Design of glass structures

Markus Feldmann

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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 reparations due to glass breakage are too expensive.
Structural glass – today
Structural glass – today
Structural glass – today

https://seele.com/locations/seele-canada-inc-ca
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**: SPECIFIC Mandate M/515 for amending existing Eurocodes and extending the scope of structural Eurocodes including Design of Glass Structures

- **2012**

- **2013**

- **2014**

- **2015**

- **2016**: WG 3 converted to SC 11; Formation of PTs for Task II&III

- **2019**: CEN TC 250 response to Mandate M/515 containing explicit Tasks

- **2020**: Formal Vote for CEN/TS

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

**Task II:**
CEN Technical Specification
CEN TS 19100 Design of Glass Structures
Timeline EN 19100 – EC 10

- **2021**: Publication of CEN/TS 19100
  - Use parallel to National Standards

- **2024**: Formal Vote

- **2025**: Start CEN ENQ of prEN 19100

- **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

**DIN**

**CEN/TC 250**

**Coordination Group**
Chairman: S Denton
Secretary: T Wilkins [BSI]

**Other Tier 1 WG’s**

**Horizontal Group Bridges**
Convenor: P Croce

**Horizontal Group Fire**
Convenor: B Zhao

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

** WG 2 Existing Structures**
Convenor: T Lang [BIA]

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

**WG 5 Membrane Structures**
Convenor: M Mollaret [AFNOR]

**WG 6 Robustness**
Convenor: J Bregulla [NEN]

**CEN/TC 250 Subcommittees**

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

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

**SC 2 - EN 1992**
Chairman: H Ganz
Secretary: D Zoriec [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 Puijim
Secretary: N Hu [DIN]

**SC 7 - EN 1997**
Chairman: A Van Selers
Secretary: G Krajewa [NEN]

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

**SC 9 - EN 1999**
Chairman: F Mazzolani
Secretary: R Sargov [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

<table>
<thead>
<tr>
<th>Part 1</th>
<th>Basis of Design and Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>safety issues, robustness and design philosophy</td>
</tr>
<tr>
<td></td>
<td>reference to product standards, types of glass</td>
</tr>
<tr>
<td></td>
<td>glass strengths and further properties</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part 2</th>
<th>Out-of-plane loaded glass elements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>laterally loaded glass elements</td>
</tr>
<tr>
<td></td>
<td>elements not carrying loads from other structural parts</td>
</tr>
<tr>
<td></td>
<td>calculation of laminated glass</td>
</tr>
<tr>
<td></td>
<td>Insulated Glass Units</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part 3</th>
<th>In-plane loaded glass elements and mechanical joints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>axially (mid plane resp.) loaded glass elements</td>
</tr>
<tr>
<td></td>
<td>elements often carrying loads from other structural parts</td>
</tr>
<tr>
<td></td>
<td>mechanical joints</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part 4</th>
<th>Glass selection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>relating to the risk of human injury</td>
</tr>
<tr>
<td></td>
<td>guidance for specification</td>
</tr>
</tbody>
</table>
Relation to product and other standards

Glass components for buildings

- **Product**
  - CEN/TC 129
  - WG 8

- **Design**
  - CEN/TC 250
  - SC 11

- **Execution**
  - CEN/TC 129

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**Components of Consequences Classes other than given in EN1990**

- 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 insurmountable national legislation

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

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... EN 16612: Glass in Building – Determination of the lateral load resistance of glass panes by calculation...

...
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

<table>
<thead>
<tr>
<th>cross sectional</th>
<th>structural</th>
</tr>
</thead>
</table>
| • 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. |
# Conceptualisation

## Organising design situations

<table>
<thead>
<tr>
<th>Design for the <strong>unfractured</strong> glass state</th>
<th><strong>SLS</strong></th>
<th>Serviceability Limit State</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>ULS</strong></td>
<td>Ultimate Limit State</td>
</tr>
<tr>
<td>Design for state <strong>during</strong> glass <strong>fracture</strong> (safe glass fracture)</td>
<td><strong>FLS</strong></td>
<td>Fracture Limit State</td>
</tr>
<tr>
<td>Design for the <strong>post-fracture</strong> state (residual load capacity)</td>
<td><strong>PFLS</strong></td>
<td>Post-Fracture Limit State</td>
</tr>
</tbody>
</table>
# Conceptualisation – Out of plane loaded components

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

**Diagram:**
- Impact event
- Calculation curve
- Residual load capacity graph
## Conceptualisation – In plane loaded components

<table>
<thead>
<tr>
<th></th>
<th>During Impact</th>
<th>After Impact</th>
</tr>
</thead>
</table>
| FLS | • Dynamic effects  
• Non linearities  
• Short term  
• Calculation  
• Simulation  
• Testing | • Sudden loss of a ply  
(or even of glass element)  
• Soft or hard impact, different energy levels |
| PFLS | • After decay of dynamic effect  
• Non linearities  
• Medium to long term  
• Calculation  
• Simulation  
• Testing | • Repair possible  
• Safe residual life time until repair |

### During Impact
- Ply fractures
  - with or without lateral impact

### After Impact
- Sudden loss of a ply
- Soft or hard impact, different energy levels
- Repair possible
- Safe residual life time until repair

- Ply fractures
- Sudden loss of a ply
- Soft or hard impact, different energy levels
- Repair possible
- Safe residual life time until repair
## Conceptualisation

<table>
<thead>
<tr>
<th>Design for the unfractured glass state</th>
<th>LSS - 0</th>
<th>LSS - 1</th>
<th>LSS - 2</th>
<th>LSS - 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLS</td>
<td>SLS</td>
<td>SLS</td>
<td>SLS</td>
<td>SLS</td>
</tr>
<tr>
<td>ULS</td>
<td>ULS</td>
<td>ULS</td>
<td>ULS</td>
<td>ULS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design for the fracture state (safe glass fracture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Design for the post-fractured state (residual load capacity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFLS</td>
</tr>
</tbody>
</table>

*It is in the hands of European countries which glass element is assigned to which LSS*
Design topics
## Overview of design topics

<table>
<thead>
<tr>
<th>Scope</th>
<th>Main Text</th>
<th>Annexes</th>
</tr>
</thead>
</table>
| **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<br>• SLS<br>• FLS<br>• PFLS | **Actions**<br>• cavity pressure for IGUs<br>**Structural Analysis**<br>• interlayer modeling<br>**Structural Provisions**<br>• glass support<br>• holes |
| **Materials/strengths** | • glass<br>• interlayer<br>• IGUs | **A** - Bending strength resistance<br>**B** - Bending strength resistance with interference factor<br>**C** - Thermally induced stress caused by temperature differentials in the glass pane<br>**D** Cold Bending |
| **Partial factors** | **Verification ULS and SLS**<br>**Deflection Limits**<br>**Verification FLS and PFLS**<br>**Joints, Connections and Supports**<br>**Structural Analysis**<br>**Structural Provisions**<br>**A** - Determination of the effective thickness according to the enhanced effective thickness approach (EET)<br>**B** - Verification of the natural frequency of the glass component<br>**C** IGUs – calculation of resulting pressure | |
| **Verification FLS and PFLS** | • testing<br>• theoretical<br>**Joints and Connections**<br>• continously edge supported<br>• point supported<br>• cantilevered | |
| **prEN 19100-2** | ... gives design rules for mechanically supported glass components **primarily subjected to out of plane loading.** | |
| **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<br>• theoretical | **A** - Calculation of the critical buckling load $N_{cr}$ or critical bending moment $M_{cr,LT}$<br>**B** - Calculation of $I_{z,eff}$ and $I_{T,eff}$ of laminated glass<br>**C** - Calculation of $K_m$-values for simplified calculation | |
# Key topics – Glass types

## Annealed

<table>
<thead>
<tr>
<th>Type of glass</th>
<th>Standard</th>
<th>( f_{\text{ck}} ) N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Float glass</td>
<td>EN 572-2</td>
<td>45</td>
</tr>
<tr>
<td>Polished wired glass</td>
<td>EN 572-3</td>
<td>33</td>
</tr>
<tr>
<td>Drawn sheet glass</td>
<td>EN 572-4</td>
<td>45</td>
</tr>
<tr>
<td>Patterned glass</td>
<td>EN 572-5</td>
<td>33</td>
</tr>
<tr>
<td>Wired patterned glass</td>
<td>EN 572-6</td>
<td>27</td>
</tr>
</tbody>
</table>

## Thermally or chemically treated

### Glass material per product (whichever composition)

<table>
<thead>
<tr>
<th></th>
<th>thermally toughened safety glass to EN 12150-1, and heat soaked thermally toughened safety glass to EN 14179-1</th>
<th>heat strengthened glass to EN 1863-1</th>
<th>chemically strengthened glass to EN 12887-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>float glass or drawn sheet glass</td>
<td>120 N/mm²</td>
<td>70 N/mm²</td>
<td>150 N/mm²</td>
</tr>
<tr>
<td>patterned glass</td>
<td>90 N/mm²</td>
<td>55 N/mm²</td>
<td>100 N/mm²</td>
</tr>
<tr>
<td>enamelled float or drawn sheet glass</td>
<td>75 N/mm²</td>
<td>45 N/mm²</td>
<td></td>
</tr>
<tr>
<td>enamelled patterned glass</td>
<td>75 N/mm²</td>
<td>45 N/mm²</td>
<td></td>
</tr>
</tbody>
</table>

**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.

[Link to glossary](https://www.baunetzniss.de/glossar/e/einschibensicherheitsglas?img=0&layout=galerie)
Key topics – Glass assemblies

mono

laminate

IGU
Key topics – Design bending strength

\[ f_{g,d} = k_e \cdot k_{sp} \cdot \lambda_A \cdot \lambda_I \cdot k_{mod} \cdot \frac{f_{g,k}}{\gamma_m} + k_p \cdot k_{e,p} \cdot \frac{f_{b,k} - f_{g,k}}{k_I \gamma_p} \]

- **\( f_{g,d} \)**: total design bending strength
- **\( f_{g,k} \)**: characteristic bending strength of annealed glass
- **\( \gamma_m \)**: material partial safety factor
- **\( k_e \)**: edge or hole finishing factor
- **\( k_{sp} \)**: surface profile factor
- **\( k_{mod} \)**: modification factor
- **\( \lambda_A \)**: relevant for surfaces larger 18 m²
- **\( \lambda_I \)**: relevant for edges longer 6 m

---

**Pre-stressing treatment**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>( k_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat treatment with horizontal process</td>
<td>0.6</td>
</tr>
<tr>
<td>Heat treatment with vertical process</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Glass material**

- Float glass
- Patterned glass
- Wired patterned glass

**Factor for the glass surface profile**

- As produced: 1.0
- Annealed edge: 0.8

**Edge finishing factor**

\[ k_{e,p} \]

- As cut, ground edges: 0.5
- Seamed edges: 0.7
- Polished edges: 1.0

**contribution of pre-stress**

- **\( f_{b,k} \)**: characteristic bending strength of prestressed glass
- **\( \gamma_p \)**: 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
**Effective thickness** to calculate the **deflection** of a pane

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

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

\[
\begin{align*}
    h_{ef,\sigma,i} &= \frac{1}{\sqrt{\sum_{i=1}^{n} h_i^3 + 12 \sum_{i=1}^{n} (h_i \cdot d_i^2)}} + \frac{2 \cdot \eta \cdot d_i}{\sum_{i=1}^{n} h_i^3} + h_i^3 + \frac{h_i}{h_{ef,w}} \\
\end{align*}
\]

Diagrams showing layered, partial shear coupling, and monolith configurations with labeled thicknesses and directions of compression and tension.
Key topics – Design of laminated glass

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

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