EUROCODES

prCEN/TS 19100

Design of glass structures

Markus Feldmann

EUROCODE Conference I Berlin I 24 May 2023

2023 EURO CODE

DIBt

Structural glass – yesterday

The first rules for glass construction are known from the Intendant of the Duke of Northumberland (1567)

(1) Because of the important wind, the glazing of the castle breaks and is lost.

(2) Therefore, it would be good that the glass of each frame is taken down and stocked in security when Our Lordship is out.

(3) When Our Lordship comes back, it is not so difficult and quite cheap to put the glass in the frame again, since the the reparations due to glass breakage are too expensive.

Structural glass – today

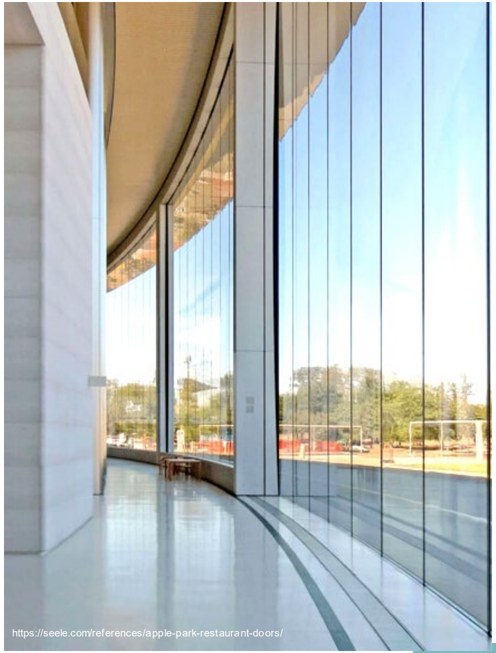

https://www.re-thinkingthefuture.com/designing-for-typologies/a4558-15-iconic-glass-buildings-around-the-world/#8708bbfe87a3f679c3c4fe38061d2114cd488c9c#253122


http://luxuryproperties.ir/uploads/images/images/Blog/Architectural%20Designs/Dramatic%20Skybridges%3B%20Architecture%20Trick%20to%20Show%20Off%20in%20Skyscraper%20Projects/35MEskybridge.jpg

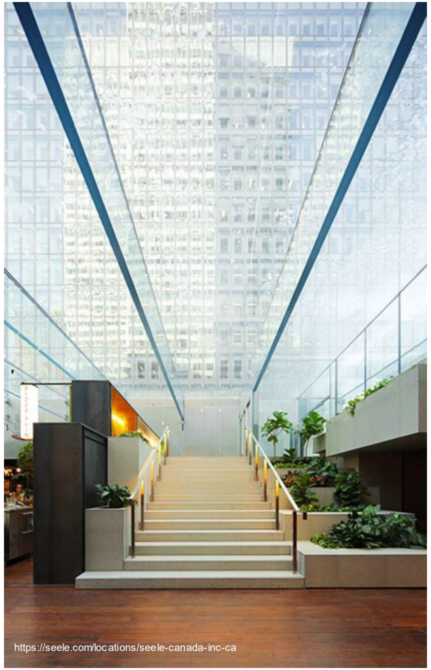
Structural glass – today


https://de.glasscon.com/produkte/structural-glass-facades

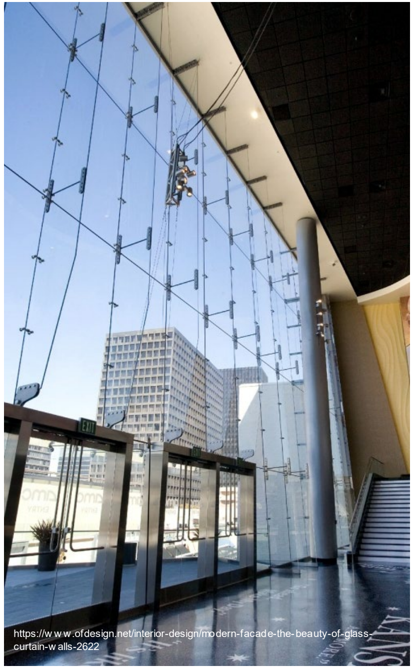
https://www.eocengineers.com/projects/apple-jungfernsteig-108/


https://seele.com/references/apple-park-restaurant-doors/

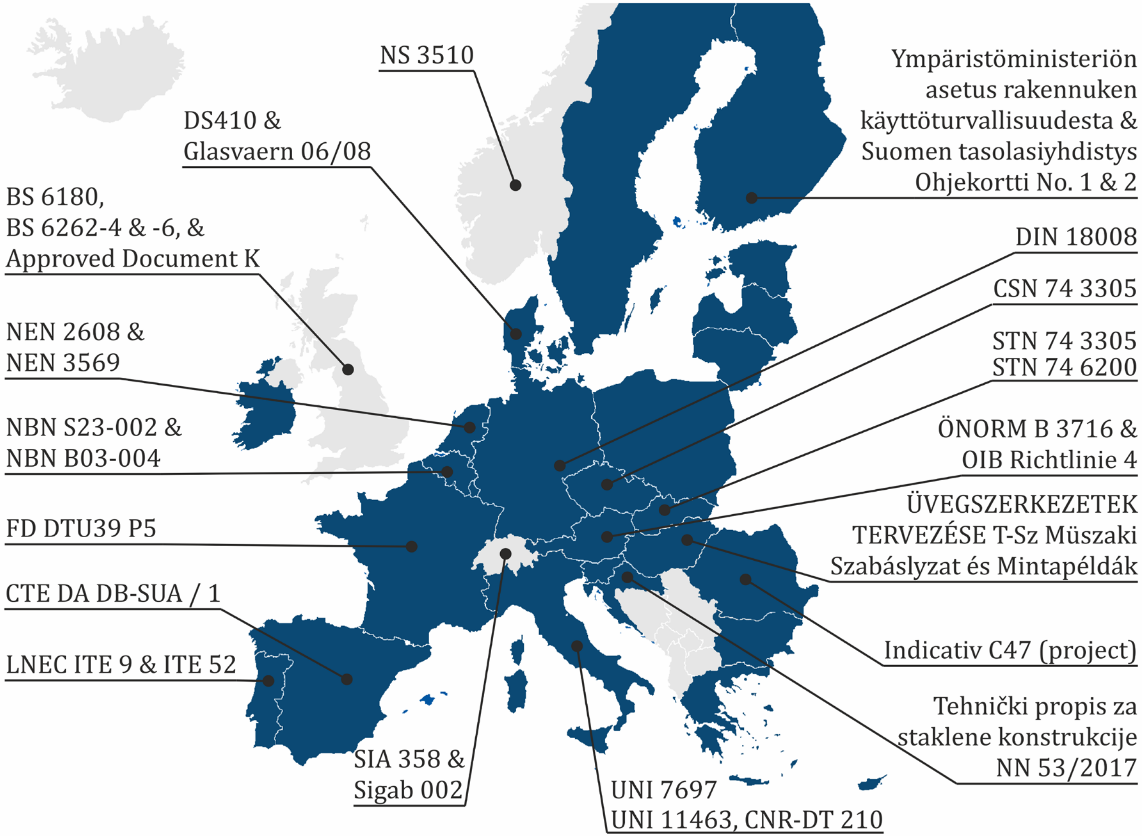
Structural glass – today


https://seele.com/locations/seele-canada-inc-ca


https://www.engadget.com/2019-09-19-apple-fifth-avenue-cube-redesigned-new-york-city.html


https://www.ofdesign.net/interior-design/modern-facade-the-beauty-of-glass-curtain-walls-2622

Current situation



Road to Eurocode 10 – Design of Glass Structures

Timeline CEN/TS 19100

2005

2012

2013

2014

2015

2016

2019

2020

SPECIFIC Mandate M/515 for amending existing Eurocodes and extending the scope of structural Eurocodes including Design of Glass Structures

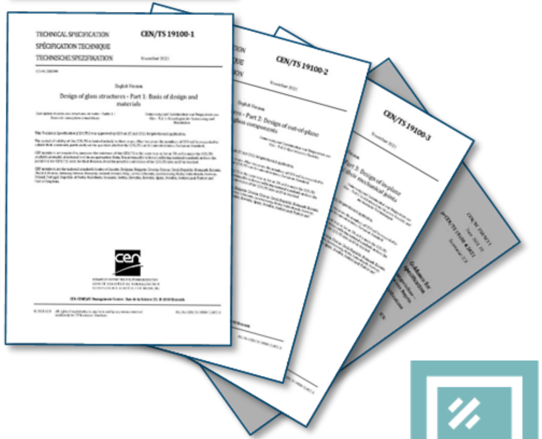
CEN TC 250 response to **Mandate M/515** containing explicit **Tasks**

Task I:
Scientific and Policy (SaP)- Report
Guidance for European Structural Design of Glass Components

WG 3 converted to SC 11
Formation of PTs for Task II&III

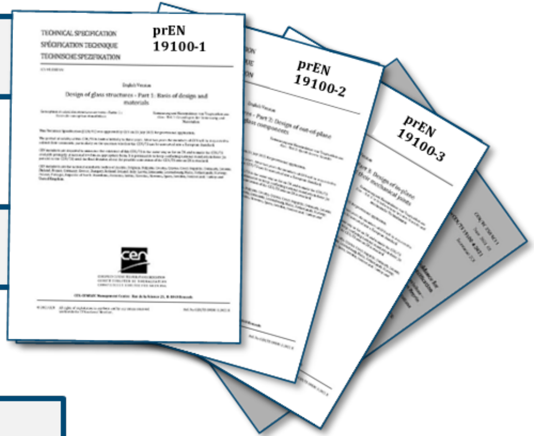
Task II:
CEN Technical Specification
CEN TS 19100 Design of Glass Structures

Formal Vote for CEN/TS



Timeline EN 19100 – EC 10

- **2021** – **Publication of CEN/TS 19100**
  Use parallel to National Standards
- **Task III:**
  Works on conversion of CEN TS to EN 19100
- **2024** – **Start CEN ENQ**
  of prEN 19100
- **2025** – **Formal Vote**
- **2026** – **Translation and preparatory works**
  for Publication of EN 19100
- **2026** – **Publication of EN 19100**
- **2027** – **Preparation of National Application Documents (NADs)**
  for EN 19100
- **2028** – **Withdrawal of National Standards**



Integration into Eurocode family

Management Group
Chairman: S Denton

Chairman's Advisory Panel(s)

CEN/TC 250
Structural Eurocodes
Chairman: S Denton
Vice Chair: M Fardis
Vice Chair: G Breitschaft
Secretary: T Wilkins [BSI]
CEN PM: P Karagianni
NEN M/515 lead: M Lurvink

CEN/TC 250
Coordination Group
Chairman: S Denton
Secretary: T Wilkins [BSI]

Horizontal Group Bridges
Convenor: P Croce

Horizontal Group Fire
Convenor: B Zhao

WG 1 Policy and guidelines
Convenor: A Bond [BSI]

Other Tier 1 WG's

WG 2 Existing Structures
Convenor: T Lang [SIA]

WG 4 Fibre reinforced polymer
Convenor: L Ascione [UNI]

WG 5 Membrane Structures
Convenor: M Mollaert [AFNOR]

WG 6 Robustness
Convenor: J Bregulla [NEN]

CEN/TC 250 Subcommittees

SC 10 - EN 1990
Chairman: P Formichi
Secretary: V Meløysund [SN]

SC 1 - EN 1991
Chairman: N Malakatas
Secretary: J Brunner [DIN]

SC 2 - EN 1992
Chairman: H Ganz
Secretary: D Zorcec [DIN]

SC 3 - EN 1993
Chairman: U Kuhlmann
Secretary: S Kempa [DIN]

SC 4 - EN 1994
Chairman: G Couchman
Secretary: T Wilkins [BSI]

SC 5 - EN 1995
Chairman: S Winter
Secretary: A Stenmark [SIS]

SC 6 - EN 1996
Chairman: R Van der Pluijm
Secretary: N Hu [DIN]

SC 7 - EN 1997
Chairman: A Van Seters
Secretary: G Kraijema [NEN]

SC 8 - EN 1998
Chairman: P Bisch
Secretary: A Correia [IPQ]

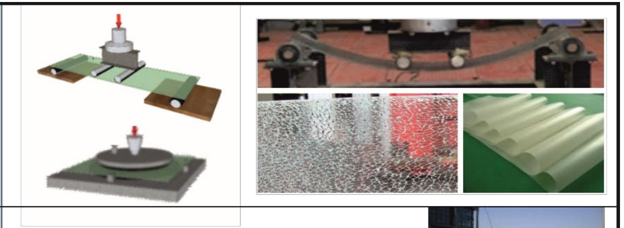
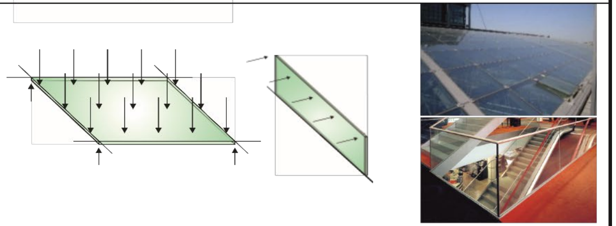
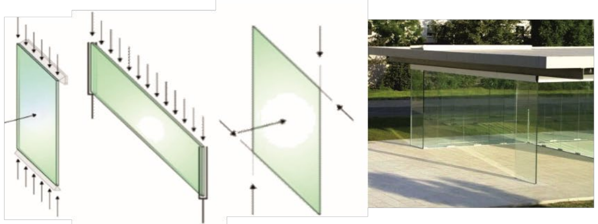
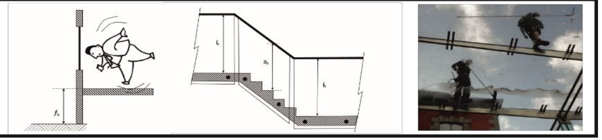
SC 9 - EN 1999
Chairman: F Mazzolani
Secretary: R Sægrov [SN]

SC 11 - EN 'Structural Glass'
Chairman: M Feldmann
Secretary: L Hoffmann [DIN]

EC 0	– EN 1990	Basis of design
EC 1	– EN 1991	Actions
EC 2	– EN 1992	Concrete
EC 3	– EN 1993	Steel
EC 4	– EN 1994	Composite
EC 5	– EN 1995	Timber
EC 6	– EN 1996	Masonry
EC 7	– EN 1997	Geotechnical
EC 8	– EN 1998	Earthquake
EC 9	– EN 1999	Aluminium
EC 10	– EN 19100	Structural Glass

Structure and content of Eurocode 10

Structure and Content of Eurocode 10

Part 1 *Basis of Design and Materials*	• safety issues, robustness and design philosophy • reference to product standards, types of glass • glass strengths and further properties	
Part 2 *Out-of-plane loaded glass elements*	• laterally loaded glass elements • elements not carrying loads from other structural parts • calculation of laminated glass • Insulated Glass Units	
Part 3 *In-plane loaded glass elements and mechanical joints*	• axially (mid plane resp.) loaded glass elements • elements often carrying loads from other structural parts • mechanical joints	
Part 4 *Glass selection*	• relating to the risk of human injury • guidance for specification	

Relation to product and other standards

Glass components for buildings

Product	Design	Execution
CEN/TC 129	CEN/TC 250	CEN/TC129
WG 8	SC 11	
… EN 16612: Glass in Building – Determination of the lateral load resistance of glass panes by calculation …	prEN 19100 – Design of Glass Structures Part 1: Basis of Design, Materials Part 2: Out-of-plane loaded Glass Part 3: In-plane loaded Glass Part 4: Glass selection relating to the risk of human injury — Guidance for specification	*Remains TS because of insur-mountable national legislation* (Part 4)
Components of Consequences Classes other than given in EN1990	Components of Consequences Class 1, 2, 3 acc. EN1990	

- *Component classification in the hands of European Countries*
- *Rules of EN 19100 tie in seamlessly with those of EN 16612*

Conceptualisation of Eurocode 10 design rules

Conceptualisation

- Glass is a perfect brittle material, no ductility.
- We must always expect a breakage of a glass ply.
- The cause of glass breakage can be anything: *“Failure of unknown origin”*

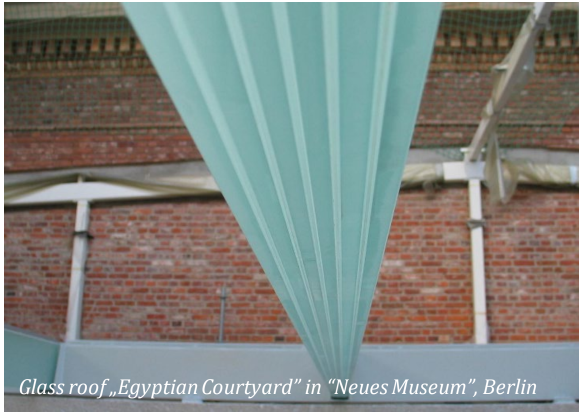
- Glass design is literally “Robustness design”.

- Eurocode 10 approach:
  - “Engineering robustness”
  - “Organising design situations”

Conceptualisation

Engineering robustness

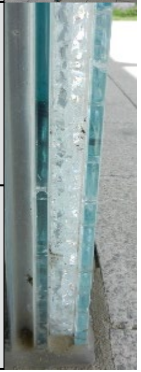
cross sectional	structural
• Number and thickness of plies • Type of glass • Type of interlayer • Edge protection • etc.	• Detailing • Type and capacity of second load path • Protection and hold back measures • etc.


Glass roof „Egyptian Courtyard" in "Neues Museum", Berlin

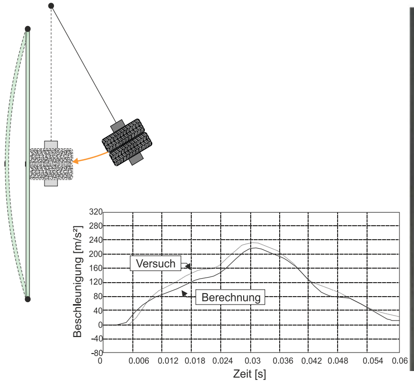
Conceptualisation

Organising design situations

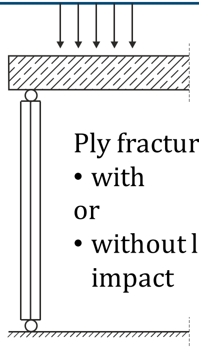
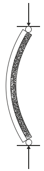
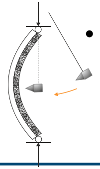
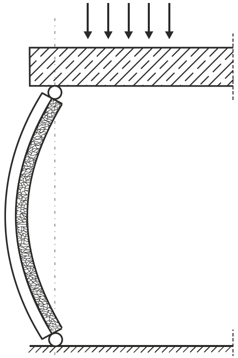
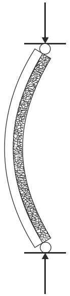
Design for the **unfractured** glass state	**SLS**	Serviceability Limit State
	ULS	Ultimate Limit State
Design for state **during** glass **fracture** (*safe glass fracture*)	**FLS**	Fracture Limit State
Design for the **post-fracture** state (*residual load capacity*)	**PFLS**	Post-Fracture Limit State



Conceptualisation – Out of plane loaded components

FLS	***During Impact*** (hard and/or soft, as required)	• Calculation • Testing • Simulation • Experience • Requirements and Test Set-Up depending on scenario	   
PFLS	***After Impact***		• No shards falling • No splinters causing severe injuries • Residual load carrying capacity after fracture for a limited time under reduced loading 

Conceptualisation – In plane loaded components

FLS	***During Impact***	• Dynamic effects • Non linearities • Short term • Calculation • Simulation • Testing	 Ply fractures • with or • without lateral impact   • Sudden loss of a ply (or even of glass element)  • Soft or hard impact, different energy levels
PFLS	***After Impact***	• After decay of dynamic effect • Non linearities • Medium to long term • Calculation • Simulation • Testing	   • Repair possible • Safe residual life time until repair

Conceptualisation

	Limit State Scenario (LSS)			
	LSS - 0	**LSS - 1**	**LSS - 2**	**LSS – 3**
Design for the **unfractured** glass state	SLS	SLS	SLS	SLS
	ULS	ULS	ULS	ULS
Design for the glass **fracture** state (safe glass fracture)		FLS		FLS
Design for the **post-fractured** state (residual load capacity)			PFLS	PFLS

It is in the hands of European countries which glass element is assigned to which LSS

Design topics

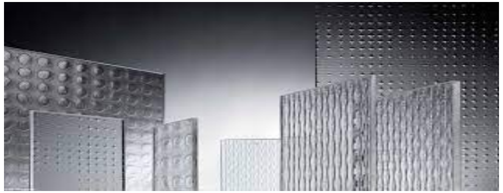
Overview of design topics

	Scope	Main Text		Annexes
prEN 19100-1	… gives basic design rules for mechanically supported glass components. This document is concerned with the **requirements for resistance, serviceability, fracture characteristics** and **glass component failure consequences** in relation to **human safety, robustness, redundancy and durability of glass structures**.	**Principles of Limit States** • ULS • SLS • FLS • PFLS **Materials/strengths** • glass • interlayer • IGUs **Partial factors** **Verification ULS and SLS**	**Actions** • cavity pressure for IGUs **Structural Analysis** • interlayer modeling **Structural Provisions** • glass support • holes	**A** - Bending strength resistance **B** - Bending strength resistance with interference factor **C** - Thermally induced stress caused by temperature differentials in the glass pane **D** Cold Bending
prEN 19100-2	… gives design rules for mechanically supported glass components **primarily subjected to out of plane loading**.	**Verification FLS and PFLS** • testing • theoretical **Deflection Limits**	**Joints, Connections and Supports** • continously edge supported • point supported • cantilevered	**A** - Determination of the effective thickness according to the enhanced effective thickness approach (EET) **B** - Verification of the natural frequency of the glass component **C** IGUs – calculation of resulting pressure
prEN 19100-3	… gives design rules for mechanically supported glass components **primarily subjected to in-plane loading**. It also covers **construction rules for mechanical joints** for in-plane loaded glass components.	**Verification FLS and PFLS** • testing • theoretical	**Joints and Connections** • sleeve bearinigs • lapped splices • friction connection **Structural Analysis** • stability • Imperfections • detailing	**A** - Calculation of the critical buckling load N_{cr} or critical bending moment $M_{cr,LT}$ **B** - Calculation of $I_{z,eff}$ and $I_{T,eff}$ of laminated glass **C** - Calculation of K_m-values for simplified calculation

Key topics – Glass types

Annealed

Type of glass	Standard	$f_{g,k}$ N/mm²
Float glass	EN 572-2	45
Polished wired glass	EN 572-3	33
Drawn sheet glass	EN 572-4	45
Patterned glass	EN 572-5	33
Wired patterned glass	EN 572-6	27

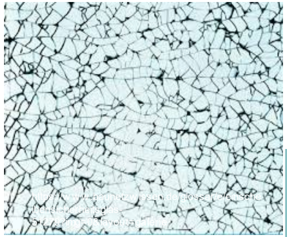


Thermally or chemically treated

Glass material per product (whichever composition)	Values for characteristic bending strength $f_{b,k}$ for pre-stressed glass processed from:		
	thermally toughened safety glass to EN 12150-1, and heat soaked thermally toughened safety glass to EN 14179-1	heat strengthened glass to EN 1863-1	chemically strengthened glass to EN 12337-1
float glass or drawn sheet glass	120 N/mm²	70 N/mm²	150 N/mm²
patterned glass	90 N/mm²	55 N/mm²	100 N/mm²
enamelled float or drawn sheet glass	75 N/mm²	45 N/mm²	
enamelled patterned glass	75 N/mm²	45 N/mm²	

NOTE 1 The values for thermally toughened safety glass and heat soaked thermally toughened safety glass can also be used for glass conforming to EN 13024-1, EN 14321-1 and EN 15682-1.

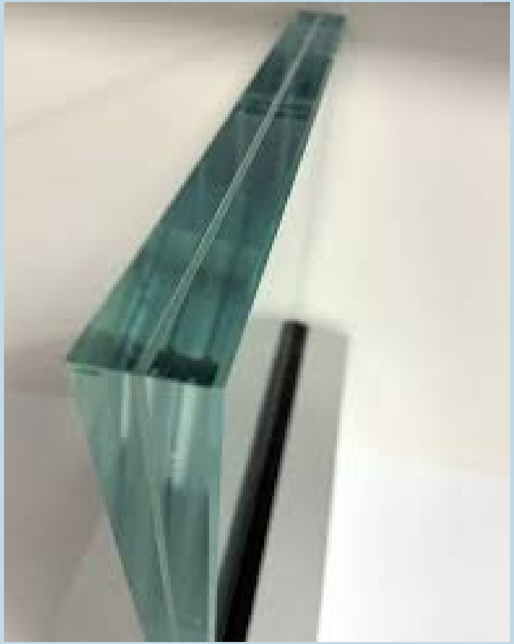
NOTE 2 The characteristic bending strength values in the table are the same as in the product standards at the time of publication of this document. In the case of revision of the values in the product standards, then the values in the product standards take precedence.



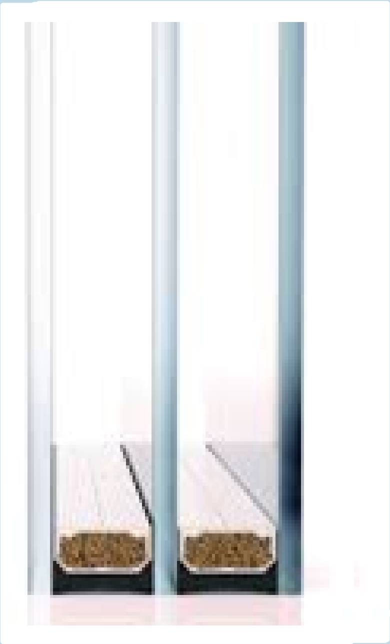
Key topics – Glass assemblies

mono

laminate



IGU



Key topics – Design bending strength

intrinsic glass strength	contribution of pre-stress

$$f_{g,d} = k_e \cdot k_{sp} \cdot \lambda_A \cdot \lambda_l \cdot k_{mod} \cdot \frac{f_{g,k}}{\gamma_m} + k_p \cdot k_{e,p} \cdot \frac{f_{b,k} - f_{g,k}}{k_i \cdot \gamma_p}$$

$f_{g,d}$	total design bending strength
$f_{g,k}$	characteristic bending strength of annealed glass
γ_m	material partial safety factor
k_e	edge or hole finishing factor
k_{sp}	surface profile factor
k_{mod}	modification factor
λ_A	relevant for surfaces larger 18 m²
λ_l	relevant for edges longer 6 m

Pre-stressing treatment	k_p
None	0,0
Heat treatment with horizontal process	1,0
Heat treatment with vertical process	0,60

Type	Load duration	Action	k_{mod}
Permanent	Permanent	Self-weight, difference in altitude, permanent cold bending	0,29
		Snow (3 to 4 weeks)[c]	0,43
			0,45
			0,58
			0,69
			0,74
			0,77
			0,89
			1,00
			1,20

Glass material[a] (whichever glass composition)	Factor for the glass surface profile k_{sp}	
	As produced[c]	Sandblasted[c]
Float glass	1,0	0,6

	Edge finishing factor k_e[a]		
	As-cut, arrissed, or ground edges[b]	Seamed edges[c]	Polished edges
Float glass	0,8	0,9	1,0
Patterned glass	0,8	0,8	0,8
Polished wired glass	0,8	0,8	0,8
Wired patterned glass	0,8	0,8	0,8

[a] Values to be used for verifications within a distance *d* measured from the edge of the pane or of the hole towards the interior of the glass surface. The value of the distance d is d = h+c, where:
- h is the thickness of the glass ply; and
- c is the distance of the cutting edge of the chamfer with the glass surface to the edge of the glass or of the hole.

[b] Arrissed or ground edges by machine or by hand where the abrasive action is across the edge.

[c] Arrissed or ground edges by machine or by hand where the abrasive action is along the length of the edge.

$f_{b,k}$	characteristic bending strength of prestressed glass
γ_p	partial safety factor for pre-stress on the surface
k_p	pre-stressing process factor
$k_{e,p}$	edge or hole pre-stressing factor
k_i	interference factor, accounting for the beneficial statistical interference between the distributions of pristine glass strengths and surface pre-stress

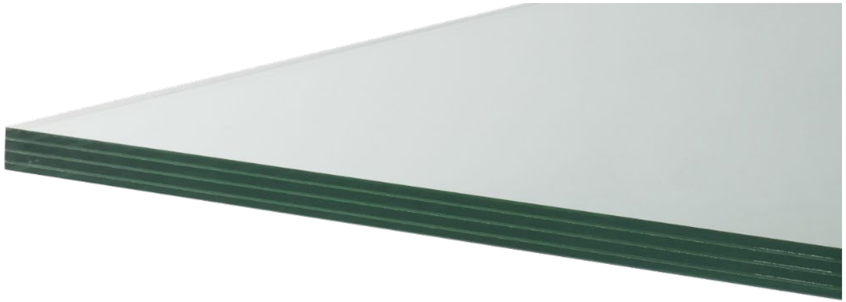
Key topics – Design of laminated glass

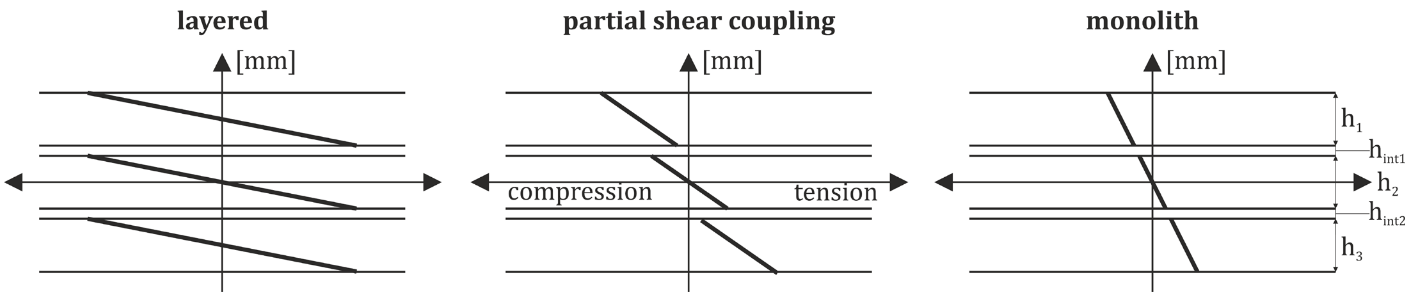
Effective thickness to calculate the **deflection** of a pane

$$h_{ef,w} = \sqrt[3]{\frac{1}{\frac{\eta}{\sum_{i=1}^{n} h_i^3 + 12\sum_{i=1}^{n}(h_i \cdot d_i^2)} + \frac{1-\eta}{\sum_{i=1}^{n} h_i^3}}}$$

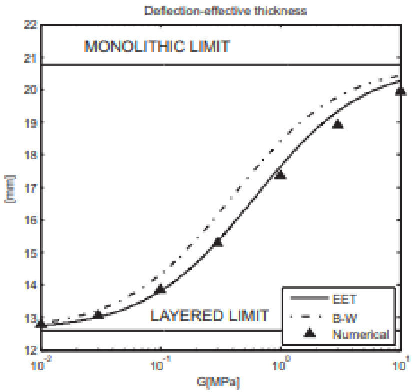
Effective thicknesses to calculate the **bending stress** in a single ply

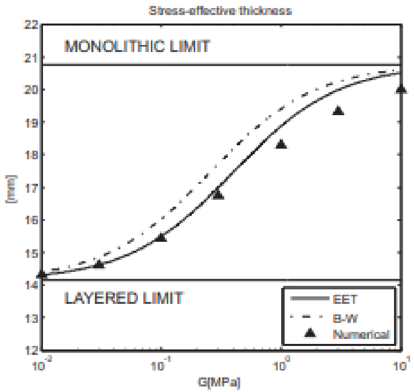
$$h_{ef,\sigma,i} = \sqrt{\frac{1}{\frac{2\cdot\eta\cdot|d_i|}{\sum_{i=1}^{n} h_i^3 + 12\sum_{i=1}^{n}(h_i \cdot d_i^2)} + \frac{h_i}{h_{ef,w}^3}}}$$



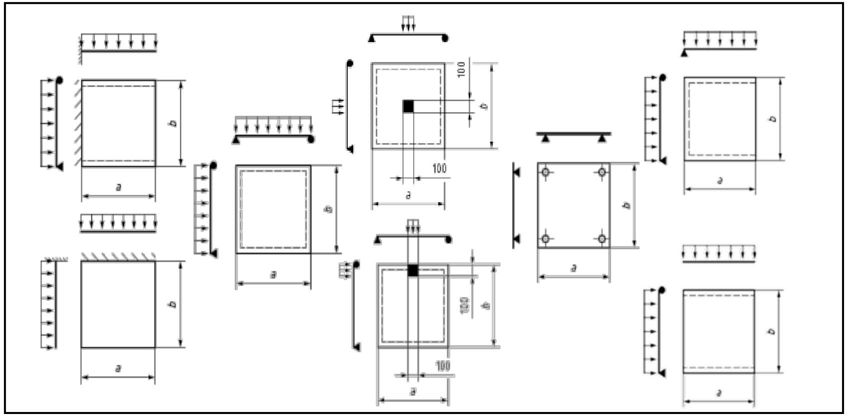


Key topics – Design of laminated glass

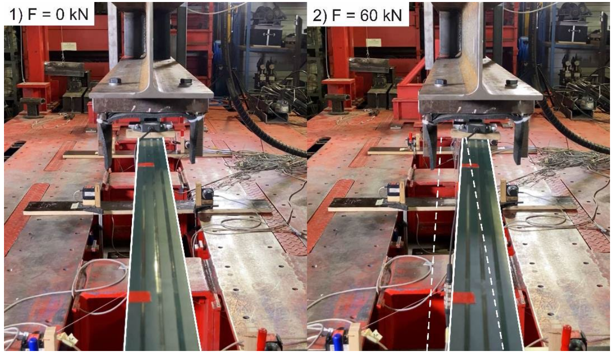




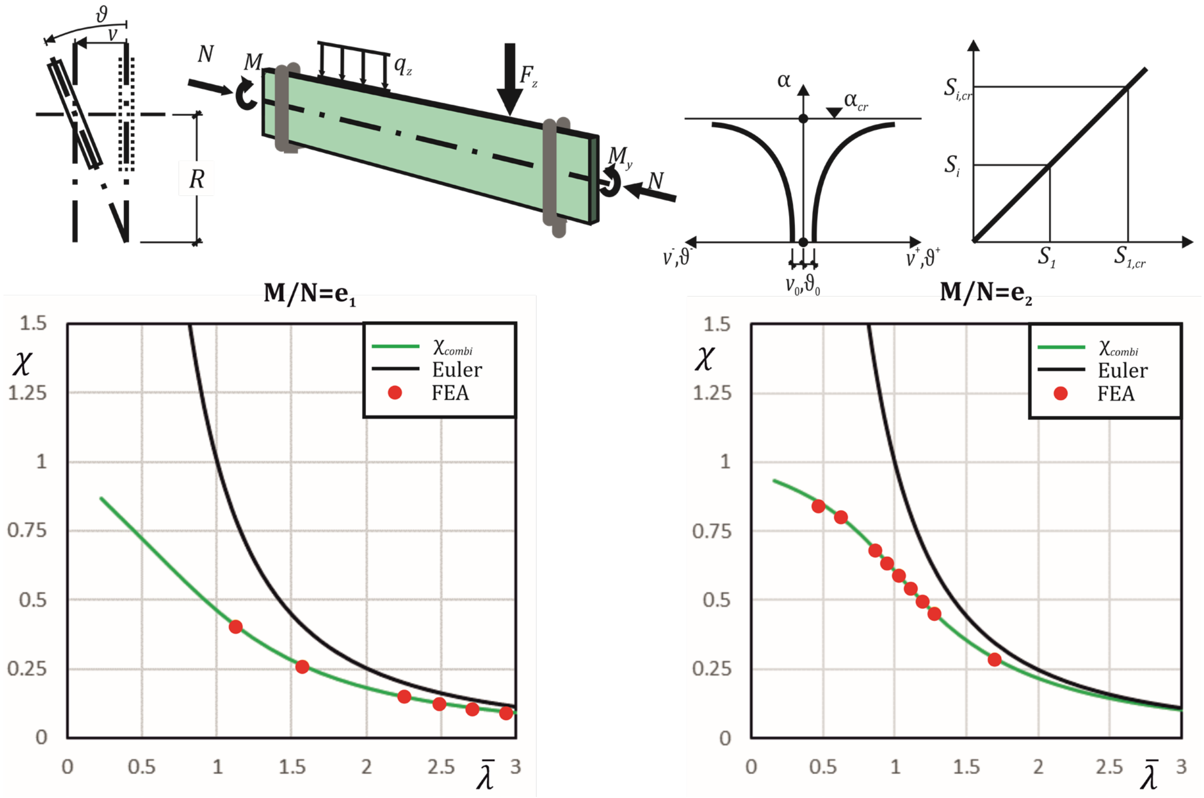
Galuppi, L.; Royer Carfagni, G.: The effective thickness of laminated glass plates, Journal of Mechanics of Materials and Structures 2012



Key topics – Buckling curves



Key topics – Buckling curves



Conclusion

Conclusion

- Eurocode 10 - Design of Glass structures joins the Eurocode suite,
  - following the principles of modern standards,
  - taking into account the special properties of glass as building material,
  - covering all topics of design in modern glass construction,
  - offering maximum flexibility at the interface to national legislation.
- Eurocode 10, like every Eurocode, fosters innovation.

Presented by
Prof. Dr.-Ing. Markus Feldmann
Chairman CEN/TC 250/SC 11

RWTH Aachen University
Institute of Steel Construction
Mies-van-der-Rohe-Str. 1
52074 Aachen

Phone: +49 241 80 25177
Email: feldmann@stb.rwth-aachen.de
www.stb.rwth-aachen.de

Source of the tables on slides
22, 23 and 25: CEN/TS 19100