in section 6.1.4 and in Fig. 6.2, the Wölfel-Bennison model, used in the American code, delivers a good approximation of the effective thickness, if the element is beam shaped. With that in mind, the results of the American and Italian approaches are expected to be similar.

Without detailing the calculation here, the effective thickness of the laminate, estimated with the EET-method is:

$h_{\mathrm{ef,w}} = 24{,}22\ mm$ (The calculation is carried out as in 6.1.3)

The load share factors of the monolithic pane and the laminate are then estimated with Eq. (6.1) as follows:

For the monolith 19 mm ply: $LSF_{19\mathrm{ply}} = \frac{19^3}{19^3+24{,}22^3} = 0{,}326$

For the laminate: $LSF_{\mathrm{lam}} = \frac{24.22^3}{19^3+24{,}22^3} = 0{,}674$

6.2.2.4 Load share factors according to PrEN 16612

The deflection effective thickness, calculated with the method presented in 6.1.2 (see also Appendix):

$$h_{\mathrm{ef,w}} = 30{,}41\ mm$$

The load share factors are estimated accordingly:

For the monolith 19 mm ply: $LSF_{\mathrm{19ply}} = \frac{19^3}{19^3+30{,}41^3} = 0{,}196$

For the laminate: $LSF_{\mathrm{lam}} = \frac{30{,}41^3}{19^3+30{,}41^3} = 0{,}804$

6.2.2.5 Comparison

The results of the calculation above are summarized in Fig. 6.8, showing the load share factors in layered and monolithic limit; as well as estimated based on the effective stiffness of the laminate.

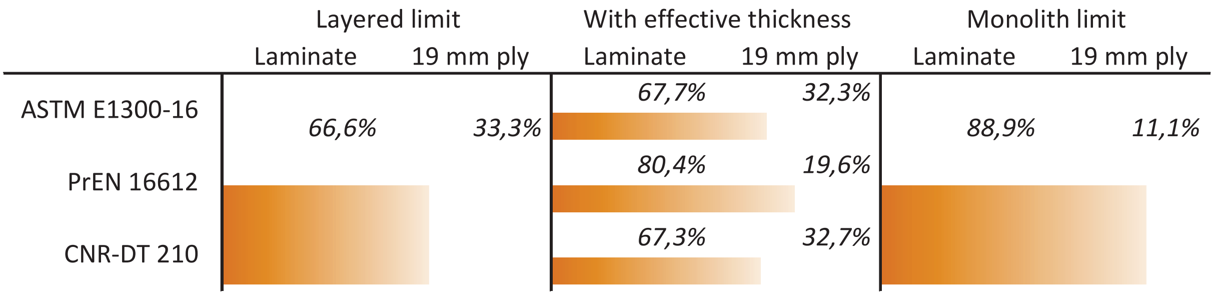


Fig. 6.8: Summary of the load share factors

Since the element is beam-shaped, the load share factors estimated with the American Standard and the Italian Recommendations, as it is expected, are basically identical: the values correspond to the layered limit. Consequently, in the case of elements with beam-like behaviour, the estimation of the effective thickness with the American or the Italian documents is not necessary. On the other hand, the results given by the draft standard are closer to the monolith limit. As shown in 6.1, effective thickness values received with the method proposed by the draft document, and consequently the load share factors as well, are questionable.

6.3 Stability analysis

The following examples intend to illustrate the verification procedures proposed in the Italian Recommendations, as presented in chapter 5. Since the other documents discussed in this thesis do not include design methods in this regard, no comparison is made here. The procedures are analogous to the one proposed for steel structural members in Eurocode 3 [10]; it is expected, that the harmonized European Standard is also going to use a similar procedure.

6.3.1 Buckling and lateral-torsional buckling

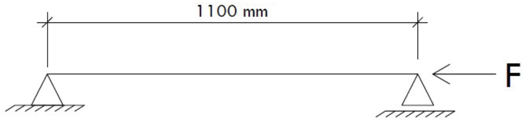
The buckling and the lateral-torsional buckling verification procedures, according to the Italian Recommendations [3], are shown on a simple calculation example. The beam-shaped, laminated glass element has a length of 1100 mm and a width of 300 mm. The laminate is composed of two 16 mm plies and a 1.52 mm thick interlayer. The beam is loaded axially in the case of buckling, and with a uniformly distributed load in the case of lateral torsional buckling. Analogous verification procedures are presented for steel members in the sections 6.3.1 and 6.3.2 in Eurocode 3 [10].

Modulus of elasticity for glass:	$E = 70000\ \mathrm{MPa}$
Shear modulus of glass:	$G = 28455\ \mathrm{MPa}$
Characteristic strength of glass for the compressed beam[5]:	$\mathrm{f_{g,k,st}} = 39{,}6\ \mathrm{MPa}$
Characteristic strength of glass for the beam under bending:	$\mathrm{f_{g,k,st}} = 25{,}9\ \mathrm{MPa}$
Design strength of glass for the compressed beam:	$\mathrm{f_{g,d}} = 15{,}8\ \mathrm{MPa}$
Design strength of glass for the beam under bending:	$\mathrm{f_{g,d}} = 10{,}4\ \mathrm{MPa}$
Interlayer shear modulus:	$0{,}44\ \mathrm{MPa}$
Deflection-effective thickness, estimated with the Wölfel-Bennison model (as in 4.5.2):	$h_{ef,w} = 21{,}54\ \mathrm{mm}$
Moment of inertia with respect to the weaker axis:	$I_{\mathrm{eq}} = \dfrac{{h_{\mathrm{ef,w}}}^3 \cdot b}{12} = \dfrac{21{,}54^3 \cdot 300}{12} = 2{,}50 \cdot 10^5\ \mathrm{mm}^4$
Torsional moment of inertia[6]:	$I_{\mathrm{t}} = 8{,}47 \cdot 10^5\ \mathrm{mm}^4$
Cross-section area of the glass parts:	$A = 2 \cdot 300 \cdot 16 = 9600\ \mathrm{mm}^2$
Elastic resistant modulus of the glass parts:	$W_{\mathrm{x}} = \dfrac{b^2 \cdot h}{6} = \dfrac{300^2 \cdot 32}{6} = 4{,}8 \cdot 10^5\ \mathrm{mm}^3$

[5] For the sake of simplicity, this example uses the same characteristic and design strength values for glass, as defined in the sections 8.7.2 and 8.7.3 in the Italian Recommendations [3], without detailing modification factors. The strength values refer to an annealed glass element subjected to a short duration load.

[6] The torsional moment of inertia adds up from the two glass plies and the torsional moment inertia of the interlayer, calculated as in 6.4.3.2 in the Italian Recommendations [3]. Here, only the result is shown.

Buckling verification



$$N_{cr}{}^{(E)} = \frac{\pi^2 E I_{eq}}{l^2}$$

$$N_{cr}{}^{(E)} = \frac{\pi^2 \cdot 70000 \cdot 2{,}50 \cdot 10^5}{1100^2} = 141{,}9\ \text{kN}$$

$$\bar{\lambda} = \sqrt{\frac{A \cdot f_{g,k,st}}{N_{cr}{}^{(E)}}} = \sqrt{\frac{9600 \cdot 39{,}6}{141{,}9 \cdot 10^3}} = 1{,}64$$

$$\phi = \frac{1 + \alpha^*(\bar{\lambda} - \alpha_0) + \bar{\lambda}^2}{2}$$

$$\phi = \frac{1 + 0{,}71(1{,}64 - 0{,}6) + 1{,}64^2}{2} = 2{,}21$$

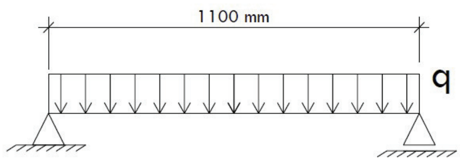
$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}}$$

$$\chi = \frac{1}{2{,}21 + \sqrt{2{,}21^2 - 1{,}64^2}} = 0{,}27$$

$$N_{b,Rd} = \chi \cdot A \cdot f_{g,d}$$

$$N_{b,Rd} = 0{,}27 \cdot 9600 \cdot 15{,}8 = 40{,}9\ \text{kN}$$

Lateral-torsional buckling verification



$$M_{cr}{}^{(E)} = C_1 \frac{\pi}{l} \cdot \sqrt{EI_{eq} \cdot GI_t} = 1{,}13 \frac{\pi}{1100} \cdot$$
$$\cdot \sqrt{7 \cdot 10^4 \cdot 2{,}50 \cdot 10^5 \cdot 28455 \cdot 8{,}47 \cdot 10^5}$$

$$M_{cr}{}^{(E)} = 66{,}3\ \text{kNm}$$

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_x \cdot f_{g,k,st}}{M_{cr}{}^{(E)}}} = \sqrt{\frac{4{,}8 \cdot 10^5 \cdot 25{,}9}{66{,}3 \cdot 10^6}} = 0{,}43$$

$$\phi = \frac{1 + \alpha^*(\bar{\lambda} - \alpha_0) + \bar{\lambda}^2}{2}$$

$$\phi = \frac{1 + 0{,}26(0{,}43 - 0{,}20) + 0{,}43^2}{2} = 0{,}62$$

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}}$$

$$\chi = \frac{1}{0{,}62 + \sqrt{0{,}62^2 - 0{,}43^2}} = 0{,}94$$

$$M_{b,Rd} = \chi_{LT} \cdot W_x \cdot f_{g,d}$$

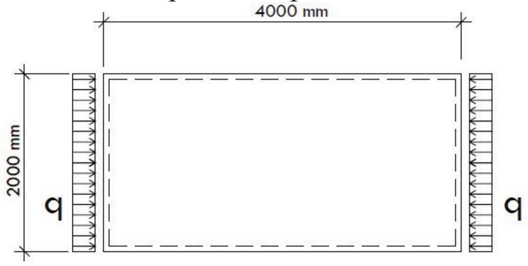
$$M_{b,Rd} = 0{,}94 \cdot 4{,}8 \cdot 10^5 \cdot 10{,}4 = 4{,}7\ \text{kNm}$$

6.3.2 In-plane compression and in-plane shear

The verification procedures for buckling as a result of in-plane compression or shear are shown in the following, simple calculation. The exemplary element is a 4000 x 2000 mm laminate with the same composition, as in the previous example. It is simply supported along all four edges, and subjected to in-plane compression or in-plane shear, failure mode respectively.

Characteristic strength of glass for the compressed unit:	$f_{g,k,st} = 39{,}6$ MPa
Characteristic strength of glass for the unit under in-plane shear:	$\tau_{g,k,st} = f_{g,k,st} = 39{,}6$ MPa
Design strength of glass for the compressed unit:	$f_{g,d} = 15{,}8$ MPa
Design strength of glass for the unit under in-plane shear:	$\tau_{g,d} = f_{g,d} = 15{,}8$ MPa
Deflection-effective thickness for the compressed unit, estimated with the Wölfel-Bennison model (as in 4.5.2):	$h_{ef,w} = 24{,}6\ mm$
Deflection-effective thickness for in-plane shear, estimated with the Wölfel-Bennison model (as in 4.5.2):	$h_{ef,w} = 21{,}2\ mm$
Cross-section area of the glass parts:	$A = 2 \cdot 2000 \cdot 16 = 64000\ \text{mm}^2$

In-plane compression



$$k_\sigma = \left(\frac{mb}{a} + \frac{a}{mb}\right)^2 = \left(\frac{1\cdot 2}{4} + \frac{4}{1\cdot 2}\right)^2 = 6{,}25$$

$$D = \frac{E{h_{\mathrm{ef,w}}}^3}{12(1-\upsilon^2)}$$

$$D = \frac{7\cdot 10^4 \cdot 24{,}6^3}{12(1-0{,}23^2)} = 9{,}17\cdot 10^7\,\mathrm{mm}^4$$

$$N_{\mathrm{cr}}{}^{(\mathrm{E})} = k_\sigma \frac{\pi^2 \cdot D}{b^2}$$

$$N_{\mathrm{cr}}{}^{(\mathrm{E})} = 6{,}25\frac{\pi^2\cdot 9{,}17\cdot 10^7}{2000^2} = 1405\ \frac{\mathrm{kN}}{\mathrm{m}}$$

$$\bar{\lambda} = \sqrt{\frac{A\cdot f_{\mathrm{g,k,st}}}{N_{\mathrm{cr}}{}^{(\mathrm{E})}}} = \sqrt{\frac{6{,}4\cdot 10^4\cdot 39{,}6}{2810\cdot 10^3}} = 0{,}95$$

$$\phi = \frac{1+\alpha^*\left(\bar{\lambda}-\alpha_0\right)+\bar{\lambda}^2}{2}$$

$$\phi = \frac{1+0{,}49(0{,}95-0{,}80)+0{,}95^2}{2} = 0{,}99$$

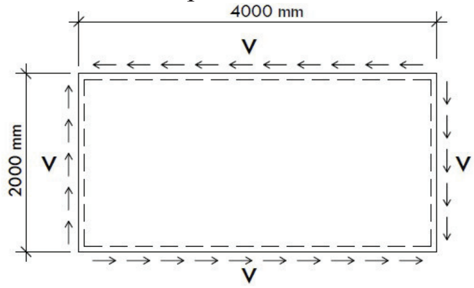
$$\chi = \frac{1}{\phi+\sqrt{\phi^2-\bar{\lambda}^2}}$$

$$\chi = \frac{1}{0{,}99+\sqrt{0{,}99^2-0{,}95^2}} = 0{,}79$$

$$N_{\mathrm{b,Rd}} = \chi\cdot A\cdot f_{\mathrm{g,d}}$$

$$N_{\mathrm{b,Rd}} = 0{,}79\cdot 64000\cdot 15{,}8 = 798{,}8\ \mathrm{kN}$$

In-plane shear



$$k_\tau = 5{,}34 + \frac{4{,}00}{(a/b)^2} = 5{,}34 + \frac{4{,}00}{2^2} = 6{,}34$$

$$D = \frac{E{h_{\mathrm{ef,w}}}^3}{12(1-\upsilon^2)}$$

$$D = \frac{7\cdot 10^4\cdot 21{,}2^3}{12(1-0{,}23^2)} = 5{,}87\cdot 10^7\,\mathrm{mm}^4$$

$$V_{\mathrm{cr}}{}^{(\mathrm{E})} = \kappa^\tau \frac{\pi^2\cdot D}{b^2}$$

$$V_{\mathrm{cr}}{}^{(\mathrm{E})} = 6{,}34\cdot\frac{\pi^2\cdot 5{,}87\cdot 10^7}{2000^2} = 912{,}7\ \frac{\mathrm{kN}}{\mathrm{m}}$$

$$\bar{\lambda} = \sqrt{\frac{A\cdot \tau_{\mathrm{g,k,st}}}{V_{\mathrm{cr}}{}^{(\mathrm{E})}}} = \sqrt{\frac{6{,}4\cdot 10^4\cdot 39{,}6}{1825\cdot 10^3}} = 1{,}18$$

$$\phi = \frac{1+\alpha^*\left(\bar{\lambda}-\alpha_0\right)+\bar{\lambda}^2}{2}$$

$$\phi = \frac{1+0{,}49(1{,}18-0{,}50)+1{,}18^2}{2} = 1{,}36$$

$$\chi = \frac{1}{\phi+\sqrt{\phi^2-\bar{\lambda}^2}}$$

$$\chi = \frac{1}{1{,}36+\sqrt{1{,}36^2-1{,}18^2}} = 0{,}49$$

$$V_{\mathrm{b,Rd}} = \chi\cdot A\cdot \tau_{\mathrm{g,d}}$$

$$V_{\mathrm{b,Rd}} = 0{,}49\cdot 64000\cdot 15{,}8 = 495{,}5\ \mathrm{kN}$$

7. Summary and outlook

The thesis has reviewed the most commonly used standards in the field of architectural glass design, and provided a general comparison of the American ASTM E1300-016 standard with the most influential European design documents. The chapters above discussed the scope of application of each standard, their safety concept and general verification procedure, as well as the proposed methods for handling load duration, laminated and insulating glass. In addition, the thesis gives a brief overview of the special design situations yet to be standardized, such as stability analysis and design in seismic areas. At the end of the comparison, some of the different design approaches were highlighted by means of calculation examples.

In conclusion, the ASTM E1300-16 differs from the European documents not only regarding its structure and general approach to glass design, but in other aspects as well. As presented in section 4.1, the scope of the American code, compared to most European standards, is relatively limited, as it is only applicable to linearly supported glazing elements. Opposed to that, the latest national standards in Europe already provide design methods for most of the conventional glazing formations, such as point-wise supported or barrier glazings. Section 4.2 presented one of the most significant differences: the ASTM standard is based on the allowable stress method, whereas the current European standards all use the limit state design approach.

The general verification procedure of the American code, as presented in section 4.3, is completely different from the ones used in the European standards. In simple cases, the verification procedure presented in the ASTM standard does not require the calculation of stresses; opposed to that, the strength verification using European documents is always carried out on the level of stresses. The glass charts of ASTM, based on empirical data, provide a straightforward approach for the design of simple elements.

Based on the same scientific background and using a common pool of research data, the standards propose similar design methods for the remaining three discussed aspects: handling of the load duration, laminated glass and insulating units. The effect of the load duration on the resistance of annealed glass, as presented in 4.4, is taken into consideration by the American and by the European standards as well. While the European documents propose the application of the k_{mod} factor, the American code includes the effect of stress fatigue in its glass type factors. However, significant differences arise, when it comes to the combination of load cases with different durations: as shown in the calculation example in section 6.2.1, the European standards require a more complex verification, than the ASTM E1300-16.

Concerning laminated glass, as it is discussed in chapters 4.5, the American code proves to be more applicable, than most of the European standards. The design method proposed by ASTM delivers accurate results for beam-like laminates, as it is shown in 6.1. However, for the design of plate-like glazing parts, or elements with less conventional loading or support conditions, the application of the EET-method, presented in 4.5.1, is recommended. A more significant difference between the American and European documents is presented in 4.6:

although the load sharing phenomena of insulating units is well described in all documents, the American code does not define climatic loading. Since this load case is not mentioned in the general load standard, published by ASCE [1], the design of insulating units requires additional documents beside the ASTM standard.

The standardization in the field of architectural glass appears to be promising, both in Europe and the United states. As several applications, such as structural glass, fire glazings, seismic design or bomb blast protective facades are not included in most design documents yet, the engineering community has high expectations towards the upcoming Eurocode and ASTM publications.

As far as the European standards are concerned, the development of the national documents is suspended, as a new Eurocode, a harmonized glass standard is to be published in 2019. The standard is currently under development by CEN. As mentioned in the earlier chapters, documents, such as the draft standards [13] [14] and the JRC Report [27] have proposed various design methods to be included in the new standard. The Eurocode 10 shall include harmonized design approaches not only for conventional glazing elements, but for glass parts functioning as primary structural members as well.

Regarding the American standardization, ASTM has established several so-called Work Items, which shall concern glass design [45]. A Work Item, as ASTM defines it, is a proposed new standard or revision under development. Three new documents have been announced, the most promising of which is the Work Item nr. WK37764, titled as “New Guide for Structural Use of Glass in Buildings”. The code shall cover the structural application of glass, complementing the existing E1300 series. The latter will be revised: the Work Item nr. WK58053 designates the new issue of the glass standard presented in this thesis. The third document announced shall cover glass railings and balustrades; it is being prepared under the designation Work Item nr. WK37764.

8. List of Figures

9. List of Tables

10. Bibliography

Standards

[1] ASCE/SEI Standard 7-16: Minimum Design Loads for Buildings and Other Structures. ASCE, 2016

[2] ASTM E1300-16: Standard Practice for Determining Load Resistance of Glass in Buildings. ASTM International, 2016

[3] CNR-DT 210/2013: Guide for the Design, Construction and Control of Buildings with Structural Glass Elements. CNR, Roma, 2013

[4] DIN 1055: Einwirkungen auf Tragwerke. Deutsches Institut für Normung.

[5] DIN 18008: Glas im Bauwesen - Bemessungs- und Konstruktionsregeln, Teil 1-7. Deutsches Institut für Normung

[6] DIN 18800-1: Stahlbauten, Bemessung und Konstruktion. Deutsches Institut für Normung, 11/1990

[7] EN 1990: Basis of structural design. CEN

[8] EN 1991: Actions on structures. CEN

[9] EN 1992: Design of concrete structures - Part 1-1: General rules and rules for buildings. CEN

[10] EN 1993: Design of steel structures - Part 1-1: General rules and rules for buildings. CEN

[11] EN 1998: Design of structures for earthqueake resistance - Part 1.: General rules, seismic actions and rules for buildings. CEN

[12] ÖNORM B 3716: Glas im Bauwesen – Konstruktiver Glasbau. Austrian Standards. 02/2012

[13] PrEN 13474: Glass in building - Determination of the strength of glass panes by calculation and testing. Draft standard. CEN, 2012

[14] PrEN 16612: Glass in building - Determination of the load resistance of glass panes by calculation and testing. Draft stanard. CEN, 2013

[15] PrEN 16613: Glass in building - Laminated glass and laminated safety glass - Determination of interlayer mechanical properties. Draft standard. CEN, 2013

[16] Technische Regeln für die Bemessung und die Ausführung punktförmig gelagerter Verglasungen. DIBt, 8/2006

[17] Technische Regeln für die Verwendung von absturzsichernden Verglasungen. DIBt, 1/2003

[18] Technische Regeln für die Verwendung von linienförmig gelagerten Überkopf-Verglasungen. DIBt, 5/1996

[19] Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen. DIBt, 6/1998

[20] Technische Regeln für die Verwendung von linienförmig gelagerten Vertikalverglasungen. DIBt, 4/1997

General literature

[21] Beason: Basis for ASTM E 1300 annealed glass thickness selection charts. In: J. Struc. Eng. 124(2), 215-221., 1998

[22] Beason; Morgan: Glass failure prediction model. In: J. Struc. Eng., 110(2), 197-212., 1984

[23] Bedon, C., Amadio, C.: Design buckling curves for glass columns and beams. Structures and Buildings, Volume 168 (2015), Issue SB7, Pages 514-526

[24] Bennison, SJ. et. al.: Structural performance of laminated glass made with a ‘‘stiff’’ interlayer. In: Glass Performance Days; 2001. page 1–9.

[25] Bosia, Kara: Design Engineering Refocused. Wiley, 2016

[26] Farkas, Gy. et. al: Betonszerkezetek méretezése az Eurocode alapján. Terc Kiadó. Budapest. 2008
Farkas, Gy. et. al: Design of concrete structures accoding to Eurocode. Terc Kiadó. Budapest. 2008

[27] Feldmann, M. et. al.: Guidance for European Structural Design of Glass Components, JRC Scientific and policy reports, Report EUR 26439 EN, 2014

[28] Flannery, P.: The evolution of ASTM E 1300, Online article, accessed: 17.08.2012. https://www.fenestrationreview.com/codes-standards/the-evolution-of-astm-e-1300-35

[29] Freitag, C., Wörner, J.-D.: Verwendung von Glas zur Aussteifung von Gebäuden. Stahlbau Spezial 2011 - Glasbau / Glass in Building. Pages 45-51.

[30] Galuppi, L., Manara, G., Carfagni, G. R.: Practical expressions for the design of laminated glass, Composites Part B: Engineering, Volume 45, Issue 1, February 2013, Pages 1677-1688

[31] Galuppi, L., Royer-Carfagni, G.: Effective thickness of laminated glass beams. New expression via a variational approach. Eng. Struct. (2012); Vol.38. page 53–67.

[32] Galuppi, L., Royer-Carfagni, G.: The effective thickness of laminated glass: Inconsistency of the formulation in a proposal of EN-standards, Composites Part B: Engineering, Volume 55, December 2013, Pages 109-118

[33] Gy, René: Stress corrosion of silicate glass: a review. Journal of Non-Crystalline Solids, Volume 316, Issue 1, February 2003, Pages 1-11

[34] Langosch, K.; Feldmann, M.: VSG-Glasstützen unter kombinierter Langzeit- und Kurzzeitbelastung. Stahlbau, 81 (2012): 149–158.

[35] Mocibob, D.: Glass Panel under Shear Loading - Use of Glass Envelopes in Building Stabilization. Dissertation, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne 2008

[36] Quiang, L. et. al: Investigation on flexural buckling of laminated glass columns under axial compression. Engineering Structures 133 (2017), pages 14-23

[37] Serafinavicius, T. et. al.: Bending Behavior of Structural Glass Laminated With Different Interlayers. Mechanics of Composite Materials, September 2013, Vol. 49 page 437-446

[38] Siebert, G.: Aktueller Stand der Glasnormung. Stahlbau, 84: 21–29. 2015
[39] Siebert, G.: Aktueller Stand der Glasnormung. Stahlbau, 85: 113–120. 2016
[40] Siebert; Maniatis: Tragende Bauteile aus Glas. Grundlagen, Entwurf und Bemessung, Beispiele. 2. Auflage. 2013
[41] Weibull, W.: A statistical theory of the strength of materials. Ingeniorsvetenskapsakademiens, Hanglinger, NR 151, Stockholm, 1939
[42] Weller, B. et. al: Berechnungstafeln für den Konstruktiven Glasbau. Stahlbau, 75: 479-487, 2006
[43] Wölfel E., Elastic Composite: An Approximation Solution and its Application Possibilities, Stahlbau, 6: 173–180, 1987

Online sources

[44] Website of ASTM International. Accessed 07.04.2017. https://www.astm.org/ABOUT/full_overview.html
[45] Website of ASTM International. Accessed: 19.07.2017. https://www.astm.org/DATABASE.CART/workitems.htm
[46] Website of Austrian Standards. Accessed 05.04.2017. www.austrian-standards.at
[47] Website of Beuth Verlag GmbH. Accessed 07.04.2017. http://www.beuth.de
[48] Website of Guardian Glass. Accessed: 01.07.2017.https://www.guardianglass.com/commercial/ToolsandResources/Resources/GlossaryandTerms/InsulatingGlass/index.htm
[49] Website of iDesignArch. Accessed: 08.06.2017. http://www.idesignarch.com/apple-store-fifth-avenue-new-york/
[50] Website of the co. Bohlin Cywinski Jackson. Accessed: 08.06.2017. http://bcj.com/projects/apple-store-fifth-avenue/
[51] Website of the co. Seele. Accessed: 08.06.2017. https://seele.com/references/apple-retail-store-5th-avenue-new-york/
[52] Website of the co. Werner Sobek. Accessed: 08.06.2017. http://www.wernersobek.de/en/projects/material/glass/etihad-museum/
[53] Website of the Deutsches Institut für Bautechnik. Accessed: 08.04.2017. www.dibt.de
[54] Website of the National Research Council of Italy. Accessed: 08.04.2017. https://www.cnr.it/en/about-us
[55] Website of Trosifol. Accessed: 01.05.2017. http://www.trosifol.com/salessupport/what-is-laminated-safety-glass
[56] Website of Trosifol. Accessed: 02.07.2017. https://www.trosifol.com/fileadmin/user_upload/Kuraray_4_1_Physical_Properties_of_Sentryglas.pdf
[57] Website of Trosifol. Product brochure. Accessed: 02.07.2017. https://www.trosifol.com/fileadmin/user_upload/Kurarayl4_3_Post-Glass.pdf

[58] Website of Waagner Biro. Accessed: 08.07.2017. http://www.waagner-biro.com/de/unternehmen/news-press/news/etihad-museum-in-dubai-waagner-biro-setzt-museumspavillion-in-rekordzeit-um

11. Appendix

Calculation data for Fig. 6.2

ASTM E1300-16	Unit	Side length ratio: shorter side / 5000 mm									
		0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0
h_1	mm	10	10	10	10	10	10	10	10	10	10
h_2	mm	10	10	10	10	10	10	10	10	10	10
E	MPa	70000	70000	70000	70000	70000	70000	70000	70000	70000	70000
a - shorter side	mm	500	1000	1500	2000	2500	3000	3500	4000	4500	5000
G_{int}	MPa	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
h_v	mm	0,76	0,76	0,76	0,76	0,76	0,76	0,76	0,76	0,76	0,76
h_s	mm	10,76	10,76	10,76	10,76	10,76	10,76	10,76	10,76	10,76	10,76
h_{s1}	mm	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38
h_{s2}	mm	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38
I_s	mm^3	578,9	578,9	578,9	578,9	578,9	578,9	578,9	578,9	578,9	578,9
Γ	-	0,041	0,147	0,279	0,408	0,519	0,608	0,679	0,734	0,777	0,812
$h_{ef,w}$	mm	13,17	14,456	15,79	16,90	17,76	18,39	18,86	19,21	19,48	19,69
$h_{ef,stress}$	mm	14,79	16,151	17,40	18,32	18,96	19,39	19,69	19,91	20,07	20,19
PrEN 16612		**0,1**	**0,2**	**0,3**	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1,0**
h_1	mm	10	10	10	10	10	10	10	10	10	10
h_2	mm	10	10	10	10	10	10	10	10	10	10
h_v	mm	0,76	0,76	0,76	0,76	0,76	0,76	0,76	0,76	0,76	0,76
H	mm	20,76	20,76	20,76	20,76	20,76	20,76	20,76	20,76	20,76	20,76
h_{m1}	mm	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38
h_{m2}	mm	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38	5,38
ω	-	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
$h_{ef,w}$	mm	15,98	15,98	15,98	15,98	15,98	15,98	15,98	15,98	15,98	15,98
$h_{ef,stress}$	mm	17,57	17,57	17,57	17,57	17,57	17,57	17,57	17,57	17,57	17,57
CNR-DT 210		**0,1**	**0,2**	**0,3**	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1,0**
h_1	mm	10	10	10	10	10	10	10	10	10	10
h_2	mm	10	10	10	10	10	10	10	10	10	10
h_v	mm	0,76	0,76	0,76	0,76	0,76	0,76	0,76	0,76	0,76	0,76
G_{int}	MPa	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44	0,44
v	-	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22	0,22
E	MPa	70000	70000	70000	70000	70000	70000	70000	70000	70000	70000
ψ x 10^6	-	40,18	10,427	4,863	2,904	1,997	1,506	1,210	1,019	0,888	0,795
$h_{ef,w}$	mm	13,12	14,279	15,46	16,43	17,17	17,70	18,09	18,38	18,60	18,77
$h_{ef,stress}$	mm	14,74	15,972	17,11	17,95	18,52	18,92	19,19	19,39	19,53	19,64
Relative to CNR-DT		**0,1**	**0,2**	**0,3**	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1,0**
ASTM $h_{ef.w}$	-	1,004	1,012	1,021	1,029	1,034	1,039	1,042	1,045	1,047	1,049
ASTM $h_{ef,stress}$	-	1,004	1,011	1,017	1,021	1,023	1,025	1,026	1,027	1,028	1,028
PrEN $h_{ef,w}$	-	1,218	1,119	1,034	0,972	0,931	0,903	0,883	0,869	0,859	0,851
PrEN $h_{ef,stress}$	-	1,192	1,100	1,027	0,979	0,948	0,929	0,915	0,906	0,900	0,895
CNR-DT 210	-	1	1	1	1	1	1	1	1	1	1

Calculation data for Fig. 6.3

ASTM E1300-16	**Unit**	**Laminate composition**					
		6.6.2	**8.8.2**	**10.10.2**	**12.12.2**	**16.16.2**	**19.19.2**
h_1	mm	6	8	10	12	16	19
h_2	mm	6	8	10	12	16	19
E	MPa	70000	70000	70000	70000	70000	70000
a - shorter side	mm	1500	1500	1500	1500	1500	1500
G_{int}	MPa	0,44	0,44	0,44	0,44	0,44	0,44
h_v	mm	0,76	0,76	0,76	0,76	0,76	0,76
h_s	mm	6,76	8,76	10,76	12,76	16,76	19,76
h_{s1}	mm	3,38	4,38	5,38	6,38	8,38	9,88
h_{s2}	mm	3,38	4,38	5,38	6,38	8,38	9,88
I_s	mm^3	137,1	307,0	578,9	976,9	2247,2	3709,3
Γ	-	0,393	0,326	0,279	0,244	0,195	0,169
$h_{ef,w}$	mm	10,25	13,06	15,80	18,49	23,78	27,70
$h_{ef,stress}$	mm	11,16	14,32	17,41	20,45	26,42	30,84
PrEN 16612		**6.6.2**	**8.8.2**	**10.10.2**	**12.12.2**	**16.16.2**	**19.19.2**
h_1	mm	6	8	10	12	16	19
h_2	mm	6	8	10	12	16	19
h_v	mm	0,76	0,76	0,76	0,76	0,76	0,76
H	mm	12,76	16,76	20,76	24,76	32,76	38,76
h_{m1}	mm	3,38	4,38	5,38	6,38	8,38	9,88
h_{m2}	mm	3,38	4,38	5,38	6,38	8,38	9,88
ω	-	0,3	0,3	0,3	0,3	0,3	0,3
$h_{ef,w}$	mm	9,75	12,86	15,98	19,10	25,35	30,03
$h_{ef,stress}$	mm	10,74	14,15	17,57	20,99	27,83	32,95
CNR-DT 210		**6.6.2**	**8.8.2**	**10.10.2**	**12.12.2**	**16.16.2**	**19.19.2**
h_1	mm	6	8	10	12	16	19
h_2	mm	6	8	10	12	16	19
h_v	mm	0,76	0,76	0,76	0,76	0,76	0,76
G_{int}	MPa	0,44	0,44	0,44	0,44	0,44	0,44
v	-	0,22	0,22	0,22	0,22	0,22	0,22
E	MPa	70000	70000	70000	70000	70000	70000
ψ	-			6,96912*10^-6			
$h_{ef,w}$	mm	9,59	12,24	14,86	17,45	22,59	26,42
$h_{ef,stress}$	mm	10,60	13,60	16,55	19,47	25,26	29,57
Relative to CNR-DT		**6.6.2**	**8.8.2**	**10.10.2**	**12.12.2**	**16.16.2**	**19.19.2**
ASTM $h_{ef.w}$	-	1,069	1,067	1,063	1,060	1,053	1,048
ASTM $h_{ef,stress}$	-	1,053	1,053	1,052	1,050	1,046	1,043
PrEN $h_{ef,w}$	-	1,016	1,051	1,076	1,095	1,122	1,136
PrEN $h_{ef,stress}$	-	1,013	1,041	1,062	1,078	1,102	1,114
CNR-DT 210	-	1	1	1	1	1	1

Calculation data for Fig. 6.4

ASTM E1300-16	Unit	Laminate composition 6.6.2	8.8.2	10.10.2	12.12.2	16.16.2	19.19.2
h_1	mm	6	8	10	12	16	19
h_2	mm	6	8	10	12	16	19
E	MPa	70000	70000	70000	70000	70000	70000
a - shorter side	mm	2000	2000	2000	2000	2000	2000
G_{int}	MPa	0,44	0,44	0,44	0,44	0,44	0,44
h_v	mm	0,76	0,76	0,76	0,76	0,76	0,76
h_s	mm	6,76	8,76	10,76	12,76	16,76	19,76
h_{s1}	mm	3,38	4,38	5,38	6,38	8,38	9,88
h_{s2}	mm	3,38	4,38	5,38	6,38	8,38	9,88
I_s	mm^3	137,1	307,0	578,9	976,9	2247,2	3709,3
Γ	-	0,535	0,463	0,408	0,365	0,301	0,266
$h_{ef,w}$	mm	10,95	13,97	16,91	19,77	25,36	29,46
$h_{ef,stress}$	mm	11,68	15,05	18,33	21,55	27,84	32,46
PrEN 16612		**6.6.2**	**8.8.2**	**10.10.2**	**12.12.2**	**16.16.2**	**19.19.2**
h_1	mm	6	8	10	12	16	19
h_2	mm	6	8	10	12	16	19
h_v	mm	0,76	0,76	0,76	0,76	0,76	0,76
H	mm	12,76	16,76	20,76	24,76	32,76	38,76
h_{m1}	mm	3,38	4,38	5,38	6,38	8,38	9,88
h_{m2}	mm	3,38	4,38	5,38	6,38	8,38	9,88
ω	-	0,3	0,3	0,3	0,3	0,3	0,3
$h_{ef,w}$	mm	9,75	12,86	15,98	19,10	25,346	30,027
$h_{ef,stress}$	mm	10,74	14,15	17,57	20,99	27,826	32,954
CNR-DT 210		**6.6.2**	**8.8.2**	**10.10.2**	**12.12.2**	**16.16.2**	**19.19.2**
h_1	mm	6	8	10	12	16	19
h_2	mm	6	8	10	12	16	19
h_v	mm	0,76	0,76	0,76	0,76	0,76	0,76
G_{int}	MPa	0,44	0,44	0,44	0,44	0,44	0,44
v	-	0,22	0,22	0,22	0,22	0,22	0,22
E	MPa	70000	70000	70000	70000	70000	70000
ψ	-			4,97050*10^-6			
$h_{ef,w}$	mm	10,001	12,742	15,426	18,074	23,299	27,179
$h_{ef,stress}$	mm	10,955	14,046	17,077	20,065	25,958	30,332
Relative to CNR-DT		**6.6.2**	**8.8.2**	**10.10.2**	**12.12.2**	**16.16.2**	**19.19.2**
ASTM $h_{ef.w}$	-	1,094	1,097	1,096	1,094	1,088	1,084
ASTM $h_{ef,stress}$	-	1,066	1,071	1,073	1,074	1,072	1,070
PrEN $h_{ef,w}$	-	0,974	1,010	1,036	1,057	1,088	1,105
PrEN $h_{ef,stress}$	-	0,980	1,008	1,029	1,046	1,072	1,086
CNR-DT 210	-	1	1	1	1	1	1