

UNIVERSITÀ DEGLI STUDI DI TRIESTE

Dipartimento di Ingegneria e Architettura

Structural and technological design of building envelopes

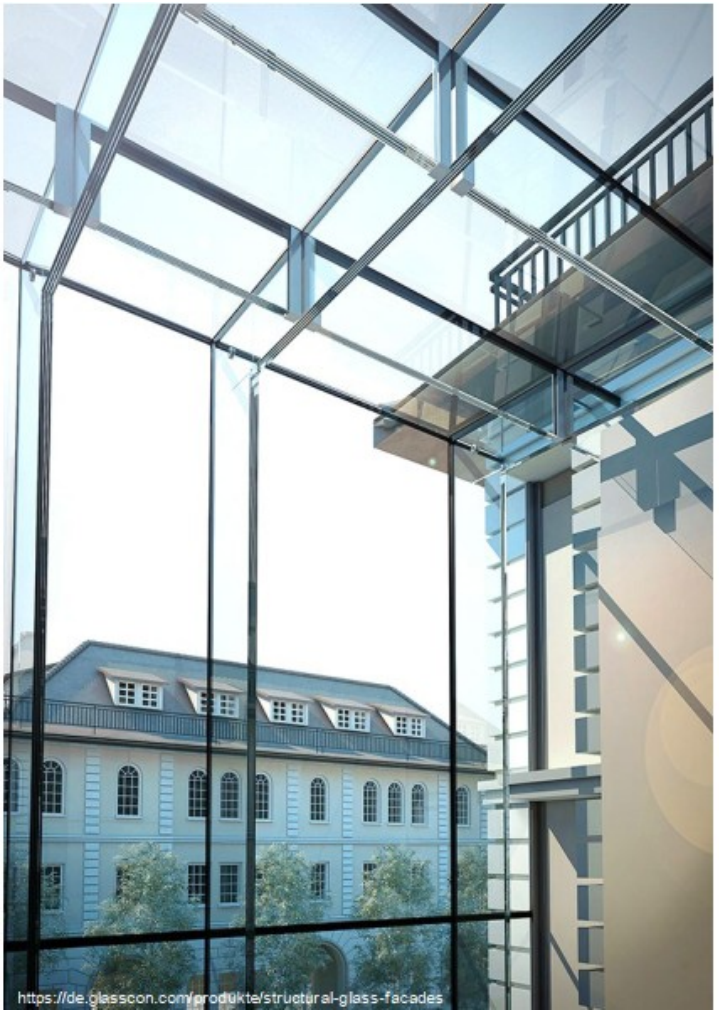
Prof.ssa Chiara Bedon


Glass facades
Partition walls



Glass structures

Glass structures



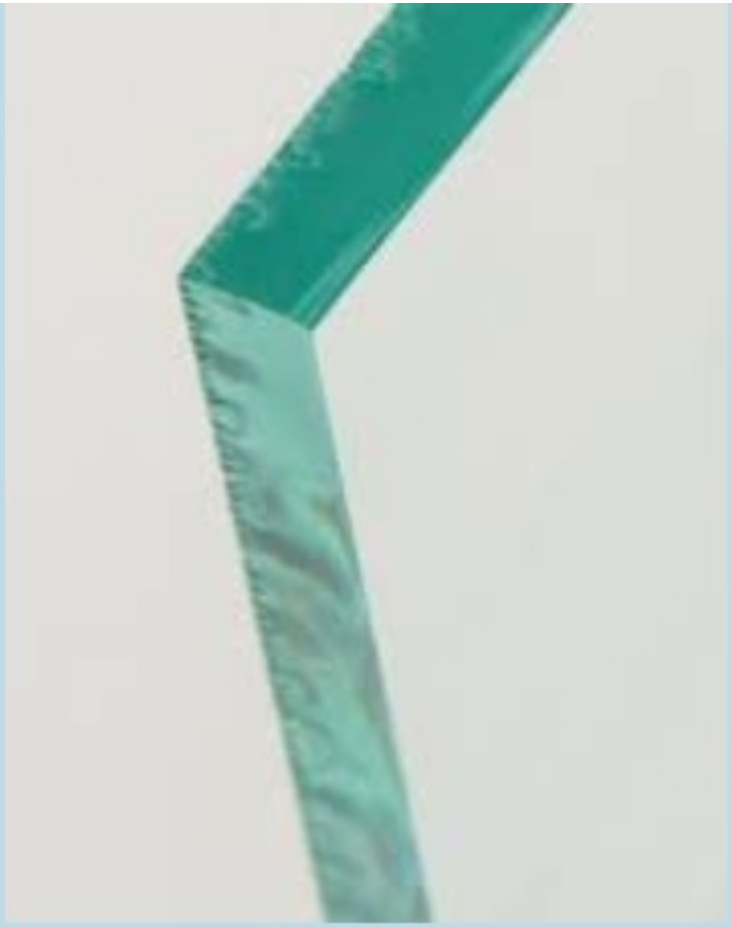




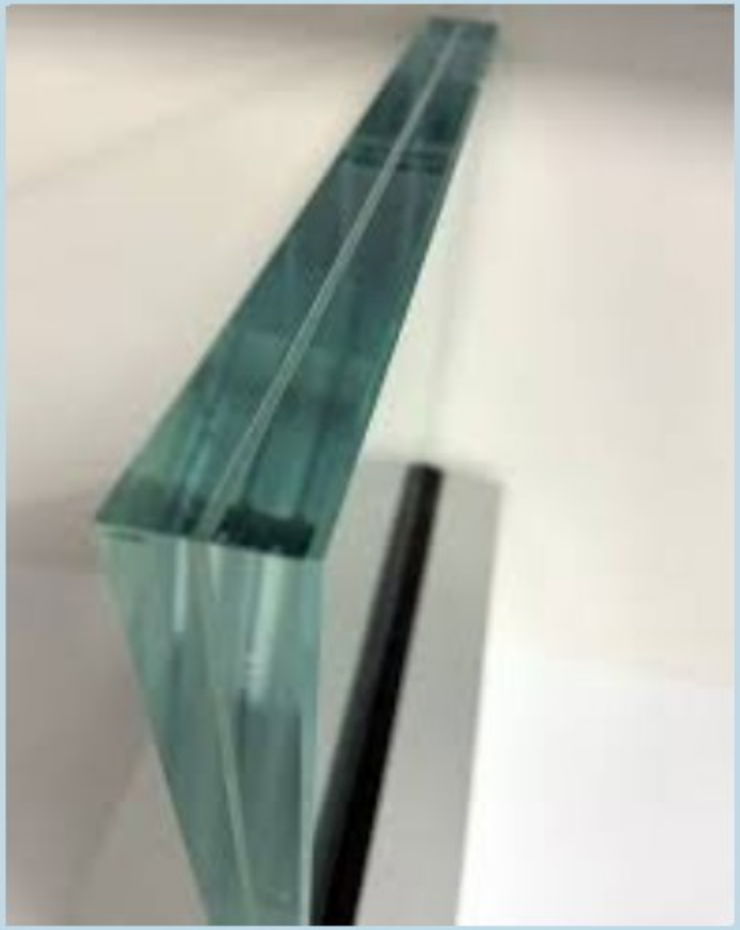
Glass structures



Monolithic



Laminated



IGU (DGU or TGU)






Privacy
Acoustic Comfort
Thermal Comfort
Energy
Solar radiation


What do we really
expect from facades?









Ordinary loads on constructions

Extreme design loads

Natural hazards

….that glass facades should be able to withstand



FACADES= physical barrier

EARTHQUAKES





HURRICANES &CLIMATE EVENTS





EXPLOSIONS
(ACCIDENTAL / HUMAN-INDUCED)





BUT:

Glass brittleness



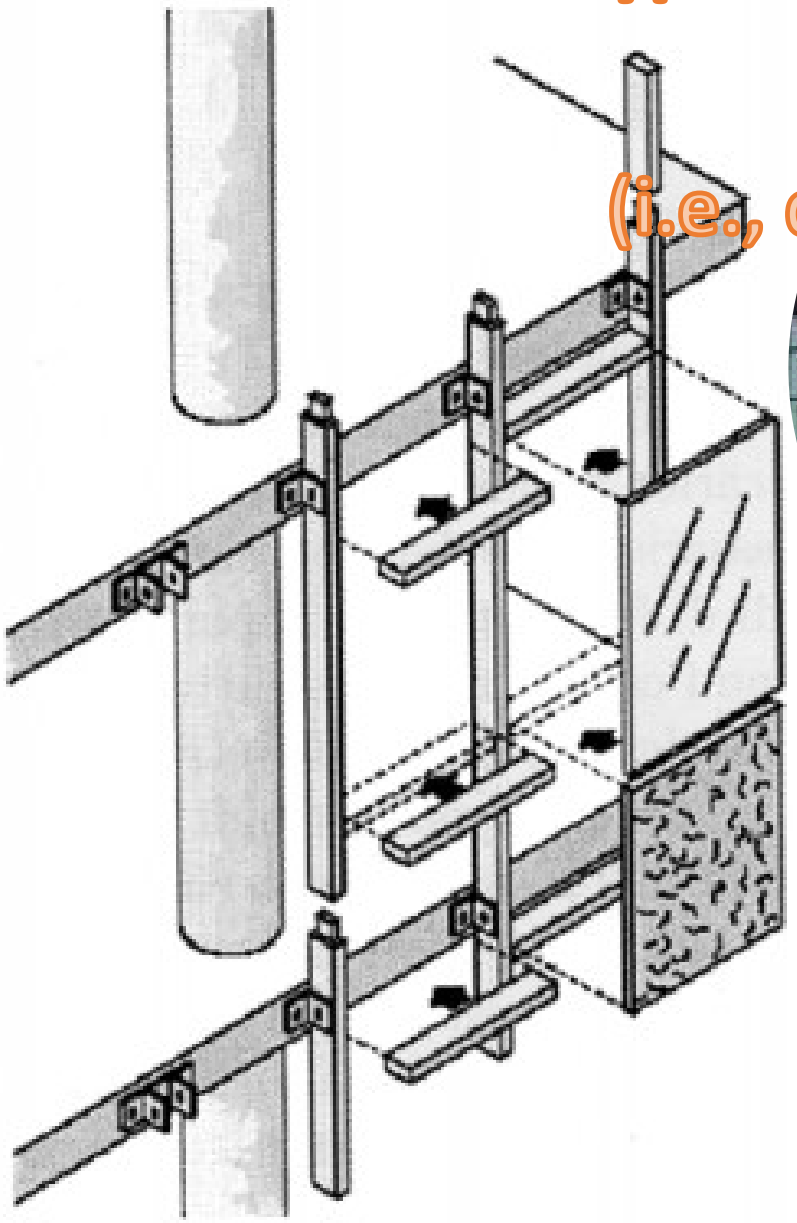



Brussels Zaventem


Extreme design loads
Explosions and impact
(human-induced or accidental)
Glass shards
are the first cause of injuries

Several types of facades

(i.e., different static schemes, mechanical restraints, load distributions)









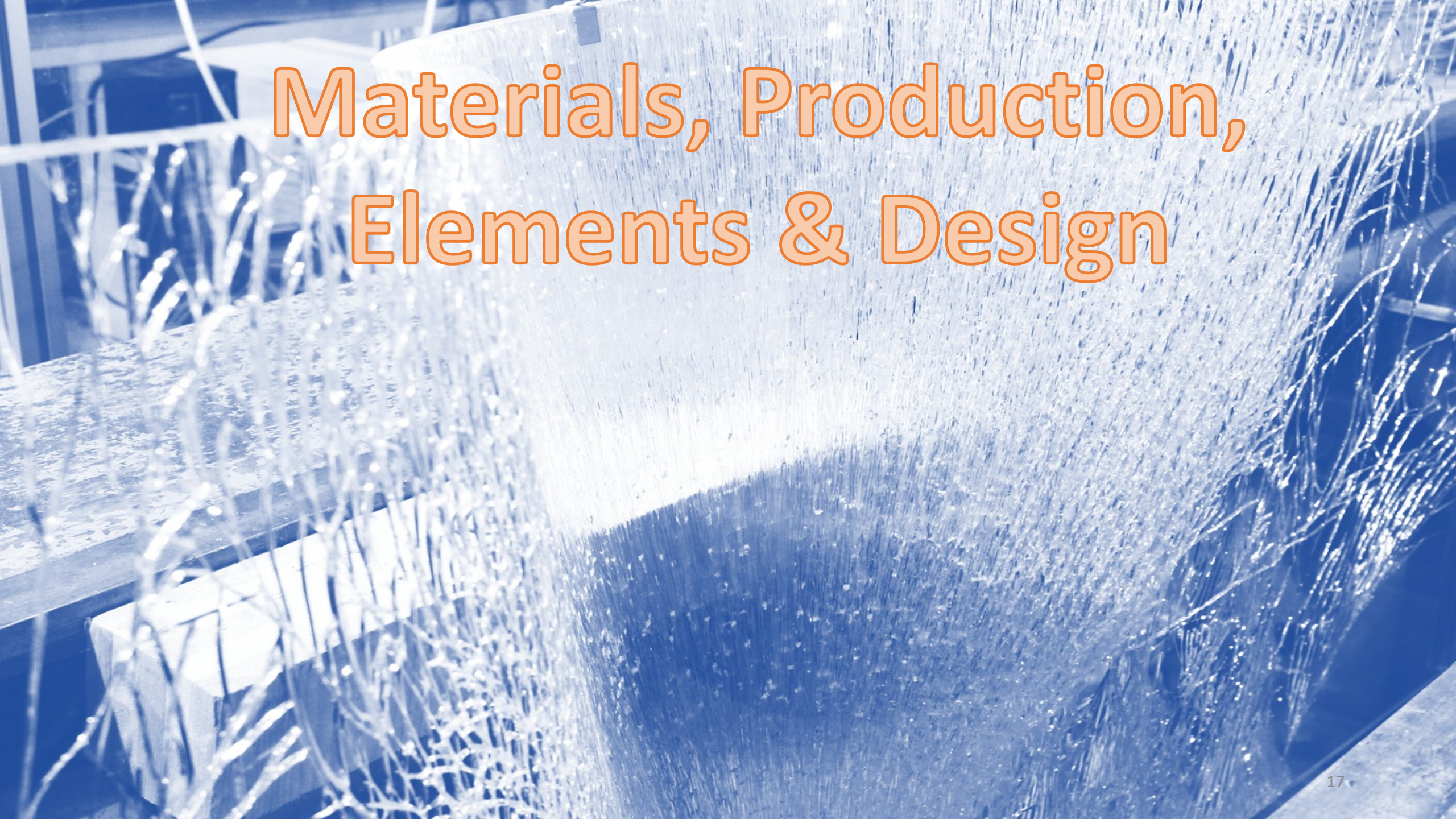


REFERENCES

- ✓ **SLIDES**

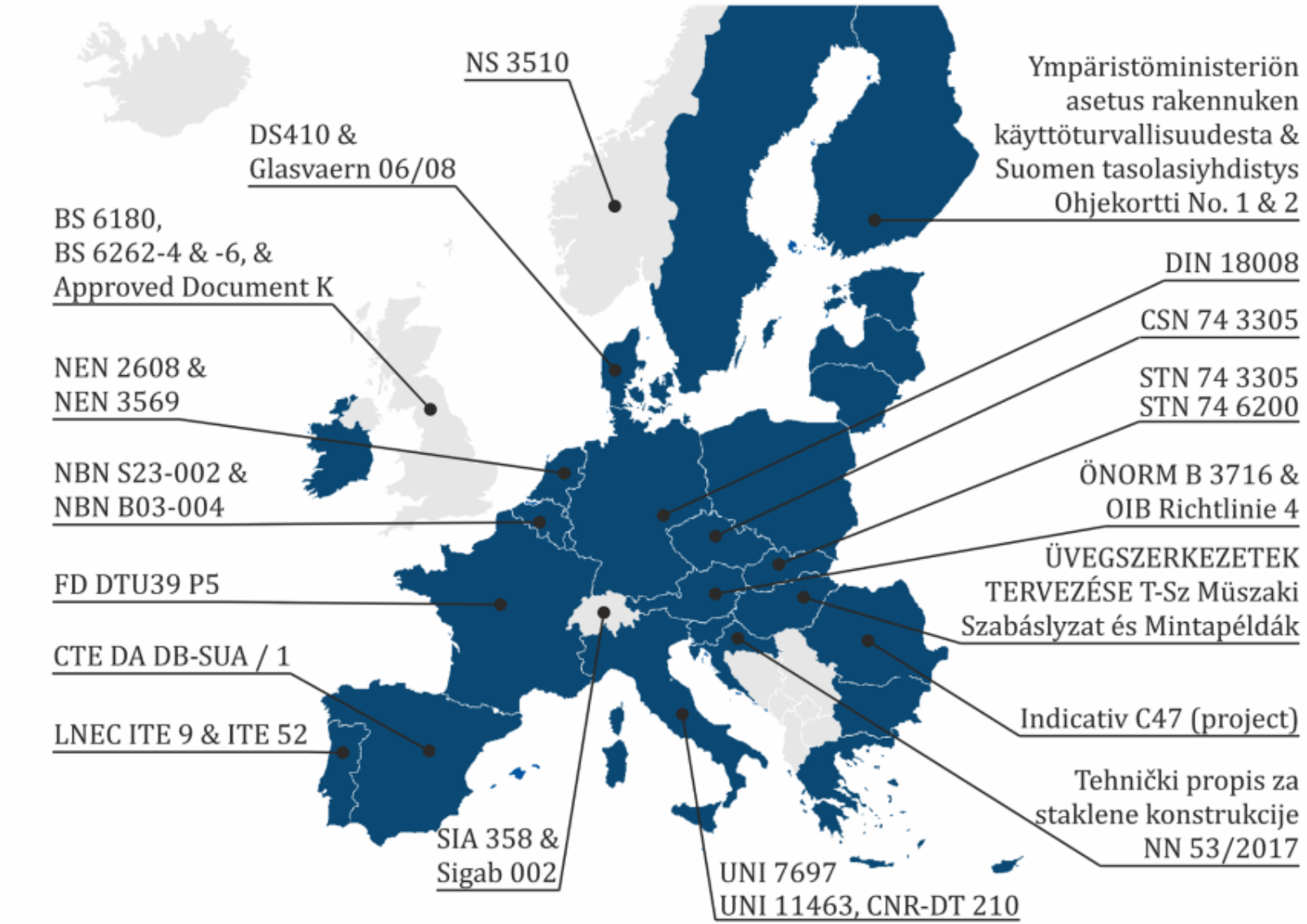


info@cism.it



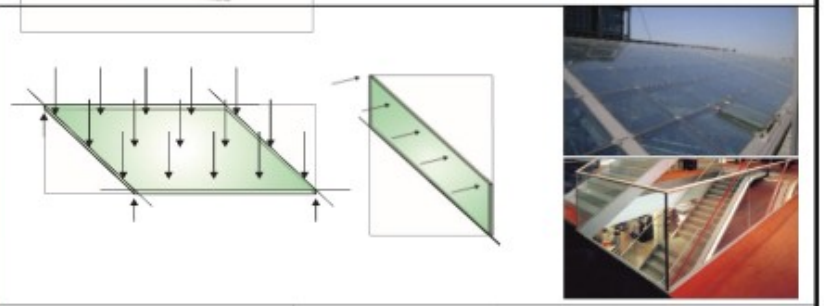
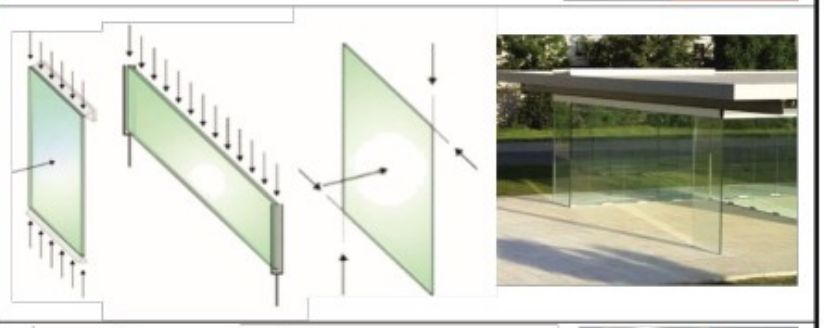
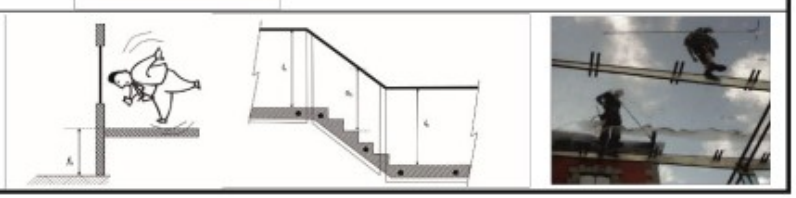
Materials, Production, Elements & Design

DESIGN STANDARDS AND TECHNICAL DOCUMENTS IN EUROPE:



Structure and Content of Eurocode 10 (October 2026)

NEW!!

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	

Procedura competitiva per lo sviluppo delle attività di ricerca fondamentale, a valere sul Fondo Italiano per la Scienza (FIS2021)

MUR
Ministero dell'Università e della Ricerca

FIS2021

UNIVERSITÀ DEGLI STUDI DI TRIESTE

Dipartimento di Ingegneria e Architettura

HOPgLAz

Holistic post-breakage characterization for optimized safe design of glass under multi-hazard

PI: Prof.ssa Chiara Bedon
Budget: 910.840 Eur
(2024-2029)

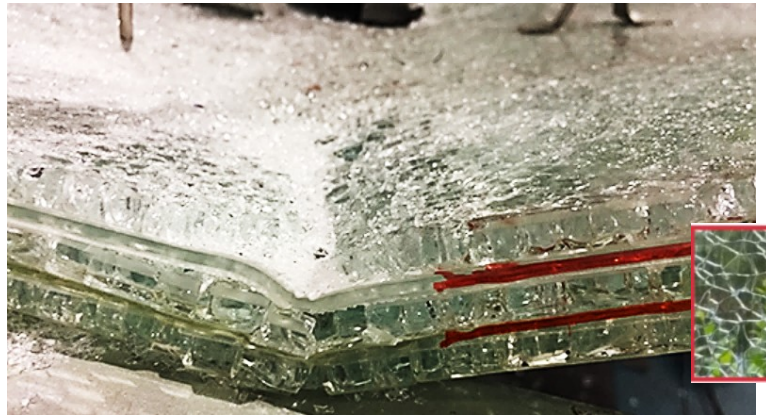
www.hopglaz.it

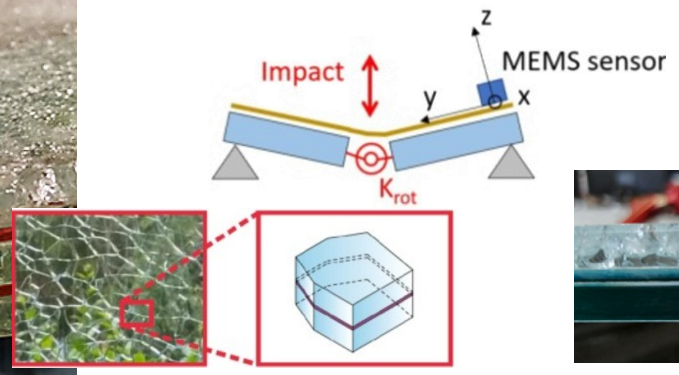
Elettra Sincrotrone Trieste | Elettra and FERMI lightsources

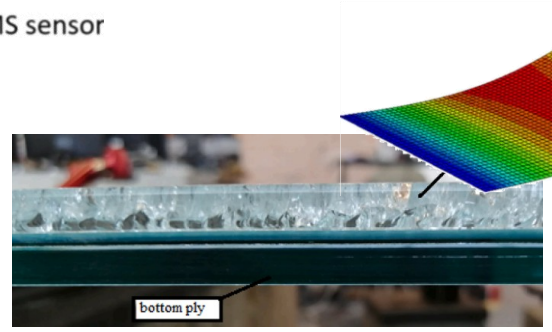
Joint Research Centre JRC

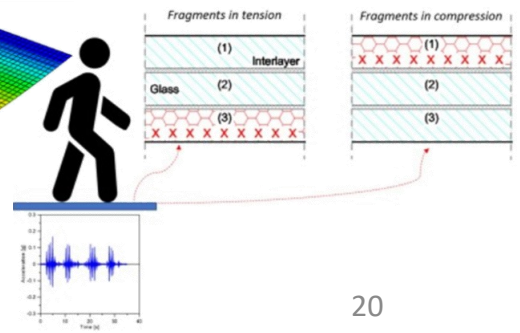
TU Delft

Silesian University of Technology















Glass products







2000 BC
Egypt





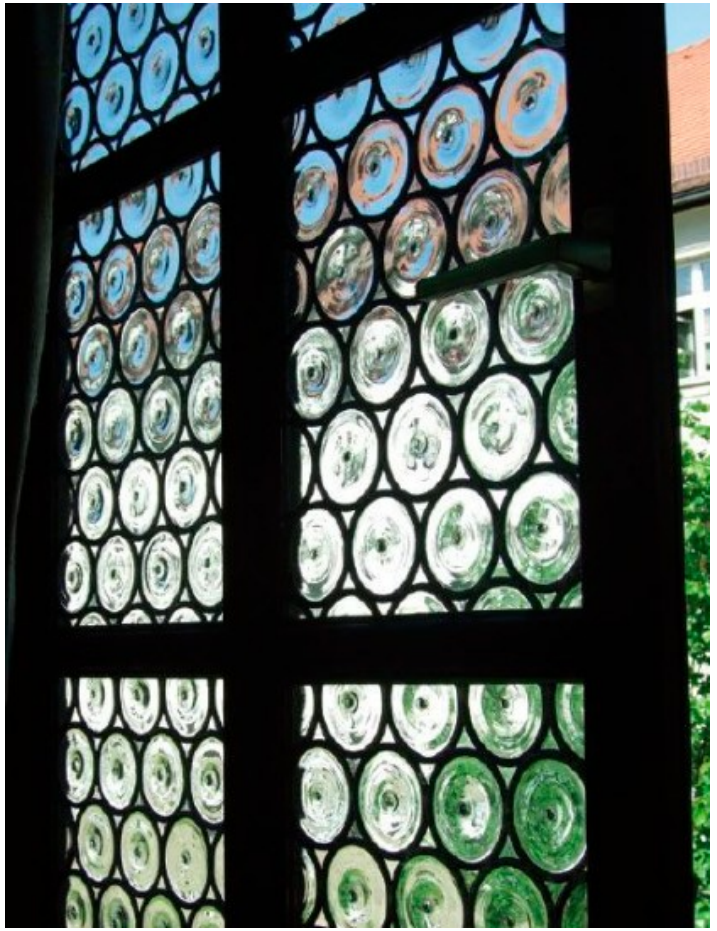
4000 BC
Mesopotamia

1688 Saint Gobain
Production of flat glass









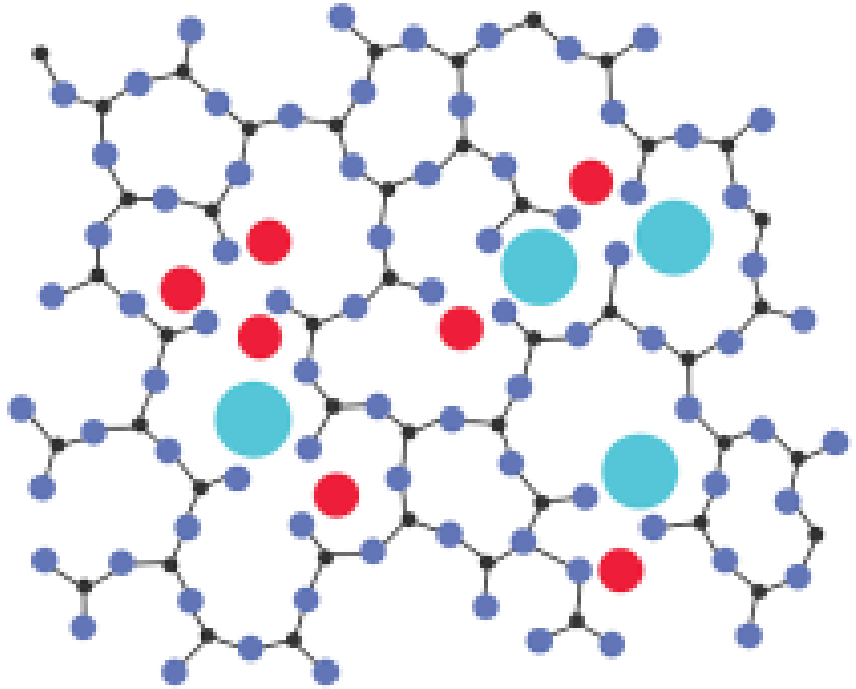
Crown glass (1750-1800)

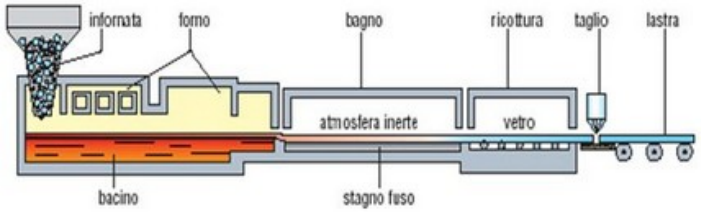




Crown glass (1750-1800)

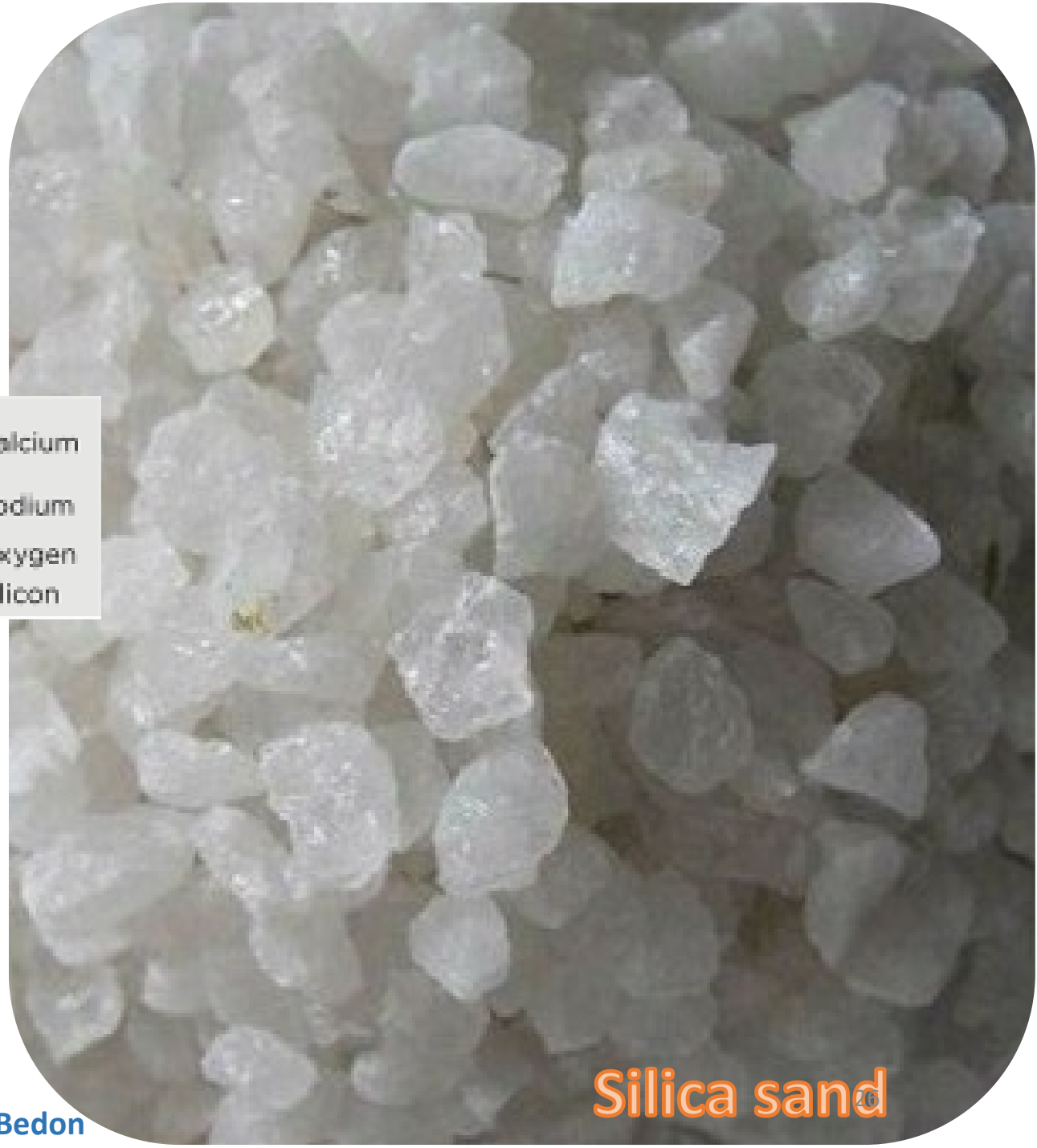






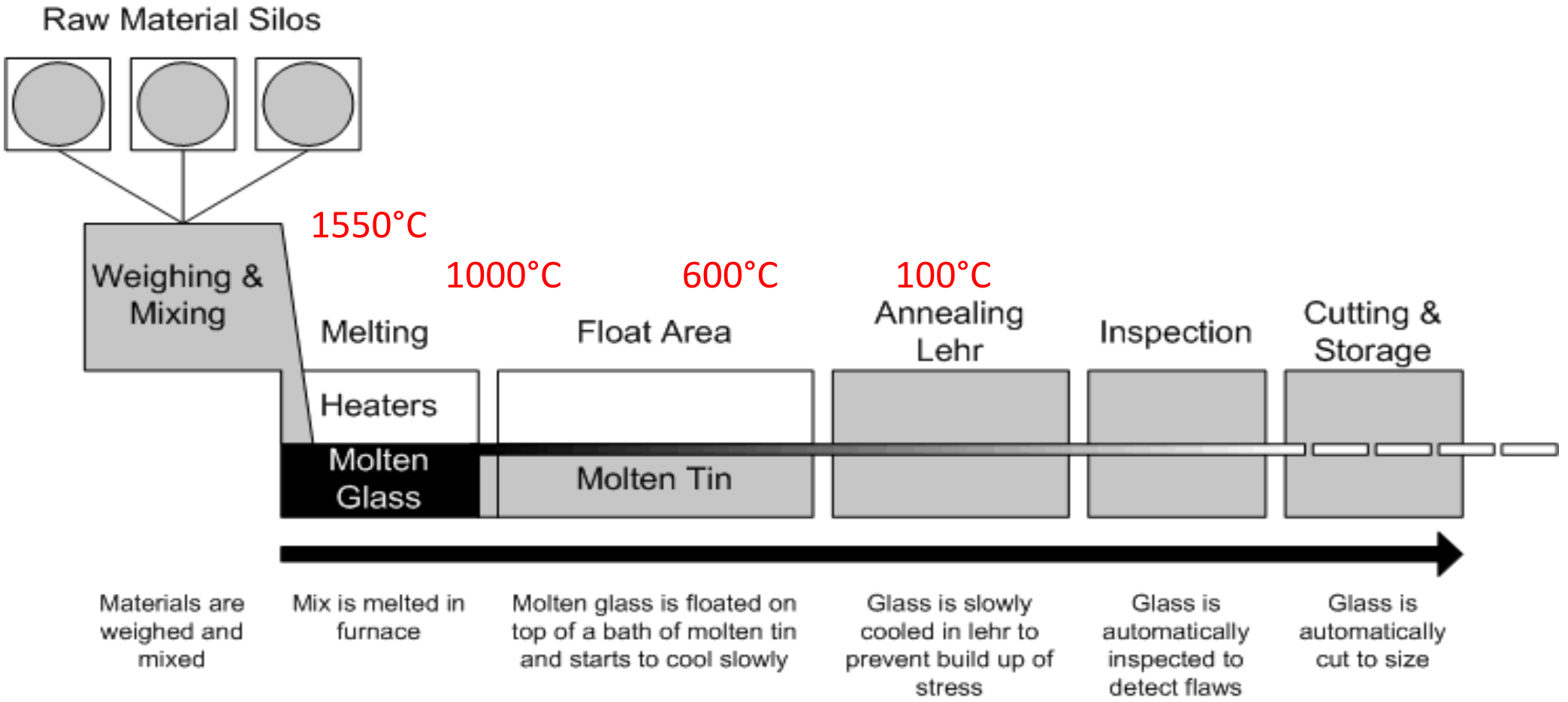


Calcium
Sodium
Oxygen
Silicon



Modern float glass production

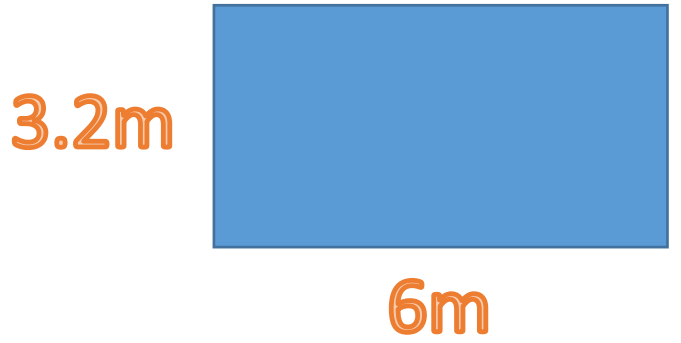
(Pilkington Brothers 1959)



Modern float glass production




22mm
19mm
15mm
12mm
10mm
8mm
6mm
5mm
4mm
3mm
2mm
1.5mm
1mm
0.55mm
0.2mm
0.1mm
0.05mm
0.025mm
STRUCTURES


3.2m
6m





2010

Dusseldorf

EXTRA SIZE

18 x 3.3m

3x10mm (4,5 tons)



EXTRA SIZE
(China)
25m long

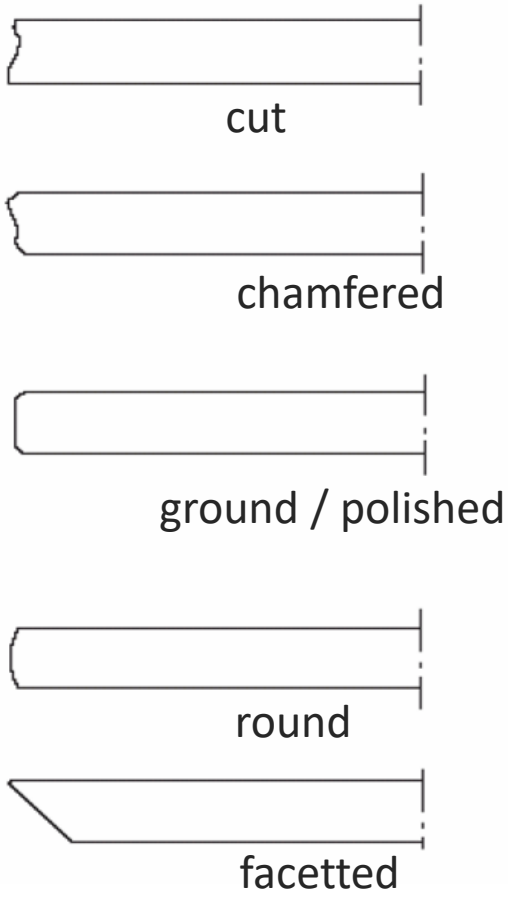
Production steps for edge finiture, holes, cuts, etc.



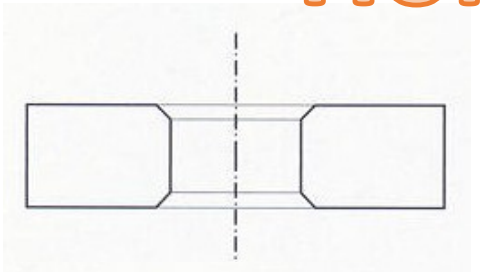


ALL BEFORE
THERMAL PRESTRESS!

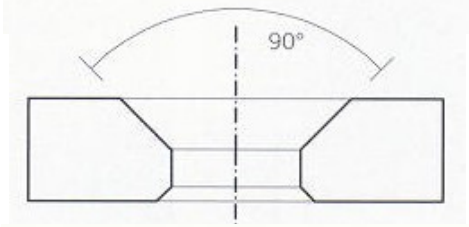
Edge Finishing



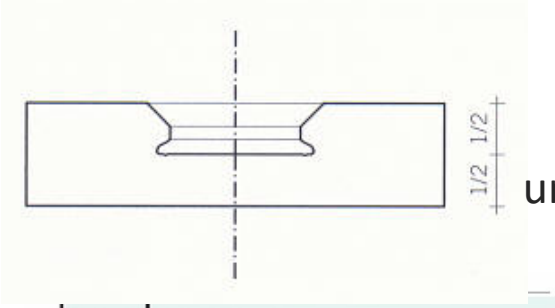
Hole Drilling / Water Jet Cutting



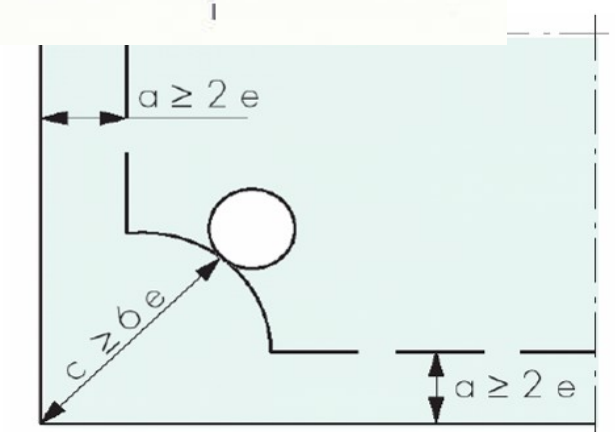
cylindrical hole



conical hole



undercut hole





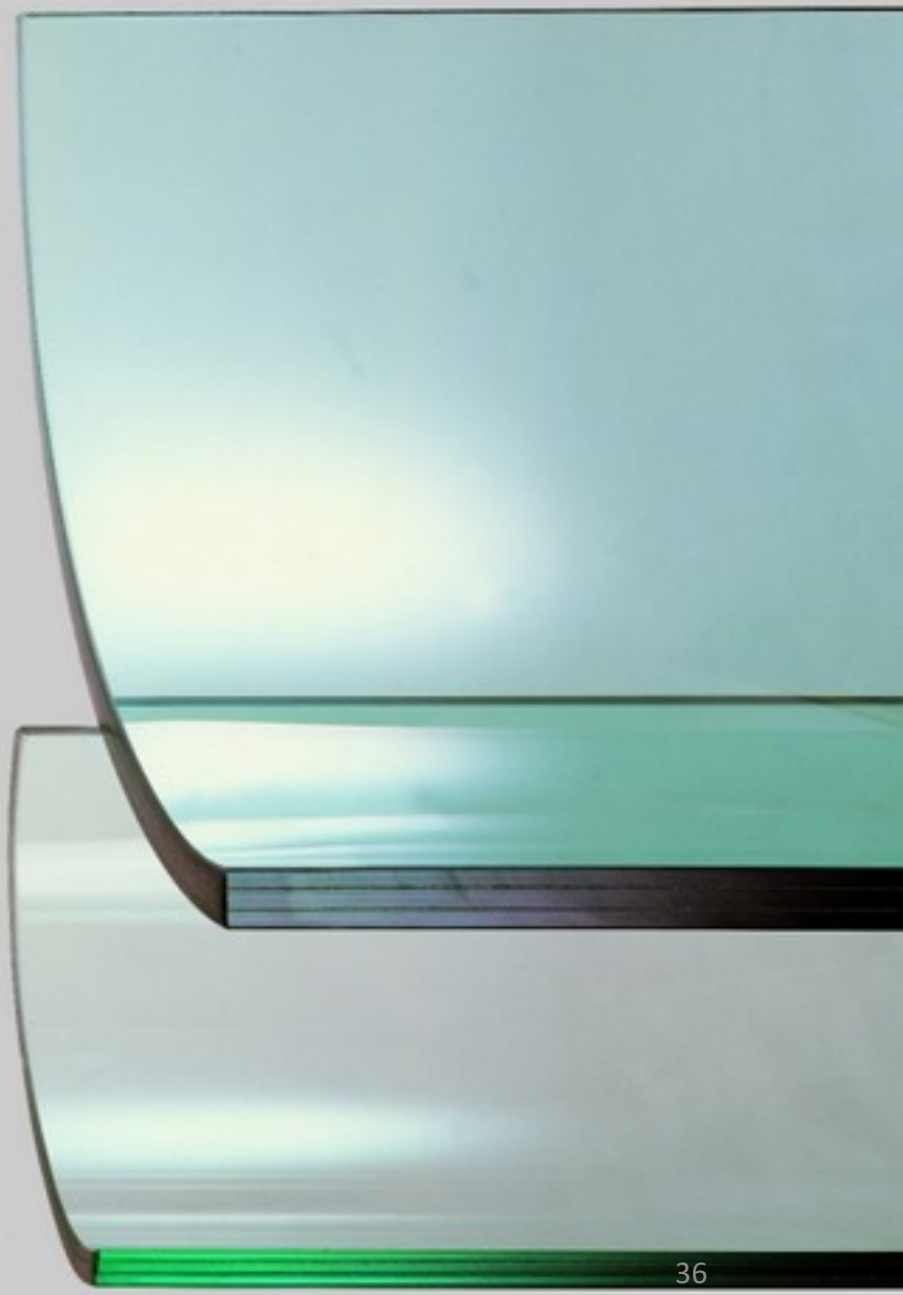
ALL BEFORE THERMAL PRESTRESS!

Curved glass



Curved glass





Typical glass properties

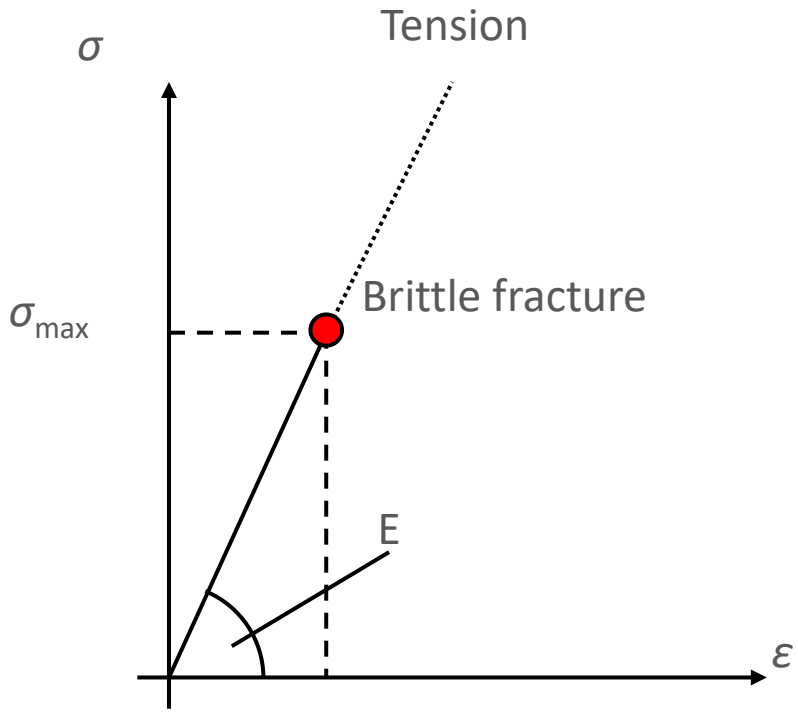
			Soda lime silica glass	Borosilicate glass
Density	ρ	kg/m³	**2 500**	2 200-2 500
Young's modulus	E	MPa	**70 000**	60 000-70 000
Poisson's ratio	ν	-	**0.23**	0.2
Knoop hardness	$HK_{0,1/20}$	GPa	**6**	4.5-6
Coeff. of thermal expansion	α_T	$10^{-6}\ K^{-1}$	**9**	Class 1: 3.1-4.0 Class 2: 4.1-5.0 Class 3: 5.1-6.0
Thermal conductivity	λ	$Wm^{-1}K^{-1}$	**1**	1
Average refractive index within visible spectrum	n	-	**1.52**	1.5

GLASS PRESTRESS
Controlled heating and cooling process

Linear elastic, brittle behaviour in tension

Glass is NOT a safe building material!!



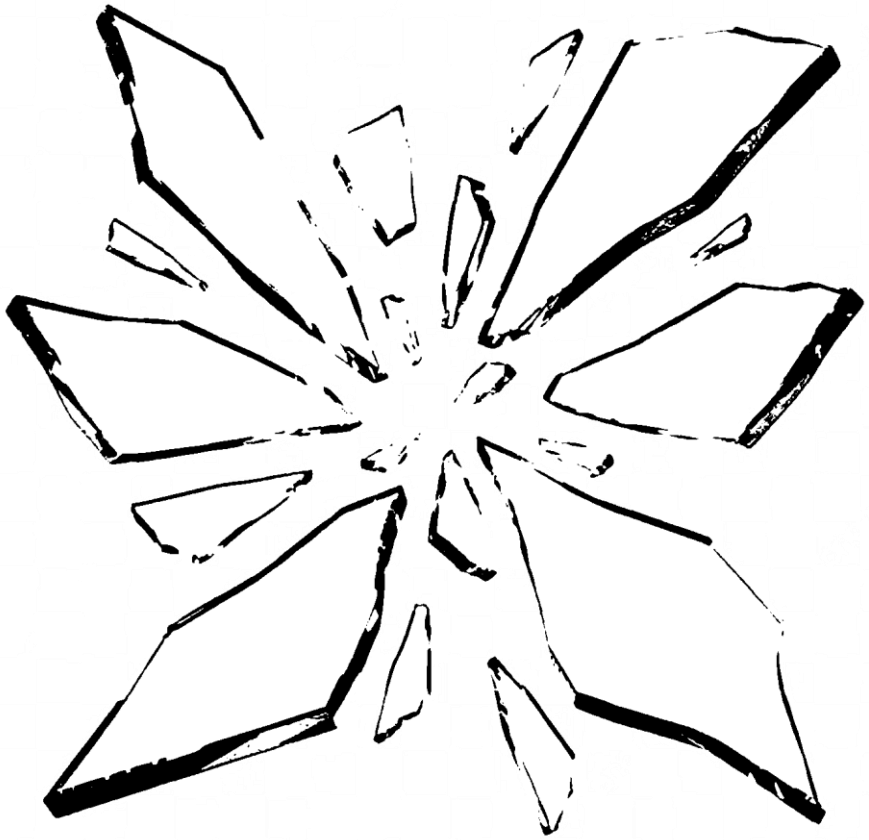


➡ Fracture mechanics concepts

➡ Static fatigue phenomena (k_{mod})

GLASS PRESTRESS

Controlled heating and cooling process





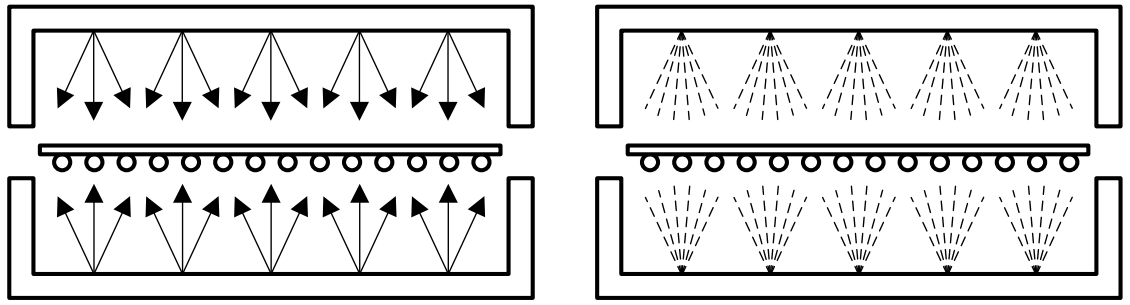


GLASS PRESTRESS

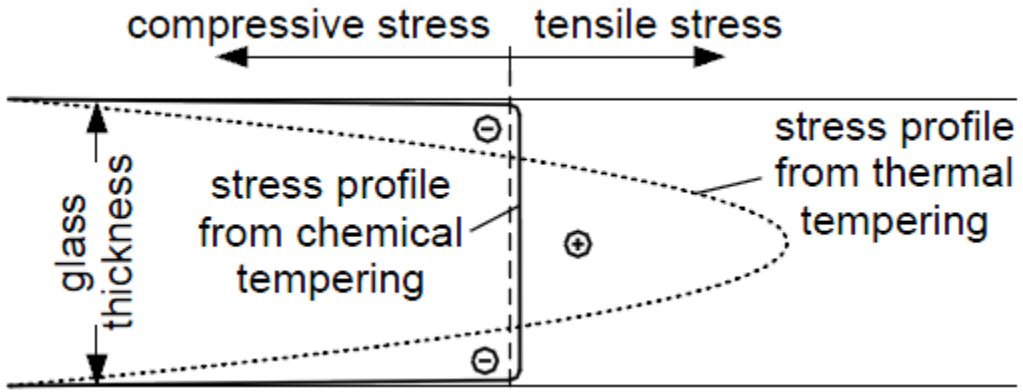
Controlled heating and cooling process

Heat strengthening process

- Cleaning
- Heating: 650 °C
  (approx. T_g + 100°C)
- Quenching (rapid cooling)



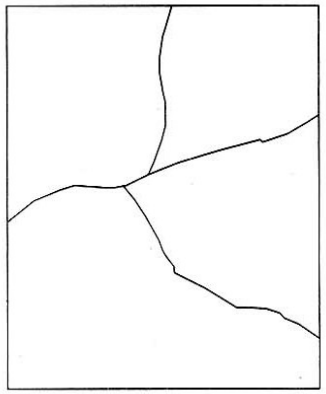
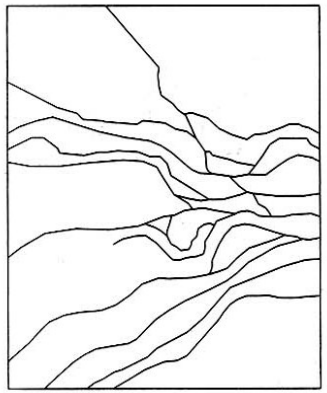
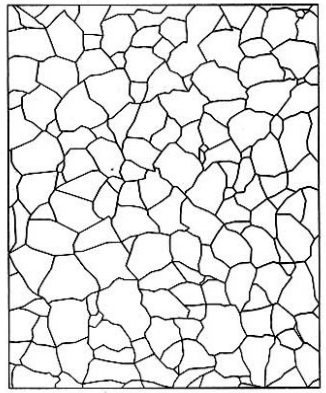
Heating Quenching



cutting, milling, drilling,… should be done BEFORE toughening (tempering)!



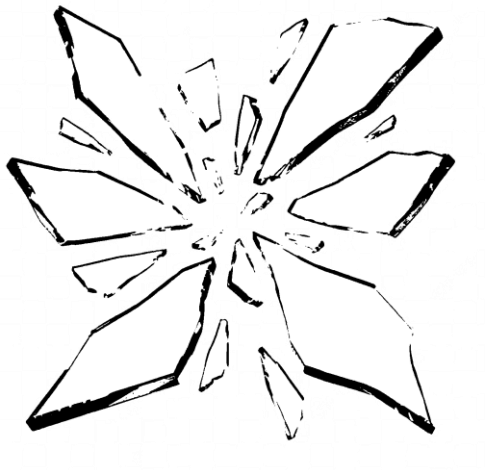
GLASS PRESTRESS Benefits

	(Almost) none	Medium	High
Prestress level	→	→	→
Fracture pattern			
Terminology	**Annealed** (ANG) (float glass)	**Heat strengthened** (HSG) (Partly toughened glass)	**Fully tempered** (FTG) (Tempered glass; thermally toughened glass)
TENSILE RESISTANCE	**45MPa**	**70MPa**	**120MPa**

(compressive resistance 500MPa)

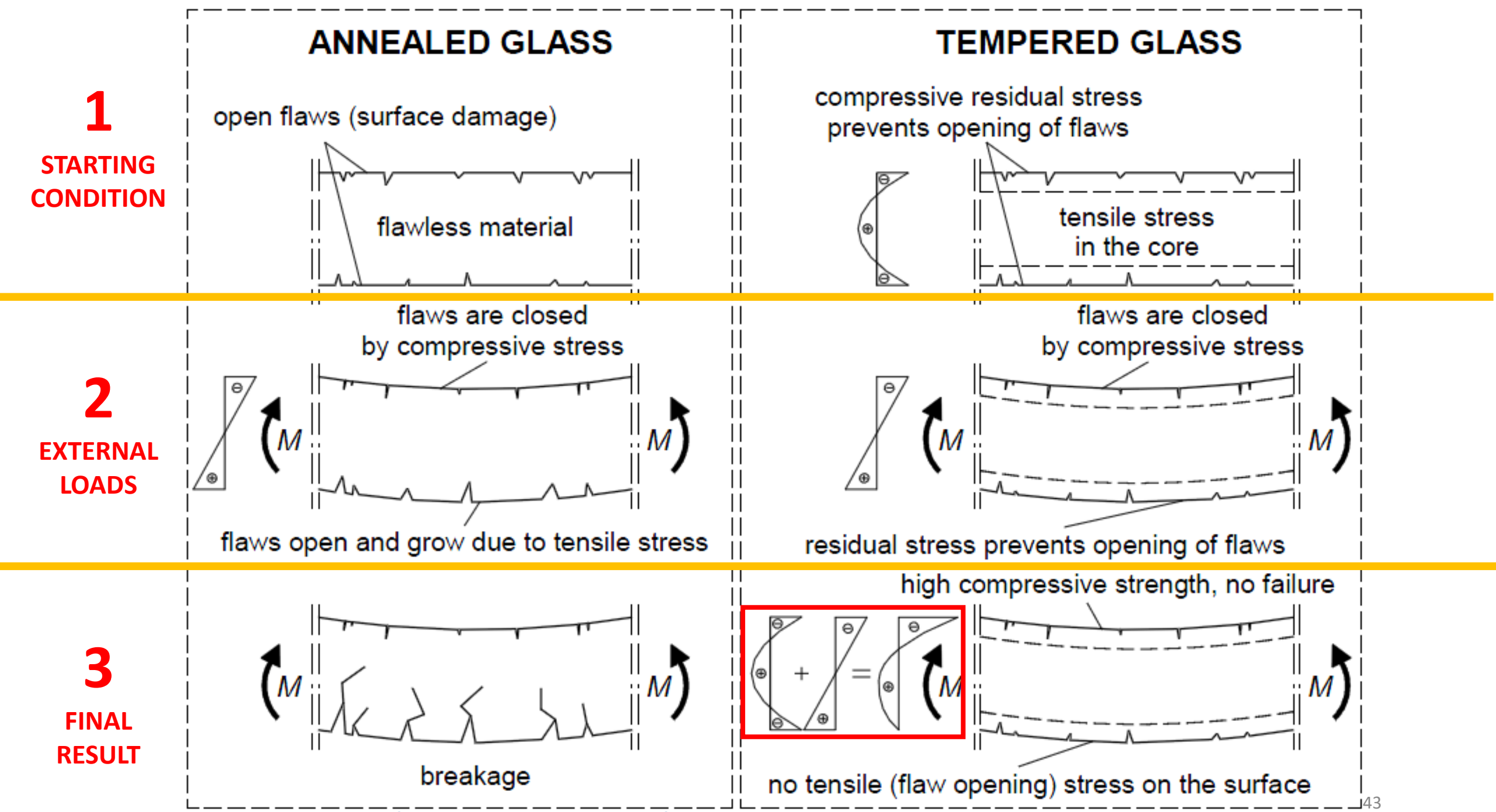
GLASS PRESTRESS
Benefits



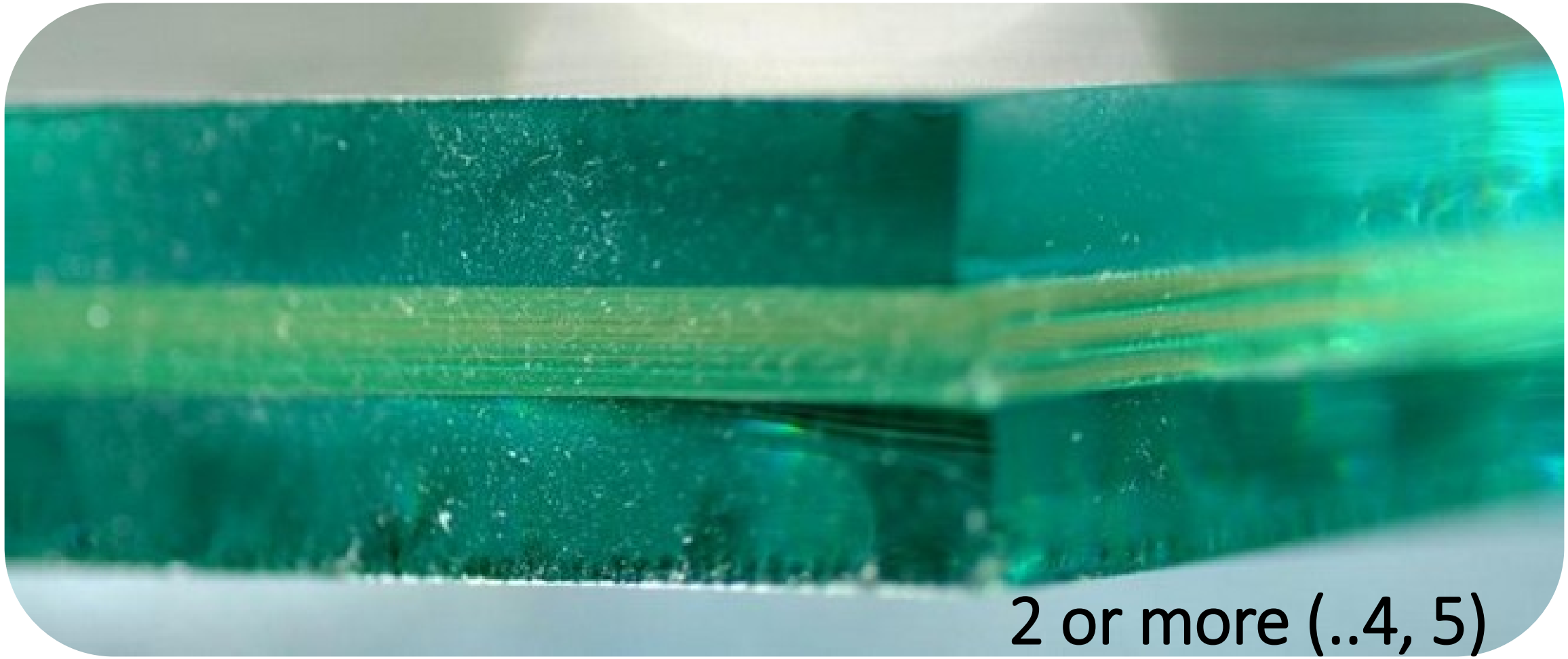


- Simply supported glass panel
- Monolithic glass
- We use first float glass, and then thermally prestressed glass




ANNEALED GLASS
TEMPERED GLASS
1
STARTING CONDITION
open flaws (surface damage)
flawless material
compressive residual stress
prevents opening of flaws
tensile stress
in the core
2
EXTERNAL LOADS
flaws are closed
by compressive stress
M
M
flaws open and grow due to tensile stress
flaws are closed
by compressive stress
M
M
residual stress prevents opening of flaws
3
FINAL RESULT
M
M
breakage
high compressive strength, no failure
+
=
M
M
no tensile (flaw opening) stress on the surface

Laminated glass



2 or more (..4, 5) glass plies

Laminated glass

Autoclave for lamination



Laminated glass



Key steps:

1) Cleaning and preparation of the laminated sandwich

2) Heating and pressurization phase (up to 140°C, with gradual ramp – approx. 2°C/minute to prevent thermal shock and glass cracking; simultaneously, compressed air is pumped into the chamber, bringing the pressure up to 10 to 15 bars – approx. 1.0 to 1.5 MPa, depending on glass thickness)

3) Soaking / Dwell phase (constant heat and pressure, for 30-60 minutes or up to 2 hours; the melted interlayer creates a perfect mechanical adhesion with glass)

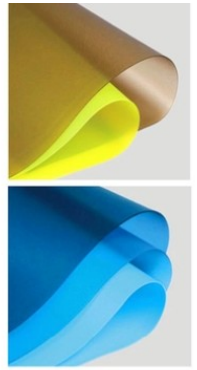
4) Controlled cooling phase (to avoid glass cracks, or warping or delamination)

5) Depressurization and unloading (once the internal temperature drops to a safe threshold (usually below 40°C–50°C), the air pressure is safely vented to atmospheric level)

6) Final check and inspections

Typical interlayer types for laminated glass





1. PVB - Amorphous thermoplastic family (1930's – Monsanto/DuPont)

- ❑ Tough, resilient, durable with high penetration resistance, sound, solar
- ❑ Mechanical behavior is temperature / load duration dependent
- ❑ The cheapest interlayer



2. TPU - Thermoplastic family (1937-Bayer)

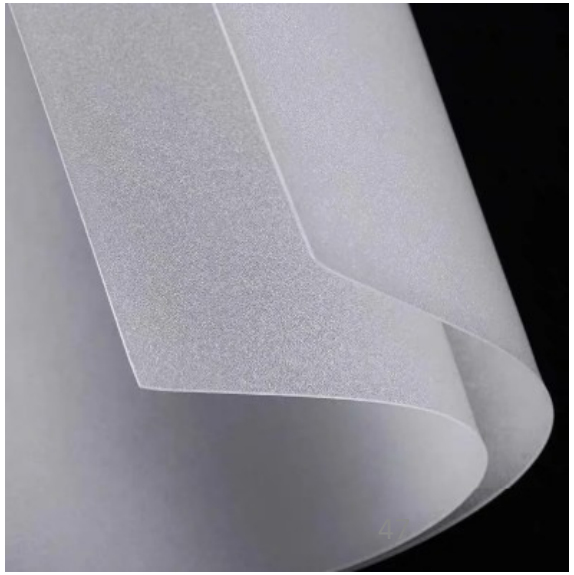
- ❑ One of the most polyvalent plastic material & most expensive one
- ❑ Performances between rubbers and plastics materials
- ❑ Excellent mechanical and viscoelastic properties at extreme temperature

3. EVA - Thermoplastic family (1950-ICI)

- ❑ Properties are less Time / temperature dependent than PVB's due to the fully cross linked (3D) structure
- ❑ Performances and properties between LDPE, plasticized PVC and flexible rubbers

4. Ionoplast: Elasto-plastic family (1960)

- ❑ Semi-crystalline thermoplastic
- ❑ Superior mechanical and viscoelastic properties

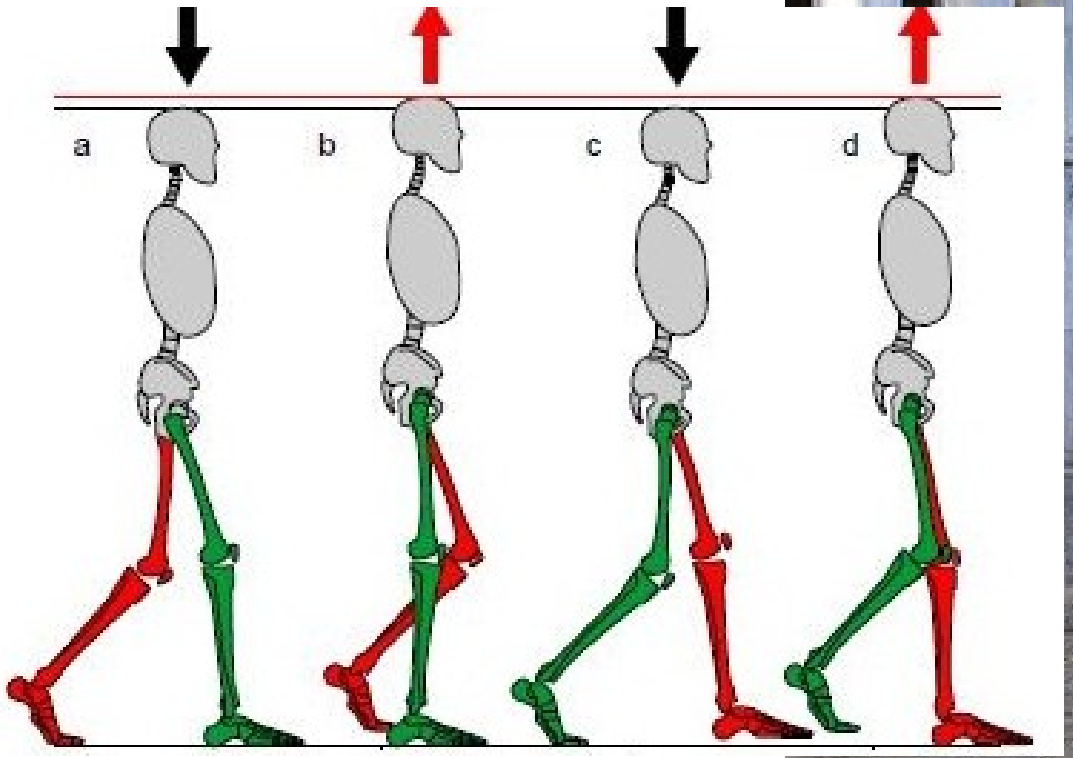


5. CIP - Thermo-set plastic family (1980's)

- ❑ Multi-components (polyester + acrylic resin +styrene) for acoustic performances
- ❑ Mono-component (acrylic resin) for safety performances

Diagnostic of existing structures

Vibrations



Aquileia (UD, Italy)

UniTS-DIA

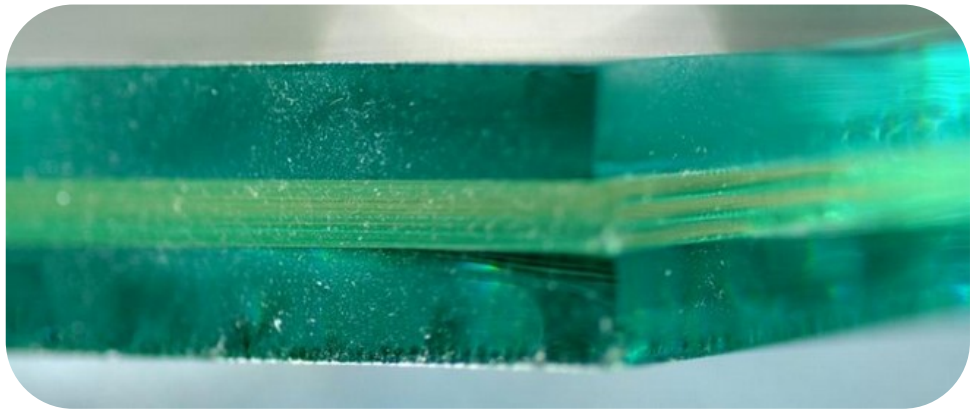

Vibration serviceability vs. degradation of in-service glass structures
Human-Structure Interaction phenomena (mass, stiffness, damping)

LAYERED LIMIT
(weak shear bonding)

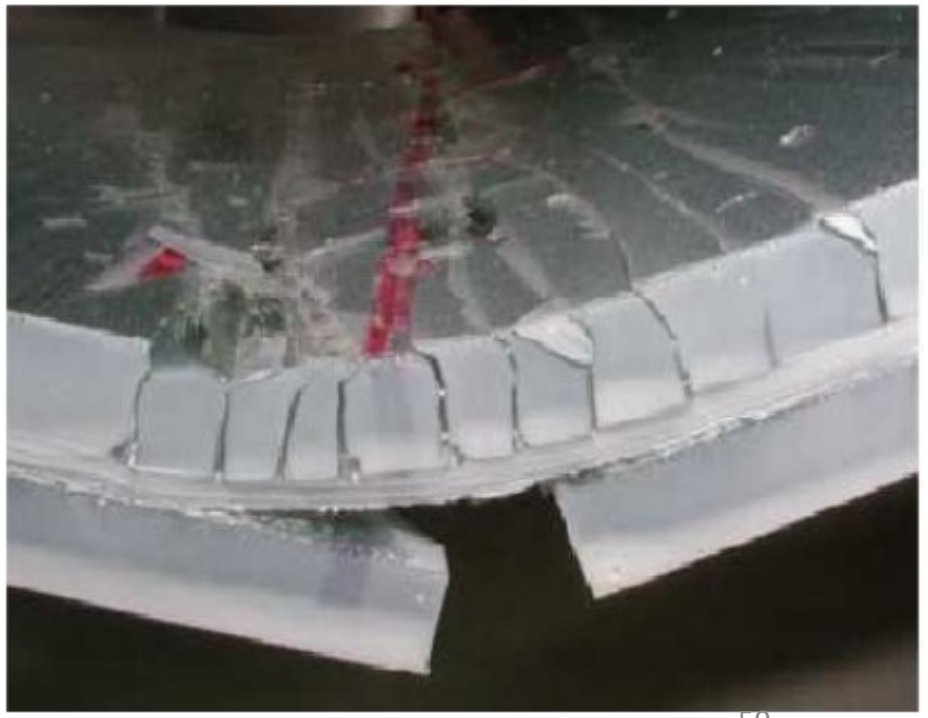


MONOLITHIC LIMIT
(ideally rigid shear bonding)

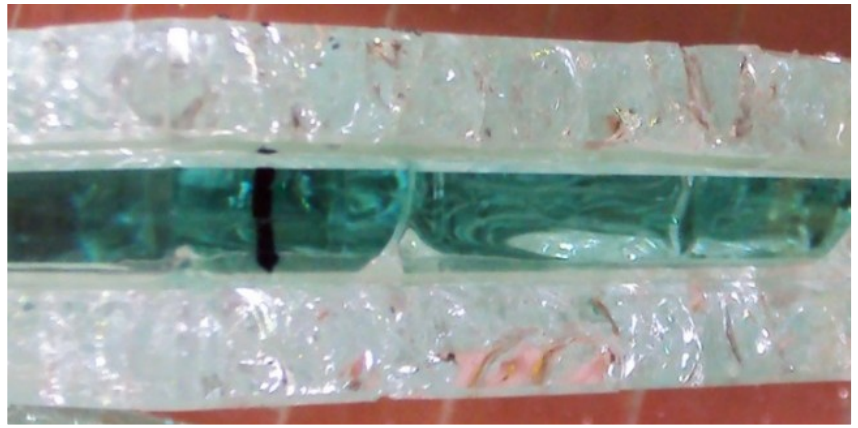




COMPLEX POST-FRACTURE BEHAVIOUR
(many influencing parametrs)



Glass brittleness

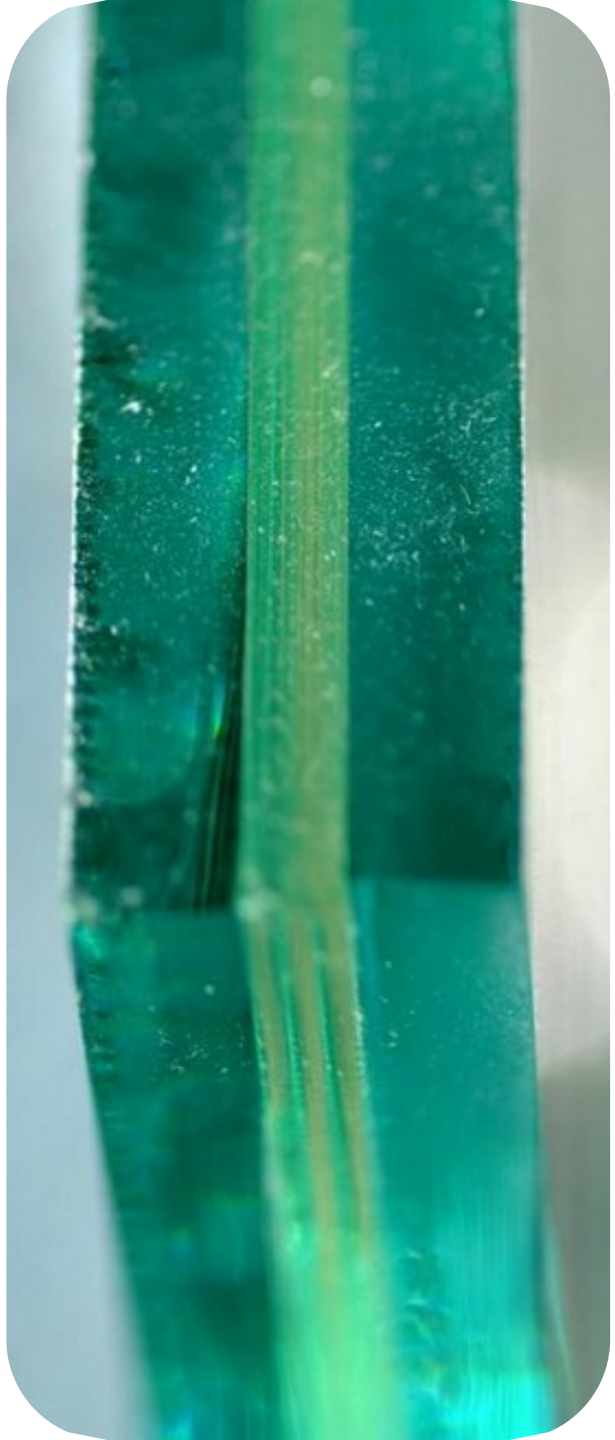






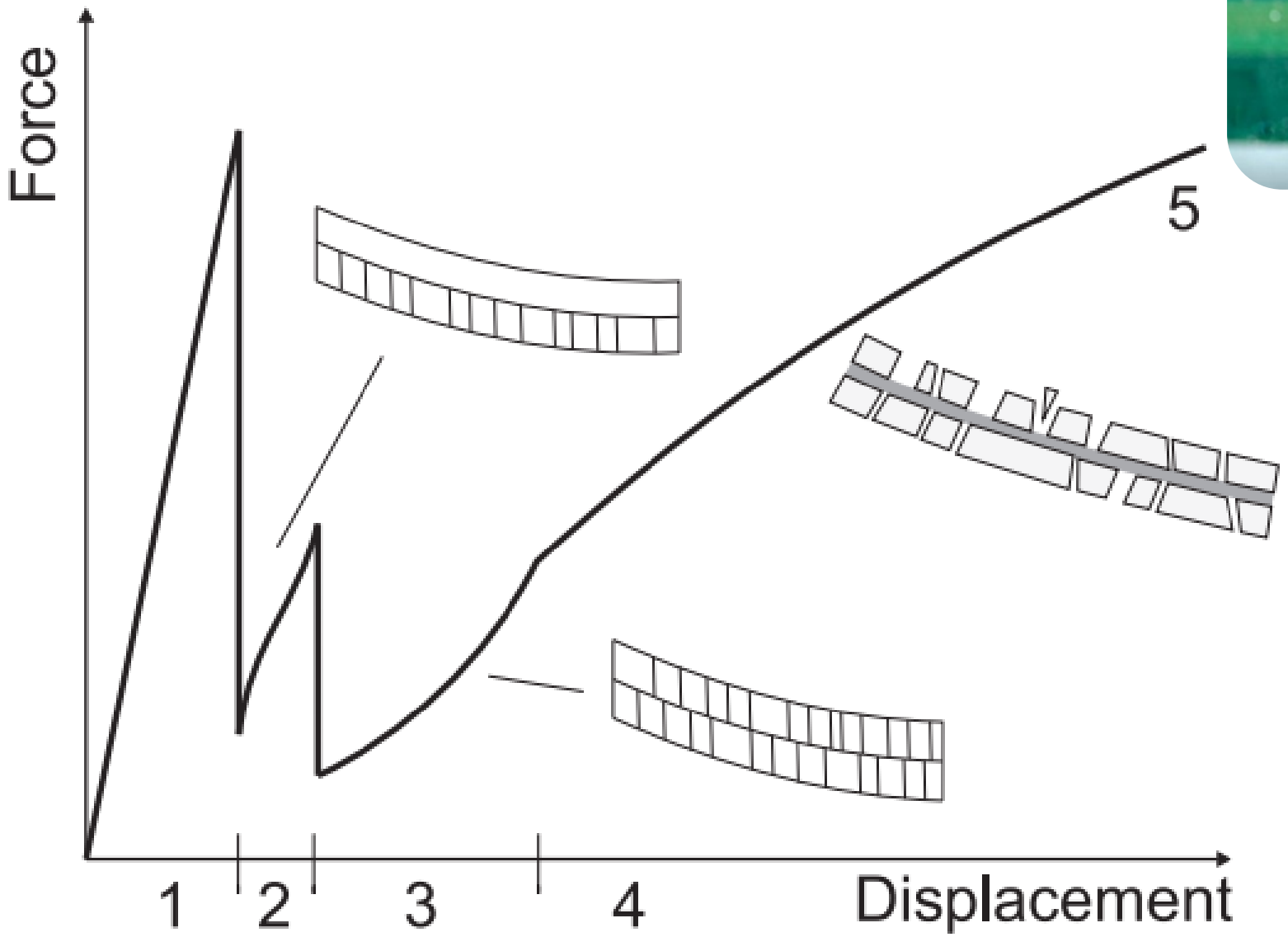


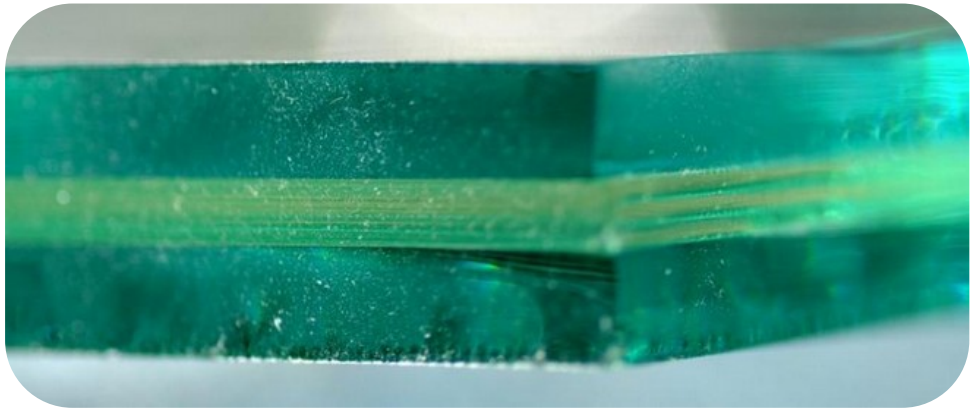




Post-cracked behaviour

- Residual stiffness?
- Tearing of interlayers?





(1) Elastic behaviour of glass plies

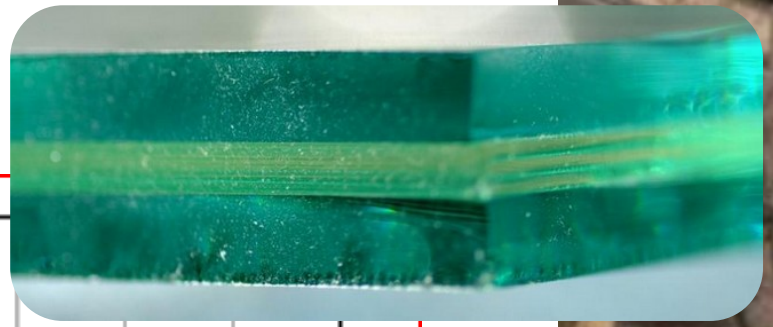
(2) The first glass ply is broken, the other is still intact; the interlayer is not damaged

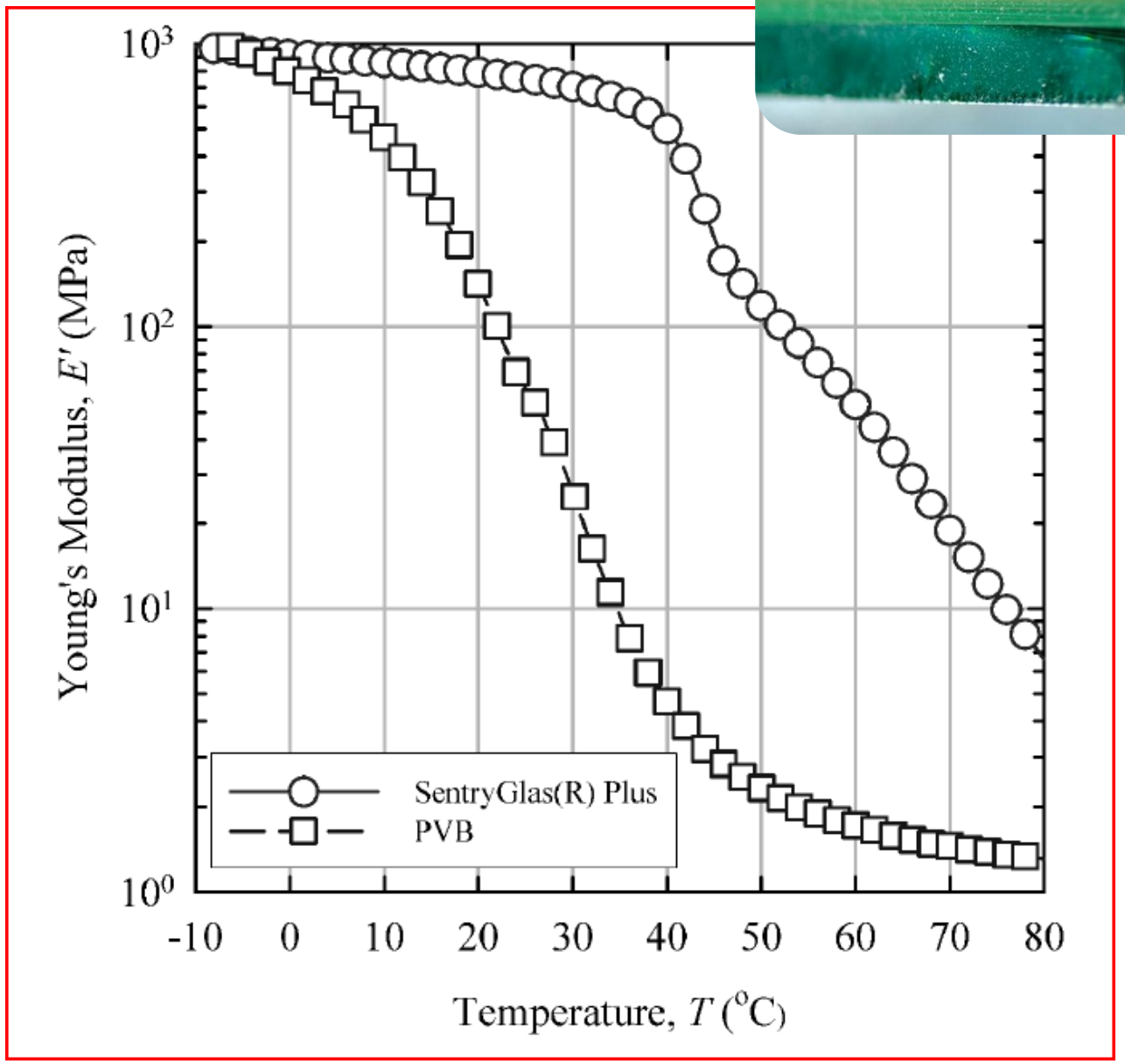
(3) The second glass ply fails; the interlayer behaves elastically

(4) The interlayer behaves plastically; the splinters are kept together by the interlayer

(5) The interlayer fails by reaching its failure strength or by cutting from the splinters

Laminated glass





Stiffness sensitivity to:

- Time loading
- Temperature
- Humidity
- Etc.

Shear Modulus (G) Comparisons (PVB or SG)

- PVB - Shear modulus, G (MPa)

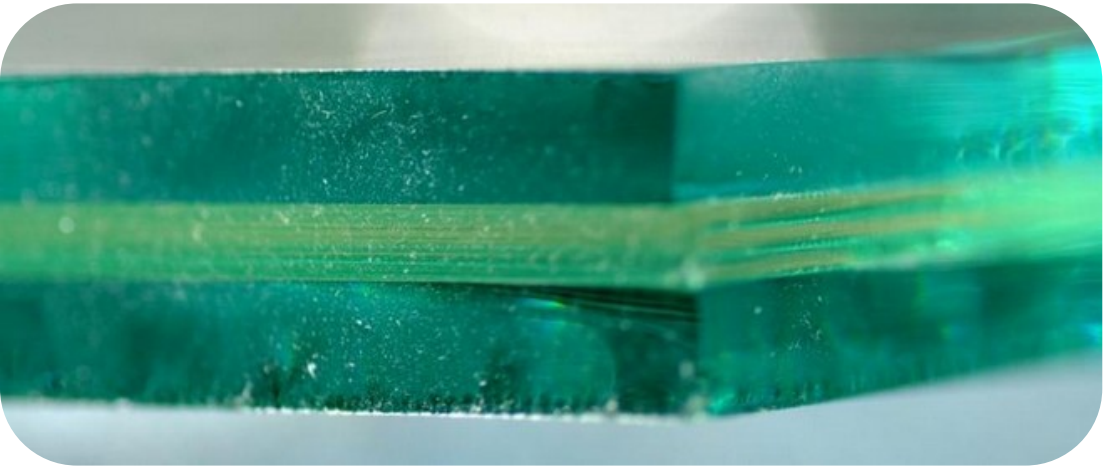
Time loading

G_{PVB}, (MPa)	3s	1 min.	1 hr.	1 day	1 mo.	> 1 yr.
20 °C	8.06	1.64	0.840	0.508	0.372	0.266
30 °C	0.971	0.753	0.441	0.281	0.069	0.052
40 °C	0.610	0.455	0.234	0.234	0.052	0.052
50 °C	0.440	0.290	0.052	0.052	0.052	0.052

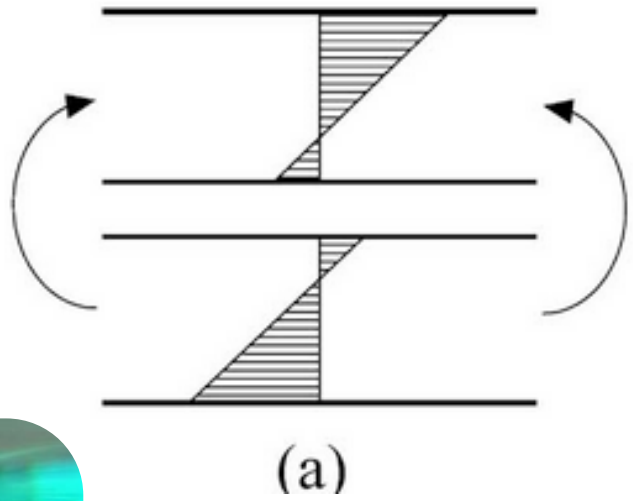
Temperature

- Ionoplast – Shear Modulus, G (MPa)

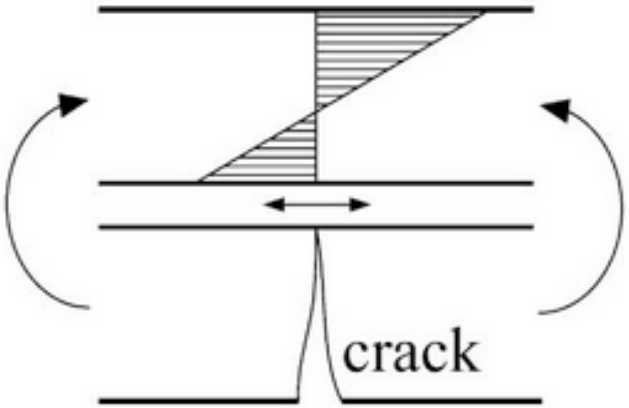
G_{SGP}, MPa	3s	1 min.	1 hr.	1 day	1 mo.	> 1 yr.
20 °C	125	96.0	42.7	21.6	9.7	6.5
30 °C	65.7	35.4	14.6	6.9	3.1	2.9
40 °C	22.2	11.6	5.1	2.9	2.8	2.0
50 °C	7.1	3.8	2.9	2.6	2.0	2.0



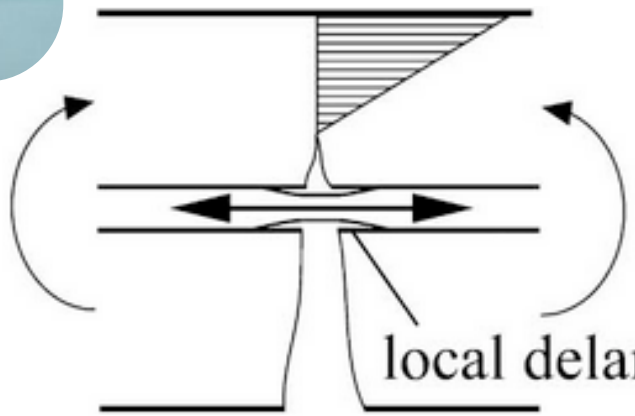
Interlayer?



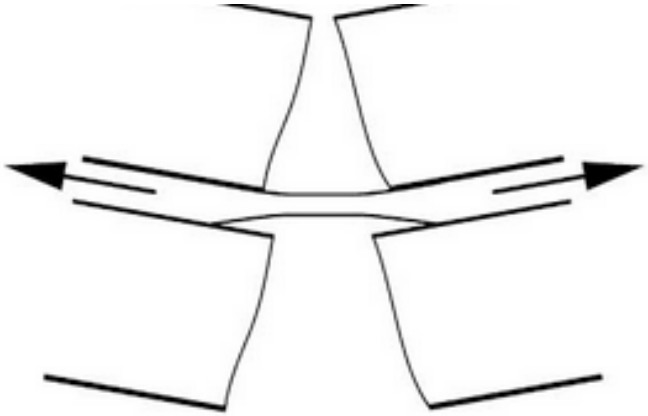
(a)



(b)



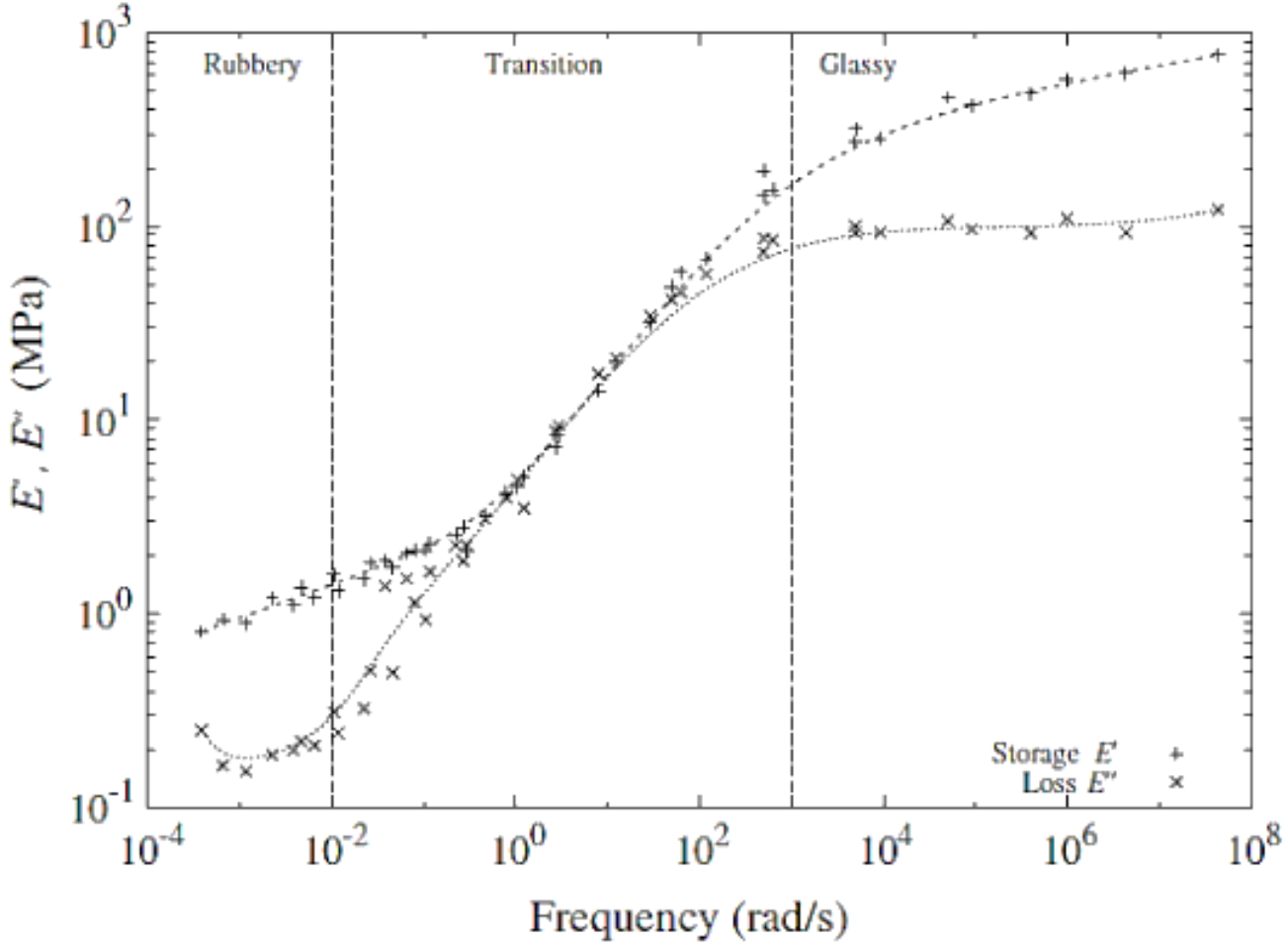
(c)



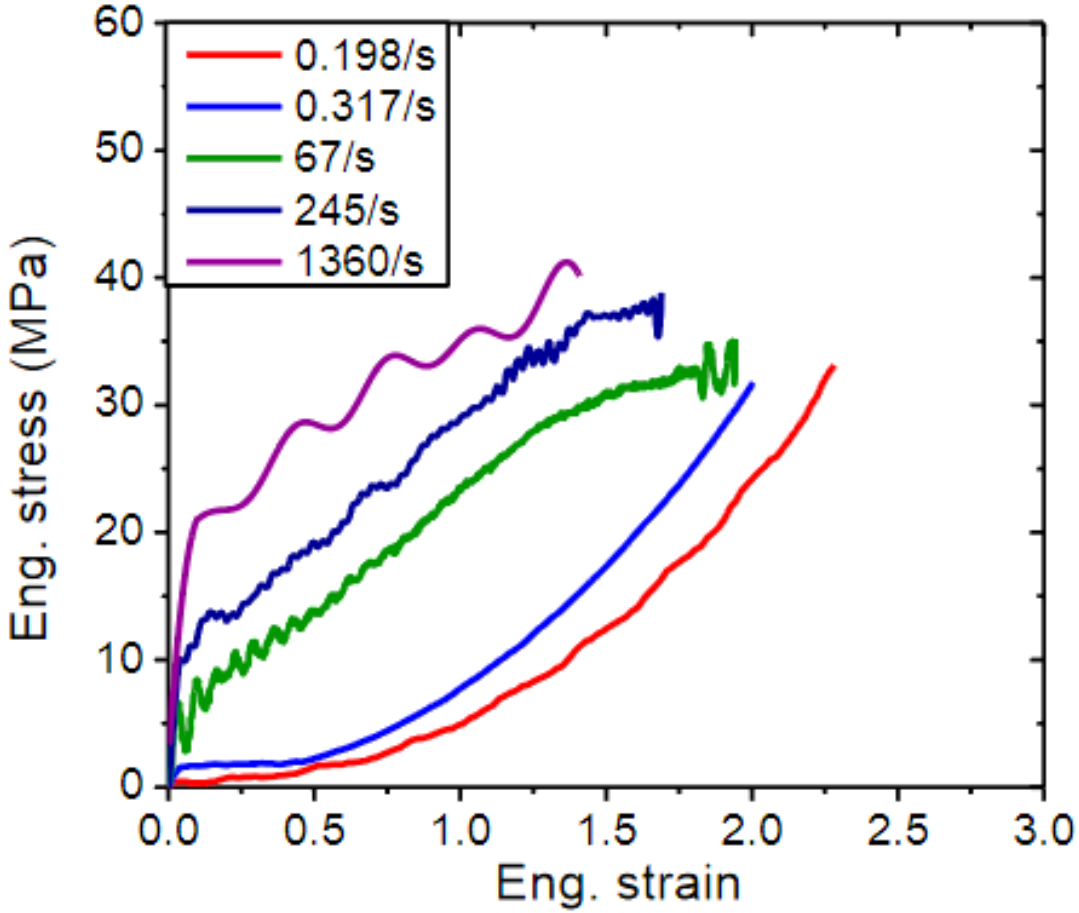
(d)

Interlayer & strain rate

PVB

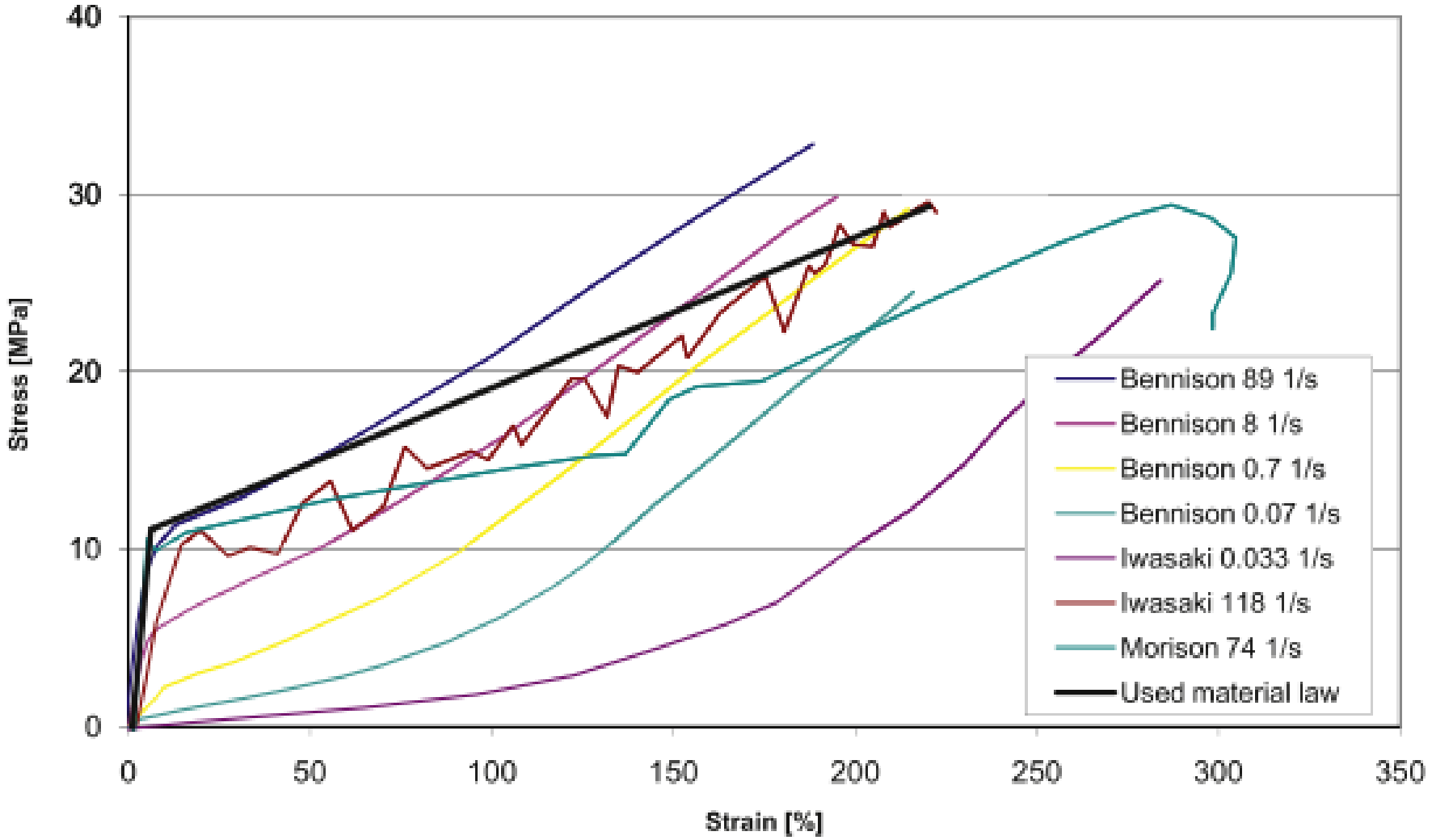


a) Modulus vs. frequency at 20°C [76]



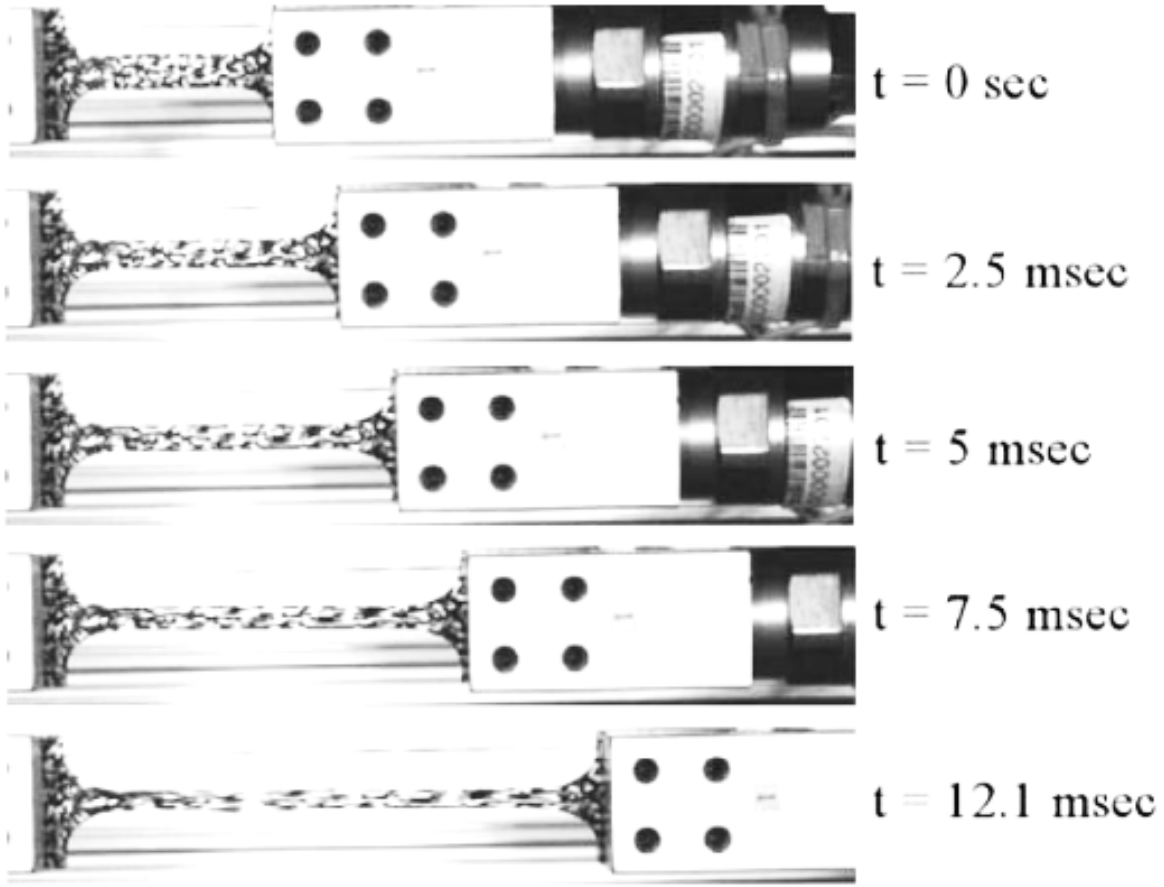
b) PVB stress-strain curves [77]

Interlayer & strain rate

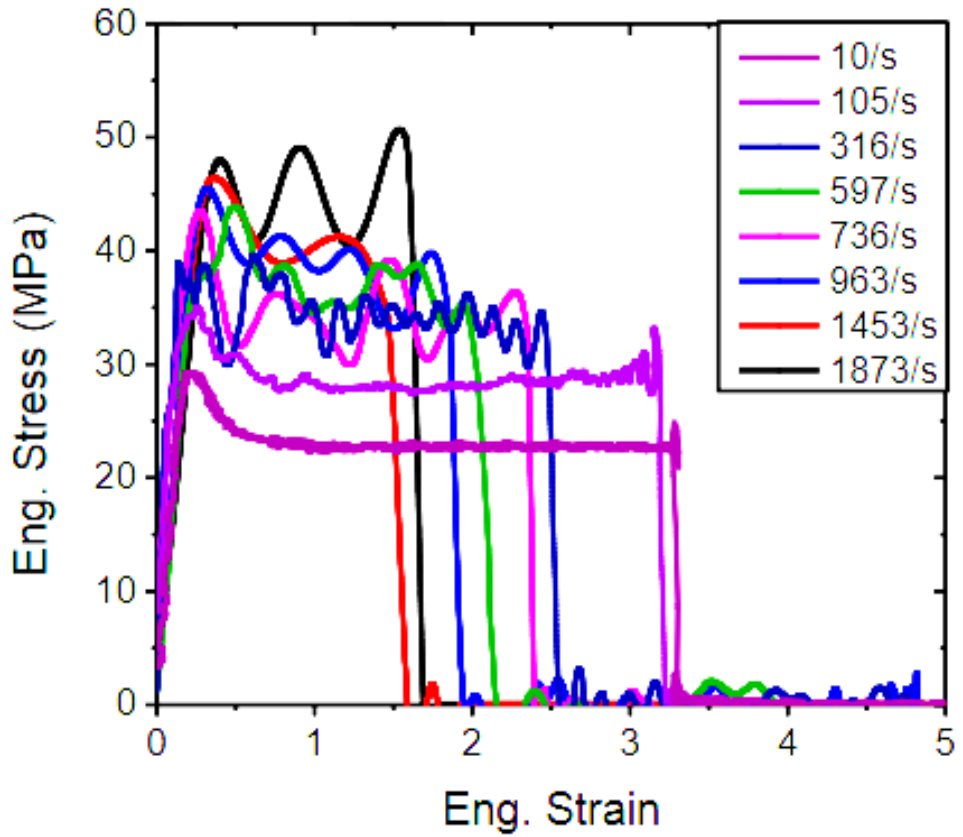


https://doi.org/10.1177/2041419615626061

Interlayer & strain rate

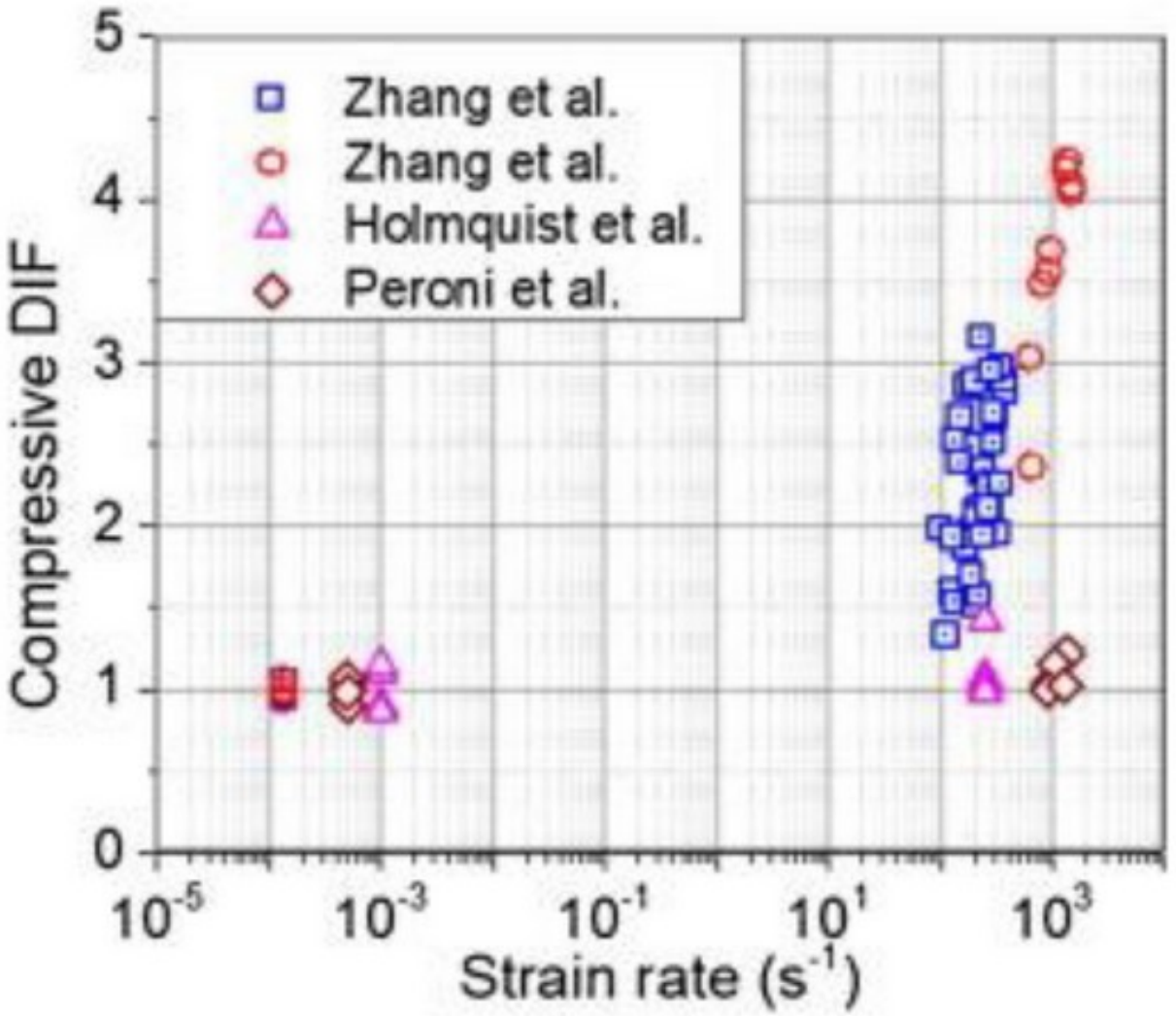


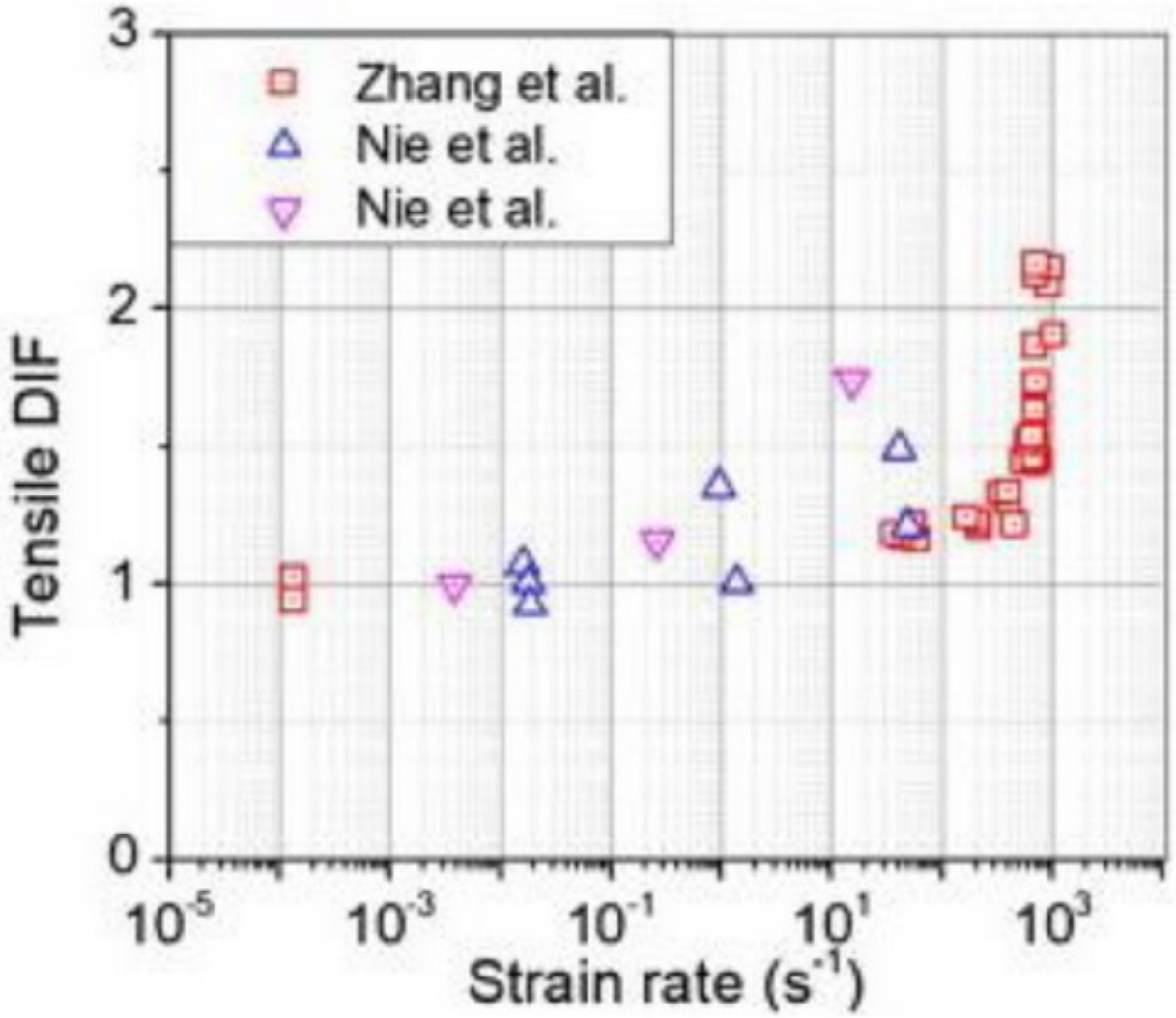
a) High speed tensile test [80]



c) SGP stress-strain curves [82]

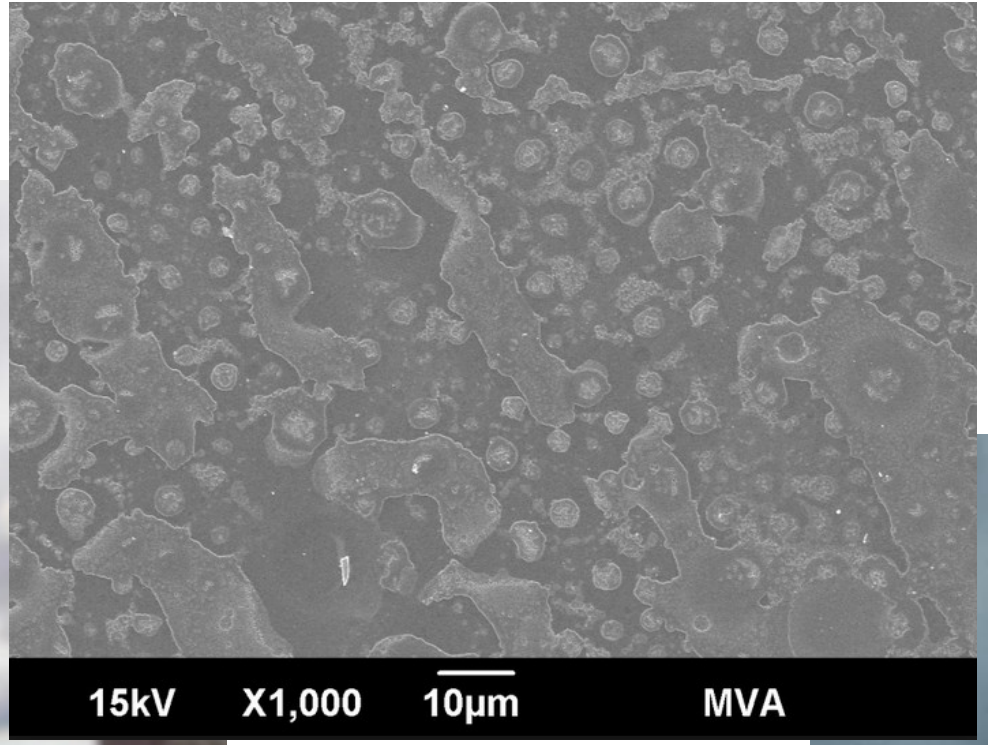
Glass & strain rate





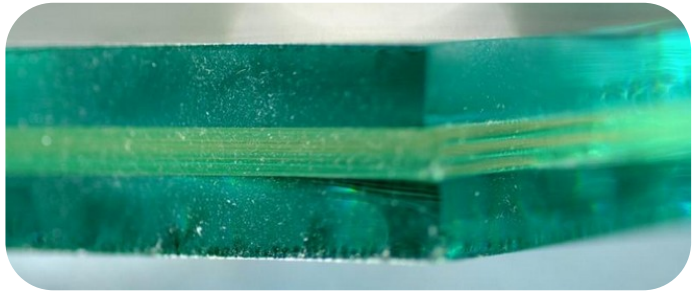
Degradation

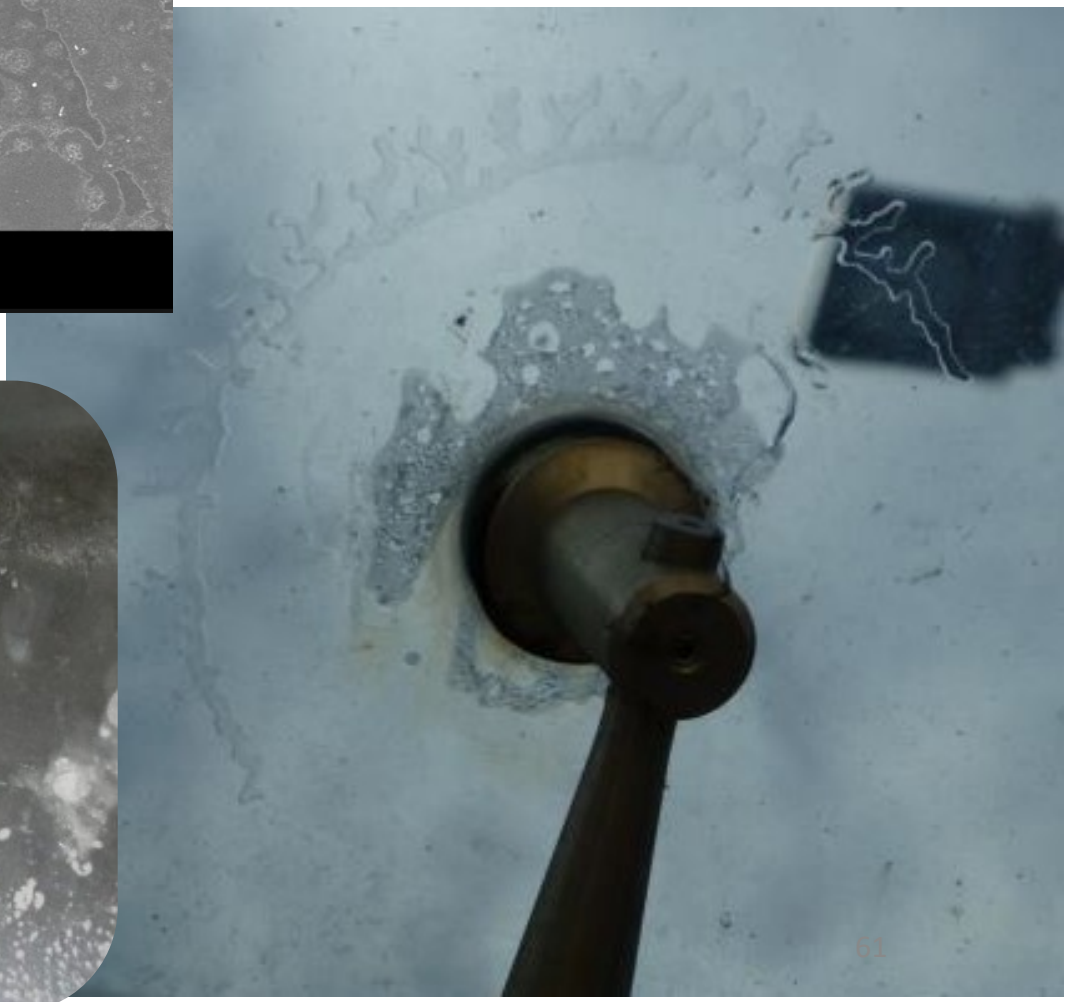




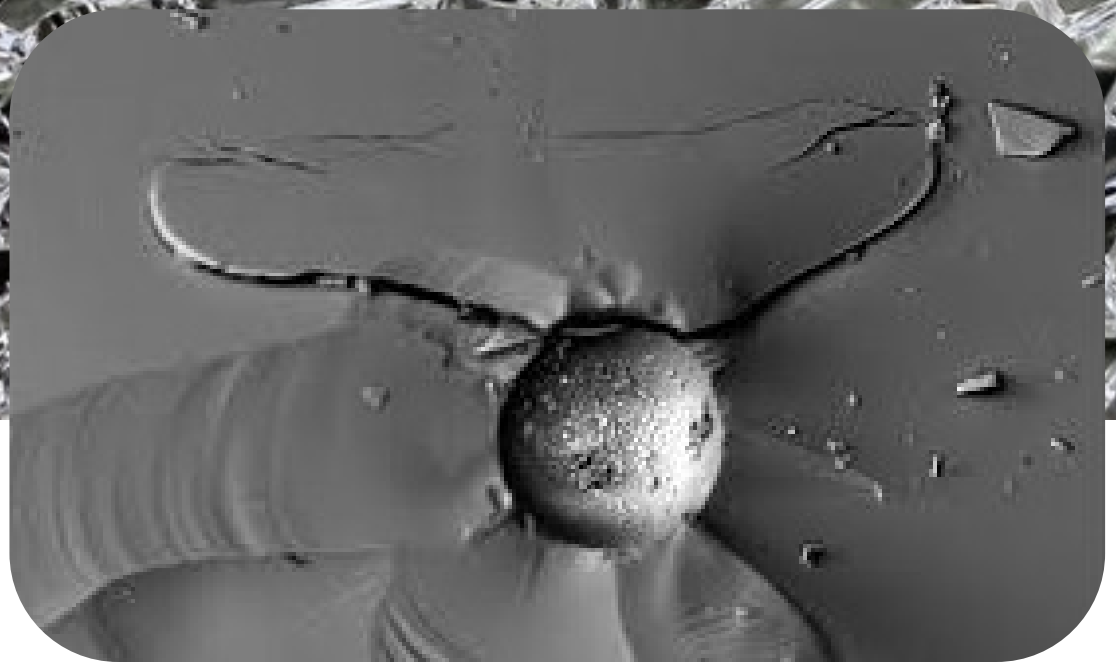


Delamination





Accidental failure



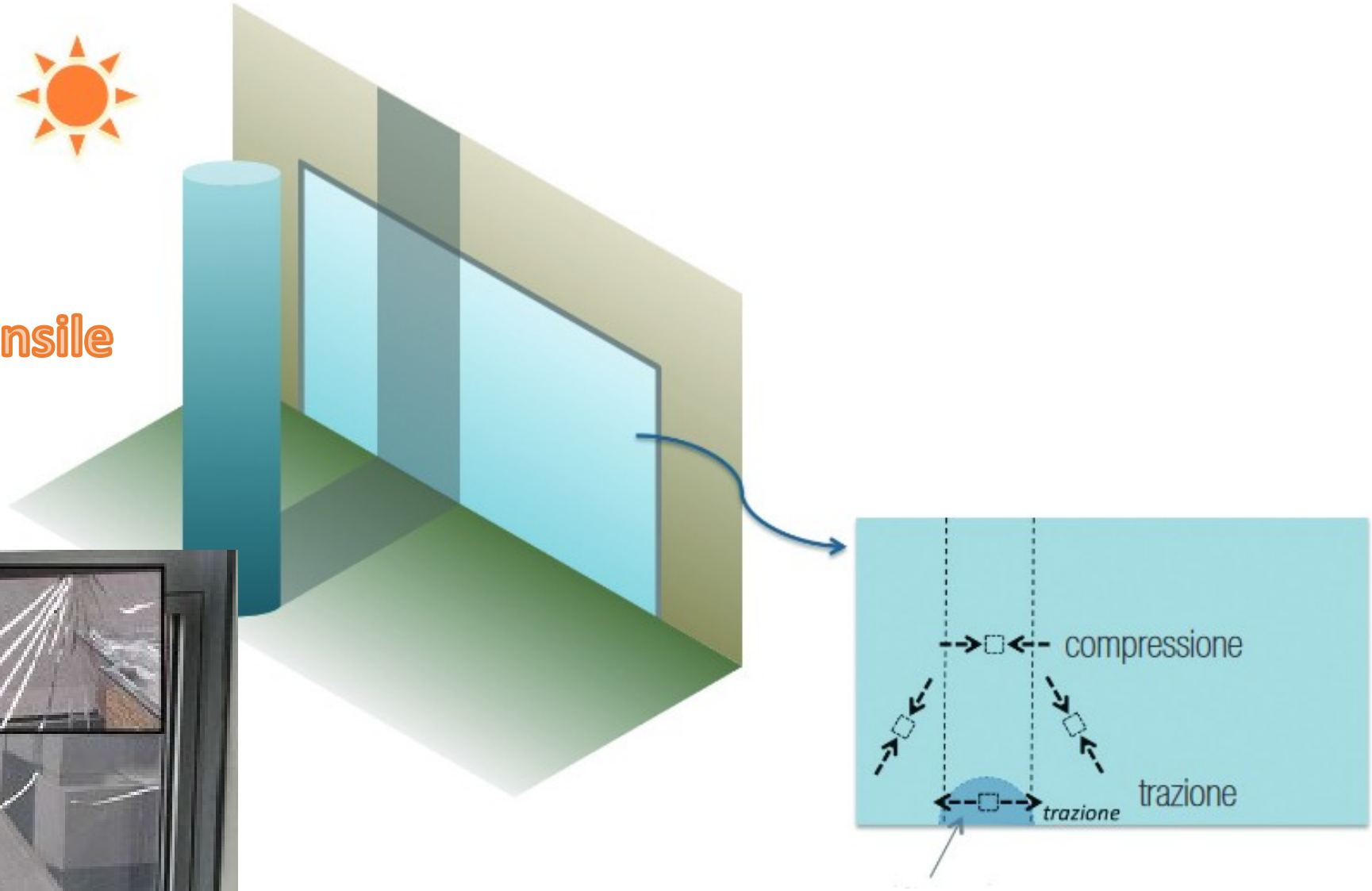
Nichel sulfide inclusions in tempered glass

Accidental failure

Thermal shock

Depends on the limited tensile resistance and thermal conductivity of glass

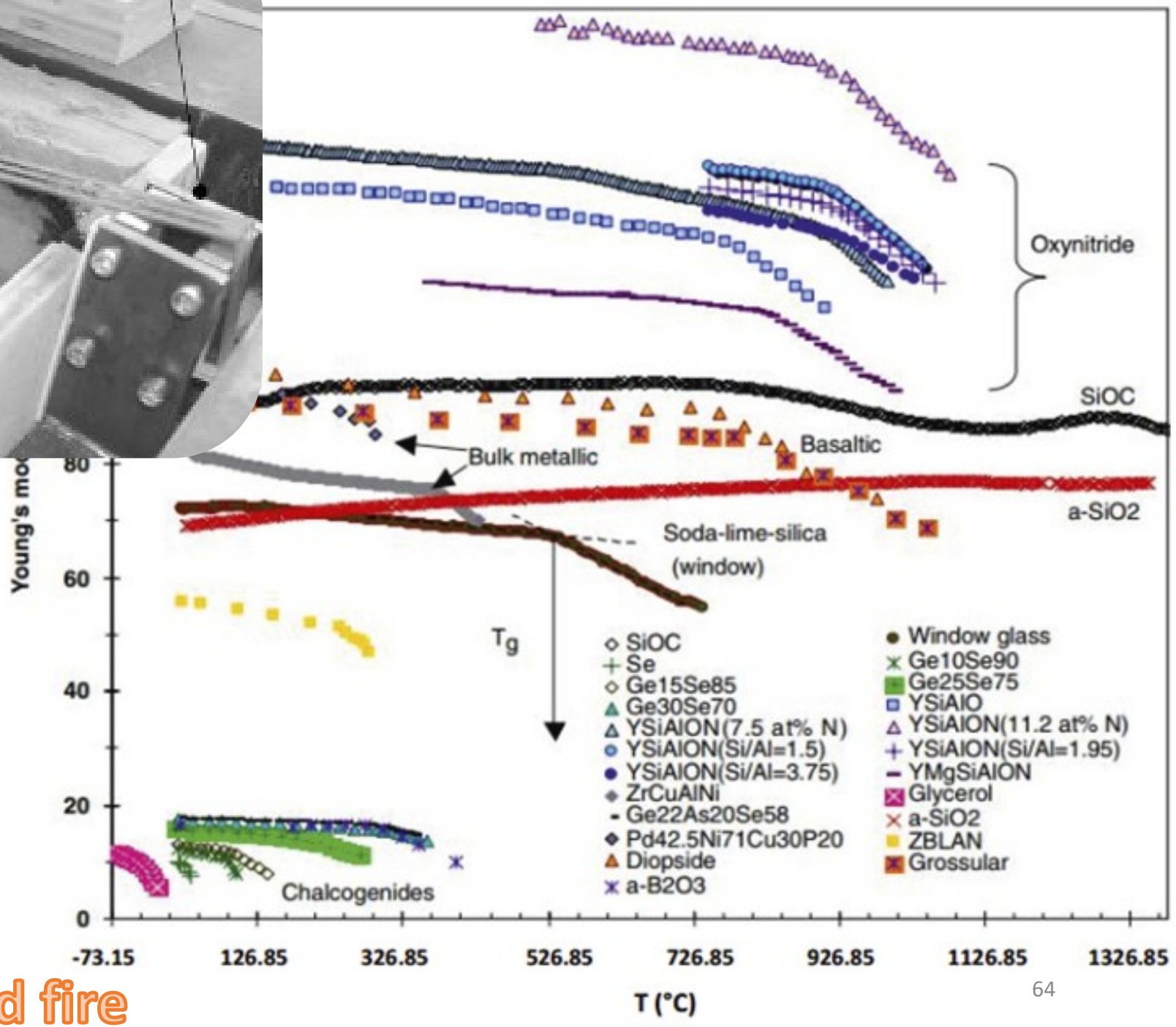




Thermal gradients involve a differential expansion, thus stress peaks







High temperatures and fire

Design strength

The design value of the tensile strength for glass elements under bending $f_{g;d}$, to be considered for ULS and CLS verifications, on the basis of the considerations discussed in Chapters 2 and 5, can be summarized as

$$f_{g;d} = \frac{k_{\mathrm{mod}} \cdot k_{ed} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} \cdot f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed}\, k_v \cdot \left(f_{b;k} - f_{g;k}\right)}{R_{M;v} \gamma_{M;v}} , \qquad (7.5)$$

where:

$f_{g;k}$: nominal characteristic value of the tensile strength under bending of annealed glass (before any heat or chemical reinforcing treatment), determined on the basis of the procedures indicated in Chapter 3. In common cases, UNI EN 572-1 is valid, for which $f_{g;k} = 45$ N/mm^2. Should the nominal value of $f_{g;k}$ be lower than the value indicated above, the glass does not fall within the materials considered by these instructions.

Reduction factor k_{mod}

$$f_{g;d} = \frac{k_{\text{mod}} \cdot k_{ed} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} \cdot f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed} \cdot k_v \cdot \left(f_{b;k} - f_{g;k}\right)}{R_{M;v} \gamma_{M;v}},$$

$$k_{\text{mod}} = 0.585 \cdot t_L^{-1/16}, \qquad \text{(time in hours)}$$

k_{mod}: reduction factor that depends on the load duration and the environmental conditions (temperature, humidity), defined in points 2.1.1.2 and 5.4.2, given by (2.16). The values of k_{mod} for different load durations (constant actions over time) are indicated in the second column of Table 2.2. For actions that vary in time, chapter 2.1 describes the analytical procedure for calculating k_{mod}. In the case of forces that vary significantly over time, k_{mod} can be calculated by applying the analytic procedure described in chapter 2.1.

Reduction factor k_{mod}

Table 2.2. k_{mod} factor derived from the LEFM theory for f_g = 45 MPa, v_0 = 0.0025 m/s and n = 16, for various load application times t_L. Comparison with values provided in prEN16612-2013.

Duration t_L	k_{mod} LEFM	k_{mod} prEN16612	**Example**
3-5 seconds	0.91 - 0.88	1.00	wind (gust)
30 seconds	0.78	0.89	temporary transit
10-15 minutes	0.65 - 0.64	0.74 - 0.72	wind (cumulative)
11 hours	0.50	0.57	daily temperature variations
1 week	0.42	0.48	snow (1 week)
3 months	0.36	0.41	snow (3 months)
6 months	0.35	0.39	seasonal temperature variations
50 years	0.26	0.29	self-weight

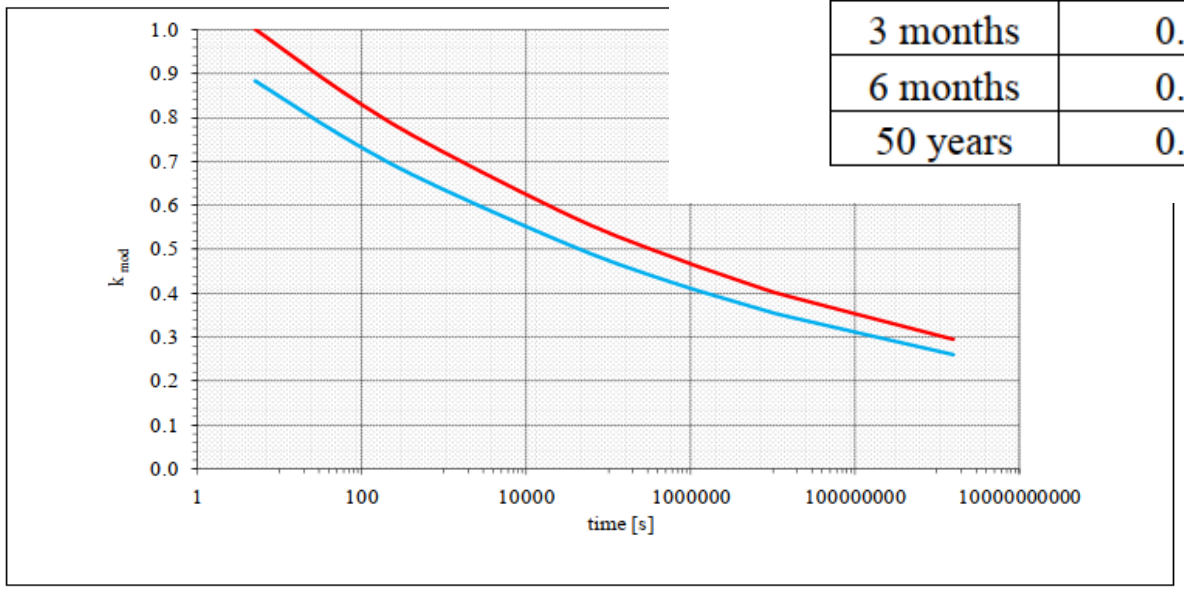


Figure 2.5. Graphical comparison between values of k_{mod}, derived with the LEFM model (f_g = 45 MPa, v_0 = 0.0025 m/s, n = 16), with the values provided in prEN 16612 (2013 edition).

Scale factor (for area) λ_{gA}

$$f_{g;d} = \frac{k_{\mathrm{mod}} \cdot k_{ed} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} \; f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed} \; k_v \cdot \left(f_{b;k} - f_{g;k} \right)}{R_{M;v} \gamma_{M;v}} \; ,$$

λ_{gA} = scale factor, which considers the area subjected to the maximum stress. This coefficient considers that, for statistical reasons, there is a higher probability of finding defects in larger areas than in smaller ones. If there are no more precise information, as discussed in paragraph 5.4.1 the following expression can be used

$$\lambda_{gA} = \left(\frac{0.24 \; \mathrm{m}^2}{k \; A} \right)^{1/7} \; , \qquad 0.75 \; \leq \; \lambda_{gA} \leq 1$$

$d < 5\ s \rightarrow \lambda_{gA} = 1$

Table 7.5. Indicative values of the k coefficient for defining the effective area in plies under bending due to out-of-plane loads (relative to the Weibull parameter $m = 7$).

Constraining conditions	k
Rectangular plate continuously constrained on 4 edges	0.145
Rectangular plate continuously constrained on 2 edges	0.054
Rectangular plate with one edge built in; uniformly distributed load	0.013
Rectangular plate with one edge built in; load distributed on a line parallel to the edge that is built in	0.019
Rectangular plate constrained at 4 points near the corners; uniformly distributed load	0.071

Scale factor (for edges) λ_{gl}

$$f_{g;d} = \frac{k_{\mathrm{mod}} \cdot k_{ed} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed}\, k_v \cdot \left(f_{b;k} - f_{g;k} \right)}{R_{M;v} \gamma_{M;v}} ,$$

λ_{gl} = scale factor for the stress near the element edge, to be applied to elements with edge *specifically* under traction (e.g. beams, fins, etc.). This coefficient considers that, from a statistical viewpoint, the length of the edge is penalizing. For tests at a distance of $d > 5\ s$ (s = element thickness), or in the case of plates under bending (due to out-of-plane load), $\lambda_{gl} = 1$ is conventionally assumed. Regarding what is shown in Section 5.4.3, if there is no precise information, the following values can be assumed for tests at a distance of $d < 5\ s$ from the edge:

$$\lambda_{gl} = \left(\frac{0.1667 \cdot 0.45\ \mathrm{m}}{k_b l_b} \right)^{1/5} \leq 1 \quad \text{for polished edges;} \quad \lambda_{gl} = \left(\frac{0.0741 \cdot 0.45\ \mathrm{m}}{k_b l_b} \right)^{1/12.5} \leq 1 \quad \text{for ground edges.}$$

(7.7)

Scale factor (for edges) λ_{gl}

$$f_{g;d} = \frac{k_{\mathrm{mod}} \cdot k_{ed} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed}\, k_v \cdot \left(f_{b;k} - f_{g;k} \right)}{R_{M;v} \gamma_{M;v}} ,$$

In these expressions, l_b represents the total length of the edge that is subject to traction. The coefficient k_b depends on the distribution of the stress along the edge: if there is no more precise information, the values given in Table 7.6 can be used.

Table 7.6. k_b coefficient for calculating the scale effect near the edge.

Edge finish	Stress distribution along the edge		
	constant	parabolic	triangular
Raw edge	k_b =1	k_b =0.2434	k_b =0.0741
Polished edge	k_b =1	k_b =0.3694	k_b =0.1667

Partial factors

$$f_{g;d} = \frac{k_{\mathrm{mod}} \cdot k_{ed} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} \; f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed} \; k_v \cdot \left(f_{b;k} - f_{g;k} \right)}{R_{M;v} \gamma_{M;v}} \; ,$$

γ_M = partial factor for tensile strength of annealed glass under bending, including model and geometry uncertainties, with regard to the ULS. For this coefficient, defined in chapter 5.3, the values given in Table 7.9 can be used.

$\gamma_{M;v}$ = partial factor relative to the increase of tensile strength (under bending) given by the prestressing treatments, as defined in Chapter 5.5. The values given in Table 7.9 can be used.

Table 7.9. Partial factors of annealed glass and prestressed glass.

	Annealed glass*	Prestressed glass*
Partial coefficients	$\gamma_M = 2.50$	$\gamma_{M;v} = 1.35$
(*) Values for ULS verifications. As regards the CLS, the ULS coefficients can be applied to those portions that remain sound.		

Reduction coefficients

$$f_{g;d} = \frac{k_{\text{mod}} \cdot k_{ed} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} \; f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed} \; k_v \cdot \left(f_{b;k} - f_{g;k} \right)}{R_{M;v} \gamma_{M;v}} ,$$

Table 7.10. R_M reduction factors of the partial coefficients for class 1 and 2 verifictions.

Class	Annealed glass	Prestressed glass
first	$R_M = 0.7$	$R_{M;v} = 0.9$
second	$R_M = 1$	$R_{M;v} = 1$

Other coefficients

$$f_{g;d} = \frac{k_{\mathrm{mod}} \cdot k_{ed} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} \; f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed} \, k_v \cdot \left(f_{b;k} - f_{g;k} \right)}{R_{M;v} \gamma_{M;v}},$$

k_{ed} e k'_{ed} : strength reduction factors defined in Section 5.4.3, respectively for annealed and pre-stressed glass, depending on the edge finish of the glass element (or of the holes), and on the distance d from the edge of the point where $f_{g;d}$ is calculated, to be applied to elements with a stressed edge (e.g. beams, fins, etc.). When $d > 5\,s$ (s = element thickness), or for plates under bending, it is assumed that $k_{ed} = k'_{ed} = 1$. When $d \leq 5\,s$, the coefficients should be calculated with a theoretical and/or experimental *ad hoc* study, in agreement with what is established in Section 5.3.3.4. As a reference, Table 7.3 gives some edge coefficient values, estimated in some elementary cases.

Table 7.3. Indicative values of the k_{ed} and k'_{ed} coefficients for verifications near the edge of glass elements and holes, in the case of elements with edge under traction.

Type of glass	Values* of k_{ed} and k'_{ed} at the edge**							
	Cut		Arrissed		Ground		Polished***	
	k_{ed}	k'_{ed}	k_{ed}	k'_{ed}	k_{ed}	k'_{ed}	k_{ed}	k'_{ed}
Annealed	0.7	0.7	0.7	0.7	0.8	0.8	0.9	0.9
Heat strengthened	to be avoided		to be avoided		0.8	0.8	0.8	0.8
Thermally toughened (tempered)	to be avoided		to be avoided		0.8	0.8	0.8	0.8
Chemically strengthened	to be avoided		to be avoided		0.6	0.7	0.6	0.7
Annealed and patterned	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
(*) Values to be used for verifications at a distance $d <$ 5 s from the edge or from holes (s = element thickness). For $d > 5\,s$ and for plates under bending it is assumed that $k_{ed} = 1$.								
(**) Edge finishes are intended as being according to UNI EN ISO 12543-5. (***) In the case of glass beams and fins where the maximum tensile stress is at the ribs, it is recommended to use polished edges with a smooth and curved profile.								

Other coefficients

$$f_{g;d} = \frac{k_{\mathrm{mod}} \cdot k_{ea} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} \; f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed} \; k_v \cdot \left(f_{b;k} - f_{g;k} \right)}{R_{M;v} \gamma_{M;v}} ,$$

k_{sf} = strength reduction factor, depending on the surface conditions of the glass. The value of k_{sf} must be calculated using an ad hoc theoretical and/or experimental study, in accordance with the procedures given in chapter 9. Some reference values are given in Table 7.4.

Table 7.4. Indicative values of the k_{sf} coefficient for the various surface profiles.

	k_{sf}	
Glass	As produced (2)	Sandblasted
Float glass	1	0.6
Drawn glass	1	0.6
Enamelled glass (float or drawn) (1)	(1)	(0.6)
Patterned glass	0.75	0.45
Enamelled patterned glass (1)	(0.75)	(0.45)
Polished wired glass	0.75	0.45
Patterned wired glass	0.6	0.36

(1) These types of glass are not generally available as annealed glass, but the value of k_{sf} must still be used to calculate the resistance of the prestressed glass.

(2) Us the "As produced" values of k_{sf} for acid-etched glass.

Other coefficients

$$f_{g;d} = \frac{k_{\mathrm{mod}} \cdot k_{ed} \cdot k_{sf} \cdot \lambda_{gA} \cdot \lambda_{gl} \; f_{g;k}}{R_M \gamma_M} + \frac{k_{ed} \; k_v \cdot \left(f_{b;k} - f_{g;k} \right)}{R_{M;v} \gamma_{M;v}} ,$$

k_v = reduction factor of the increase in tensile strength of glass produced using a prestressing treatment (temperature, hardening), to be taken as being null in the case of annealed glass (no treatment). The coefficient k_v must be calculated by an *ad hoc* theoretical and/or experimental study, in compliance with the general indications given in Chapter 9. Indicative values of k_v are given in Table 7.8.

Table 7.8. Indicative values of the reduction factor for tensile strength of the glass following a pre-stressing treatment.

Prestressing treatment	k_v
No treatment	0
Heat treatment with horizontal process	1
Heat treatment with vertical process	0.60
Chemical strengthening *	0.95
(*) The indicated coefficient can only be used if the chemically strengthened glass is controlled and qualified following the procedures indicated in Section 9.	

Design deflection limits

Table 7.11 Values of the design deflection for linear constraints.

Single glass (monolithic or laminated)		Insulating units		No. of constrained edges
Plate centre	Plate edge	Plate centre	Plate edge	
1/60 (1) of $L_{min;}$ < than 30 mm(3)		1/60 (1) of $L_{min;}$ < than 30 mm(3)	1/200 (2) of $L_{min;}$ < than 12 mm(4)	4
	1/100 (2) of $L_{inf;}$ < than 50 mm(3)		1/150 (2) of $L_{inf;}$ < than 50 mm(3)	3
	1/100 (2) of $L_{inf;}$ < than 50 mm(3)		1/150 (2) of $L_{inf;}$ < than 50 mm(3)	2

Notes: (1) at the centre of the plate;
(2) unsupported plate edge
(3) from DTU 39-P4:2012
(4) from UNI EN 1279-5:2010
L_{min}: shorter edge size
L_{inf}: span of the free edge

Table 7.12 Values of the design deflection for point-fixed elements.

Single glass (monolithic or laminated)	Insulating units	L_{inf} (3)
1/100 (1) of the distance between the constraining points L_{inf} and < than 50 mm(2)	1/150 (1) of the distance between the constraining points L_{inf} and < than 50 mm(2)	Figure 7.1-a
1/50 of the cantilever length L_{inf} and < than 50 mm((2)	1/75 of the cantilever length L_{inf} and < than 50 mm(2)	Figure 7.1-b

(1) most deformable edge of the plate;

(2) from Cahier 3574_V2:2011;

(3) L_{inf} is defined with reference to Figure 7.1.

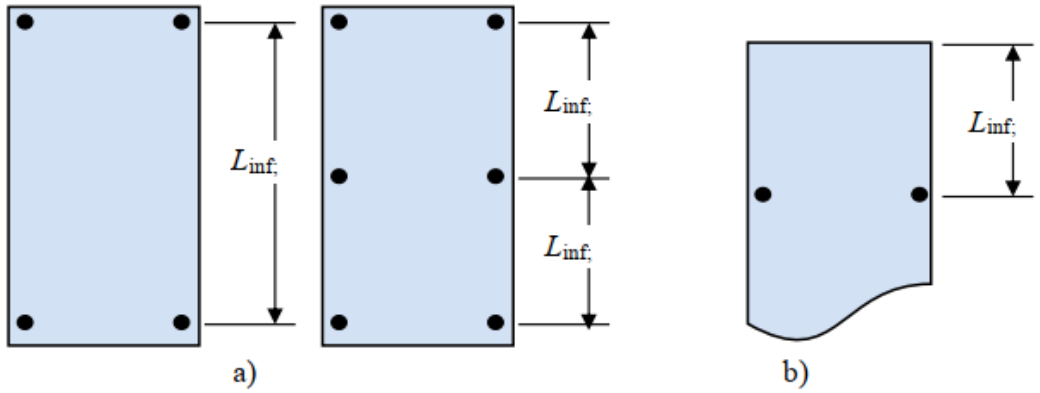


Figure 7.1. Point-fixed plates.

Continuous Facades



A **curtain wall** is:

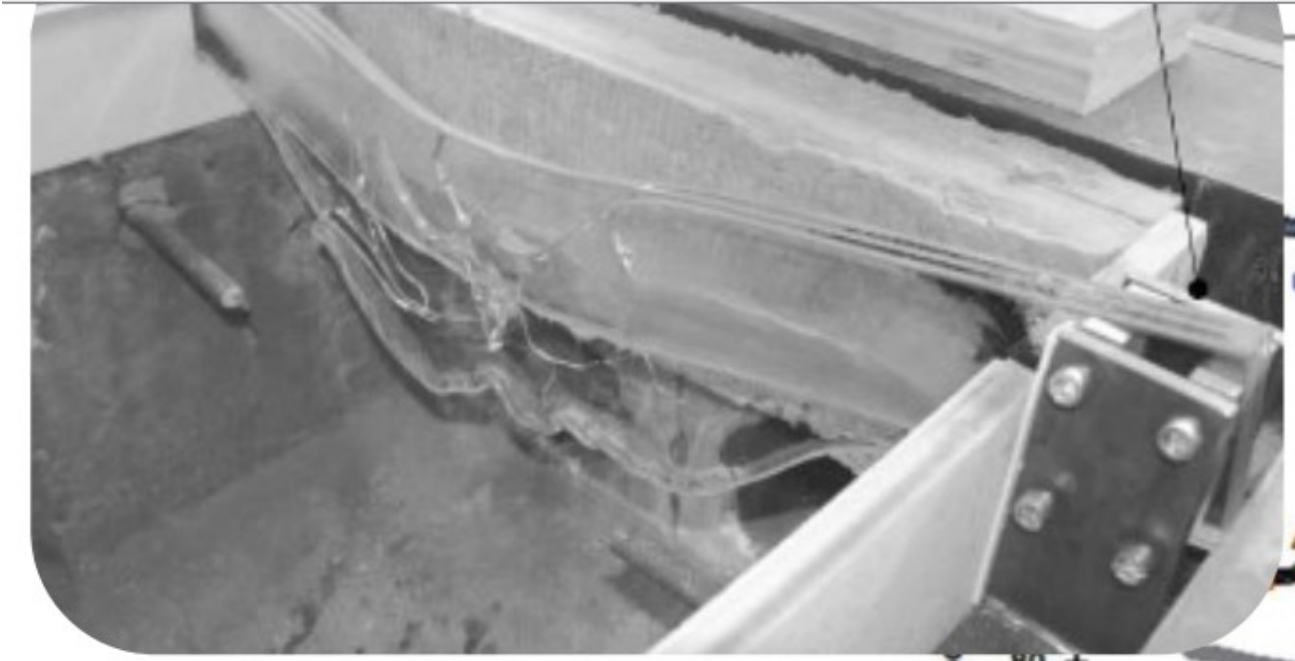
- a continuous cladding system composed of lightweight materials
- a system that—either on its own or in conjunction with the building structure—fulfills the standard functions of an external wall
- a system designed to support its own weight and withstand wind pressure. These loads are transferred to the primary load-bearing structure via connections to the building's floor slabs or columns
- Furthermore, a curtain wall must provide all the performance characteristics of a traditional building envelope and can be constructed with either transparent or opaque surfaces



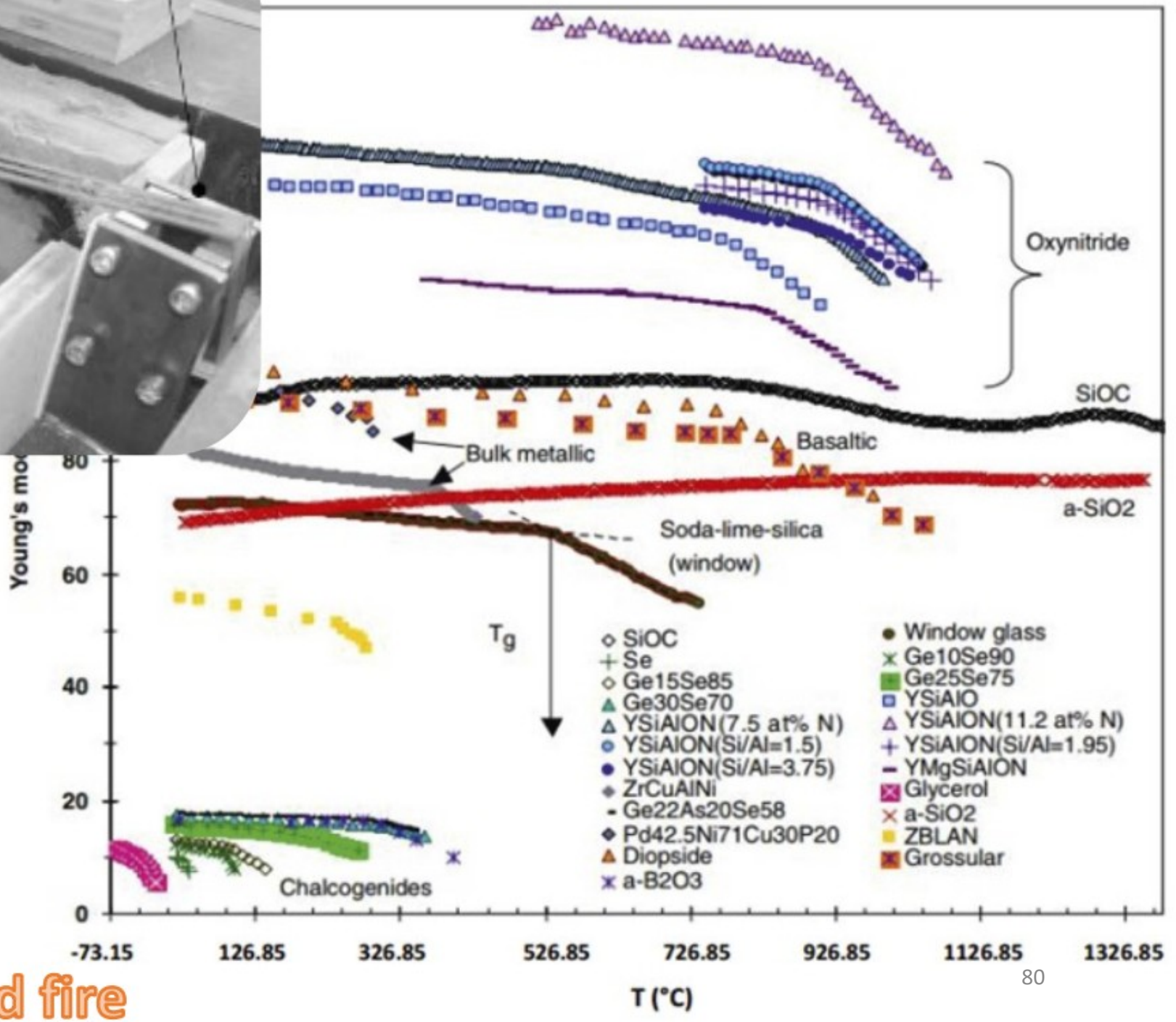
A **curtain wall**, in particular, must be designed:

- to resist air and water infiltration
- to withstand wind loads, as well as its own self-weight
- to accommodate seismic movements
- and, in specific cases, it may also be designed to provide resistance to fire, ballistic impact (from firearms), and/or explosions



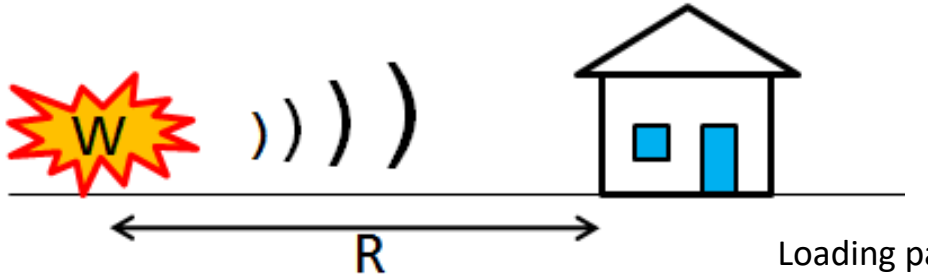






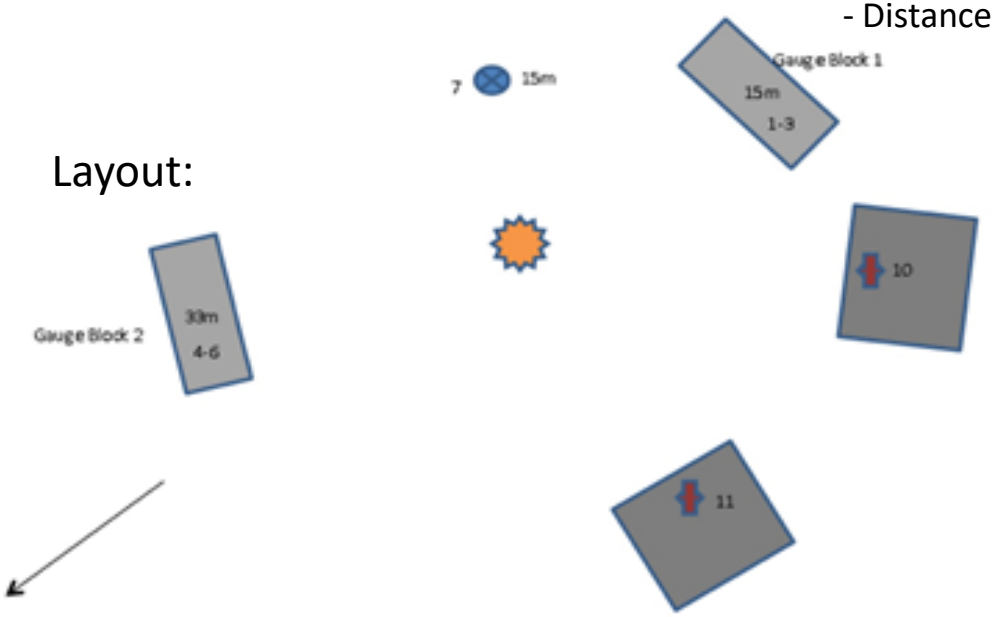
High temperatures and fire

Experimental Testing: Arena Test



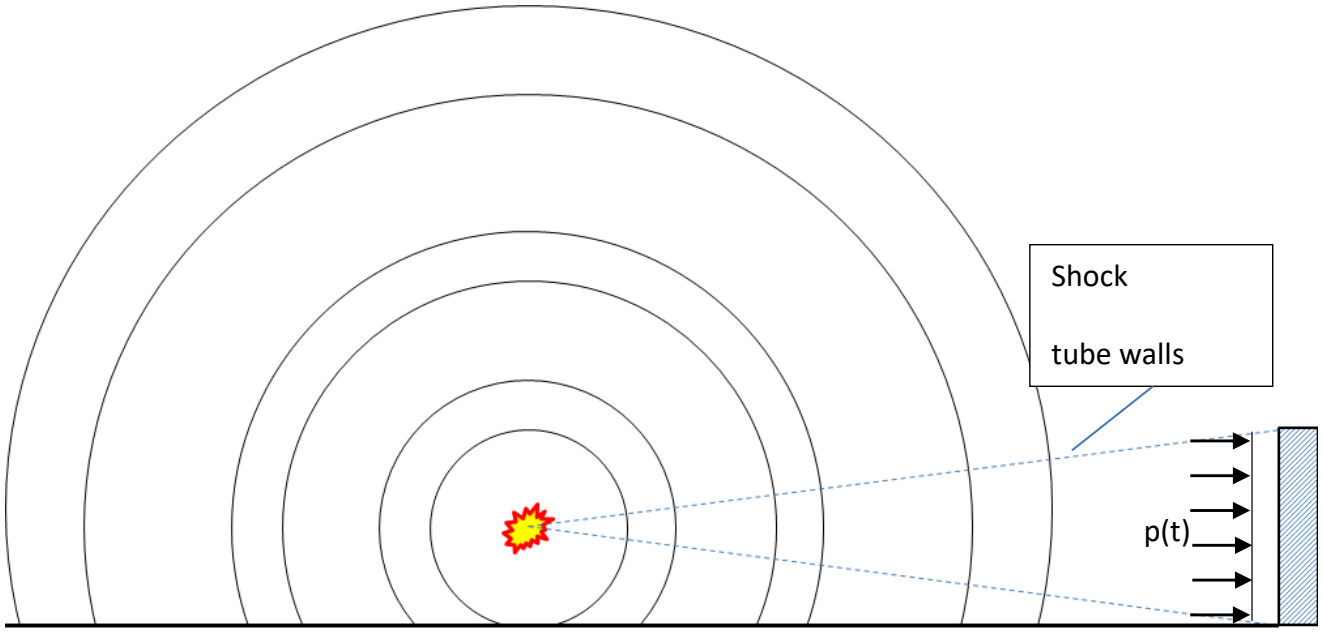
Loading parameters:
- Charge weight W
- Distance R

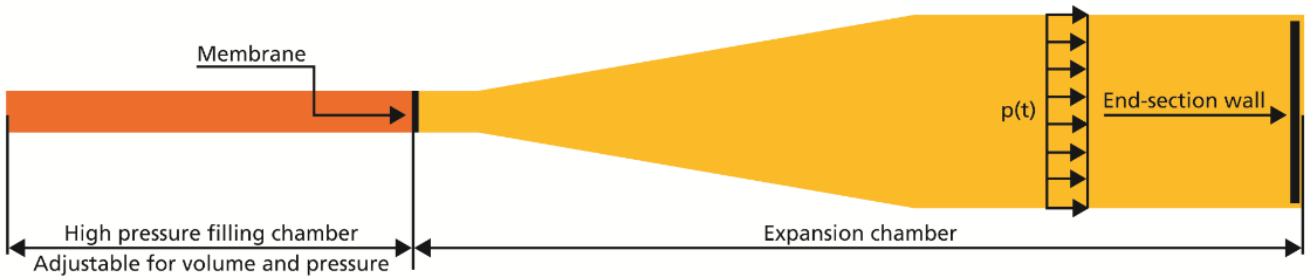
Layout:

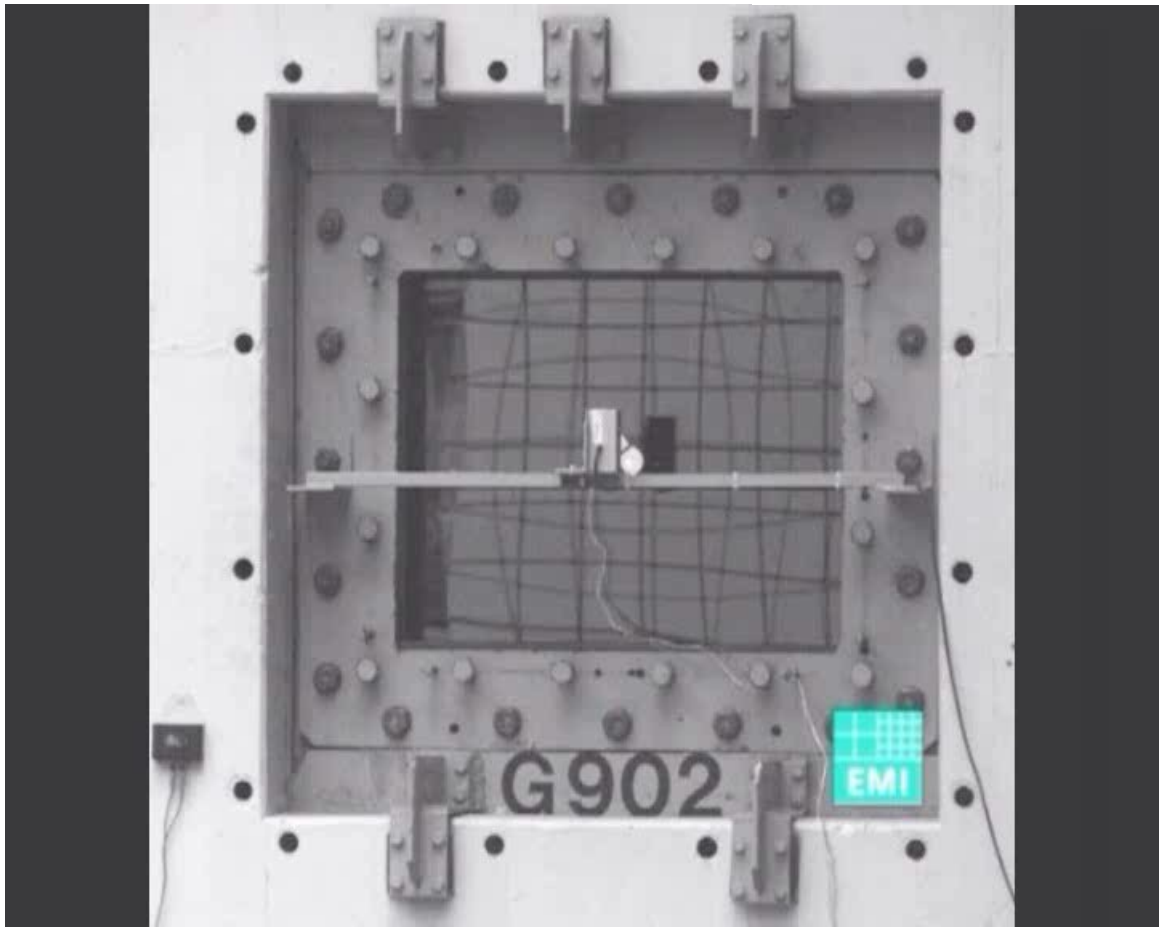


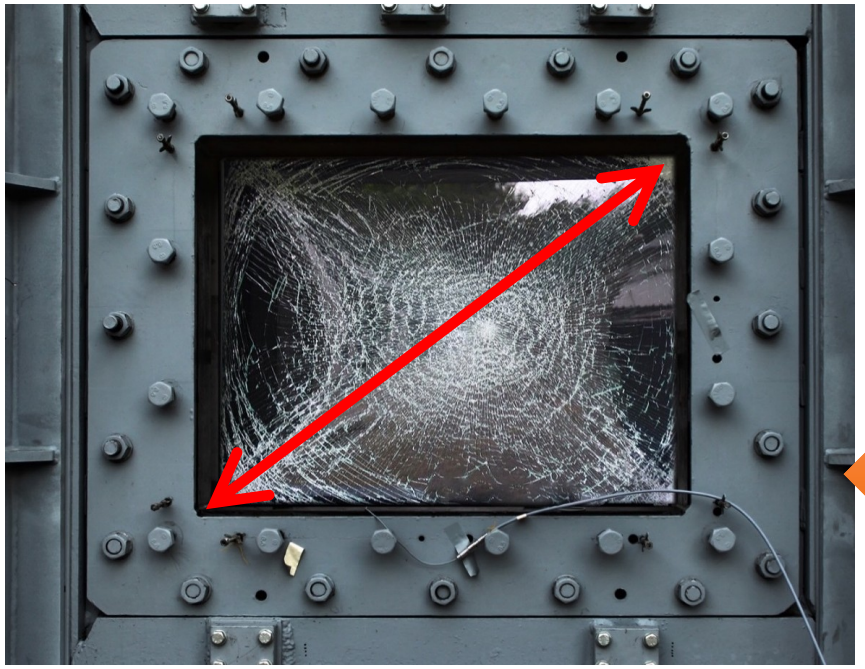


Experimental Testing: Shock-tube









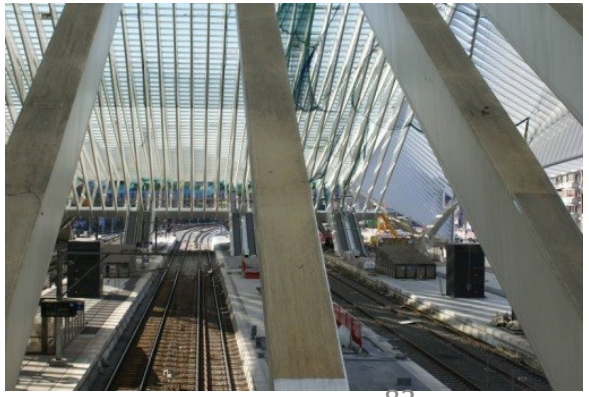
Glass panel in standard test frame



Building



European Parliament, Strasbourg



Railway station Liège

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TG Resistance of Structures to Explosion Effects

Resistance of Structures to Explosion Effects

VTT

INERIS

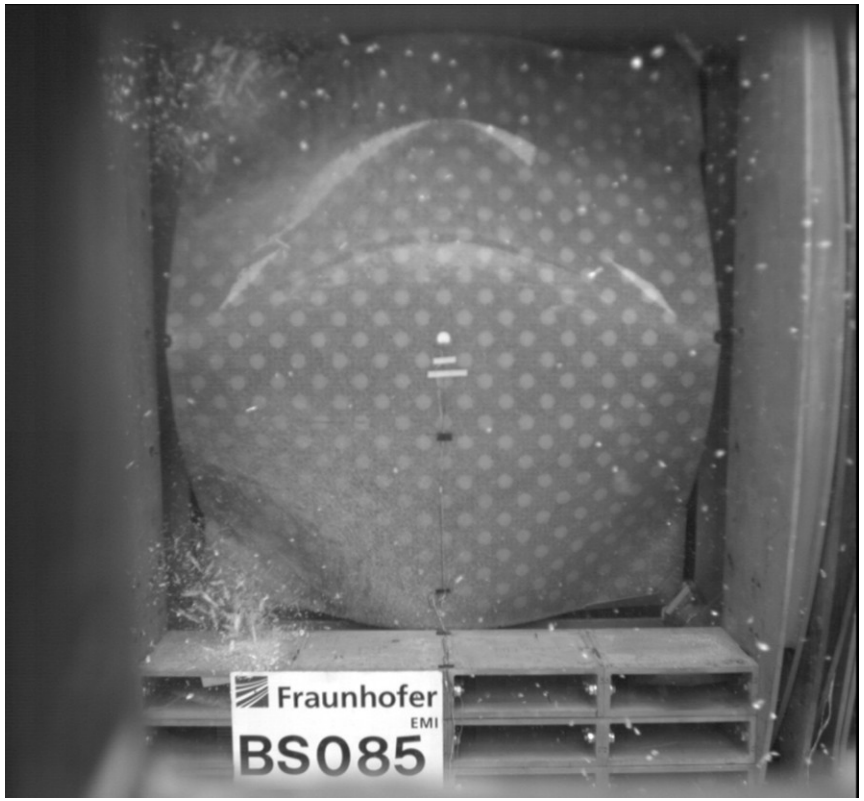
maîtriser le risque pour un développement durable

TNO innovation for life

CPNI Centre for the Protection of National Infrastructure

Royal Military Academy

Wehrtechnische Dienststelle für Schutz- und Sondertechnik (WTD 52)



Fraunhofer EMI

BAM Bundesanstalt für Materialforschung und -prüfung

ENSTA Bretagne

cea

University of Defence, Brno

Multiconsult

SÄLZER building security Part of Schüco

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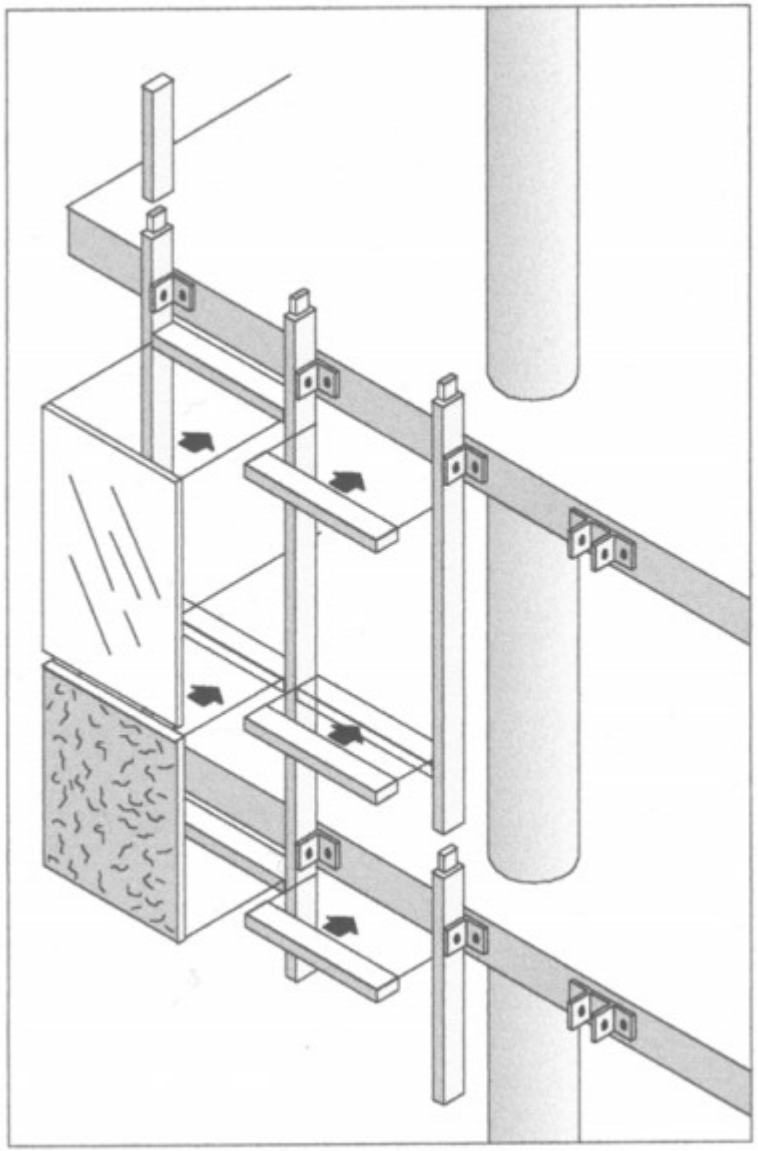


Tacoma Building, Chicago, 1884, Holabird & Roche, primo edificio con facciata esterna non portante applicata allo scheletro dell'edificio

- Initial applications in buildings in the late 1800s
- Significant development by window and facade contractors during the 1940s and 1950s
- Further technological advancement from the 1960s and 1970s, with the introduction of structural silicones and the potential elimination of visible metal framing
- From the 1990s onwards, the curtain wall evolved further—moving beyond a "simple external wall" to become a photovoltaic, energy-generating, and media-integrated system

Mullion-and-transom facades (stick system)

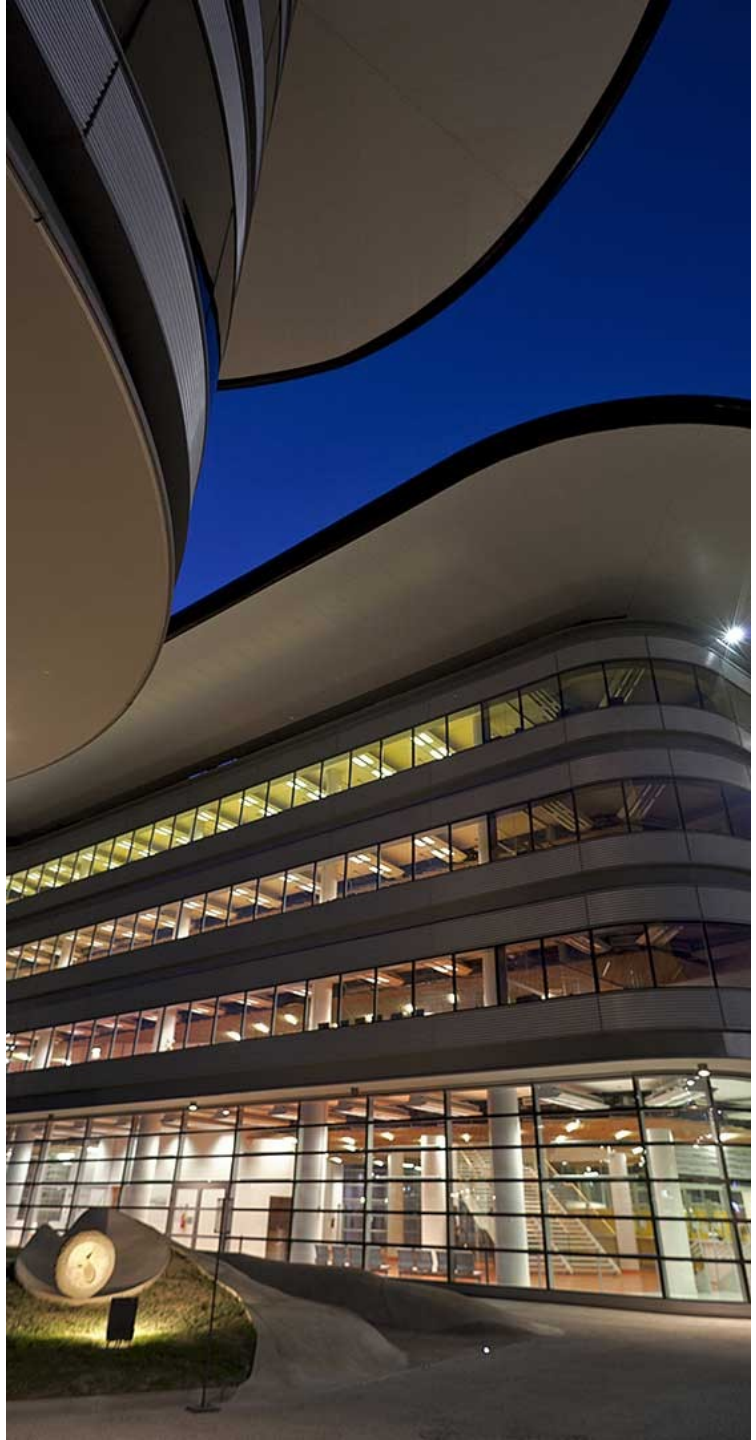
- one of the most common types
- mullions (vertical members), attached to the building's load-bearing structure
- transoms (horizontal members), attached to the mullions
- panels (fixed/non-openable)—either opaque or transparent window units, attached to the mullions and transoms



PROS & CONS:

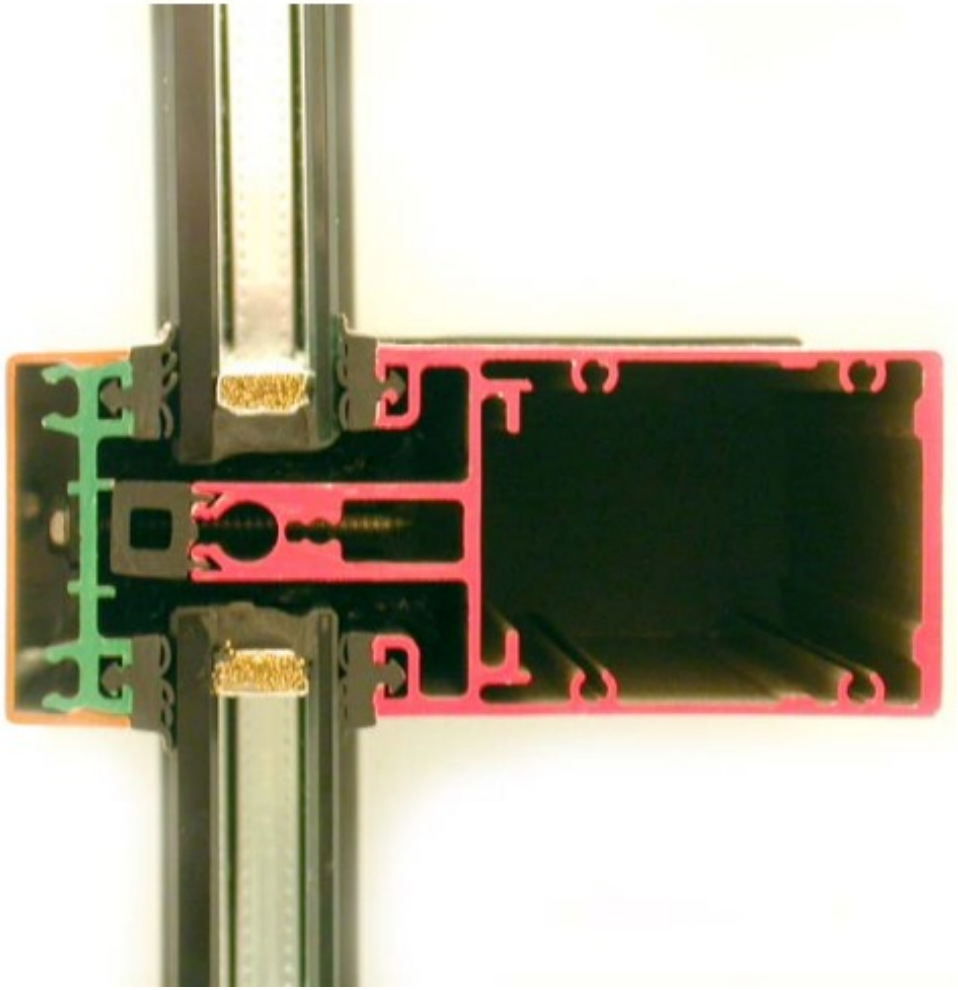
- visibility of the orthogonal metal structural elements on the exterior of the glazed surface
- cost-effectiveness, due to the small size of the individual components

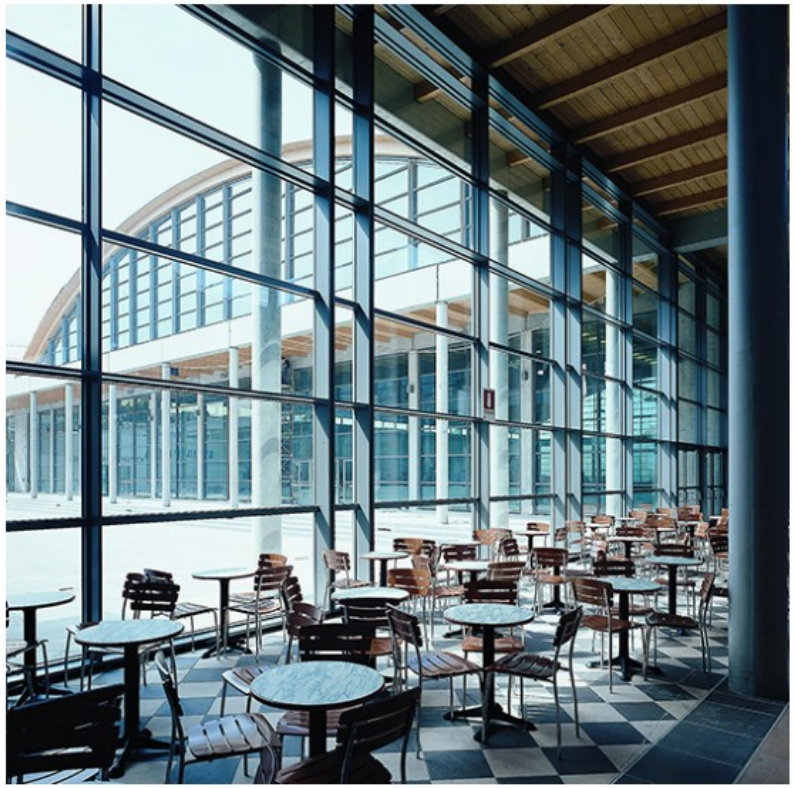
labor-intensive on-site assembly



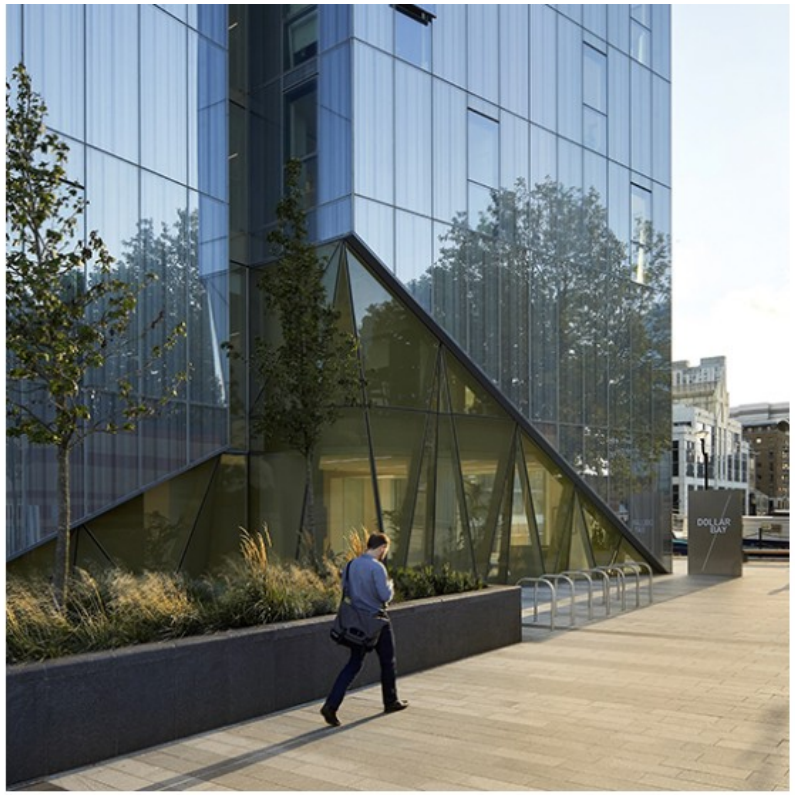








Facciate montanti e traversi a pressore



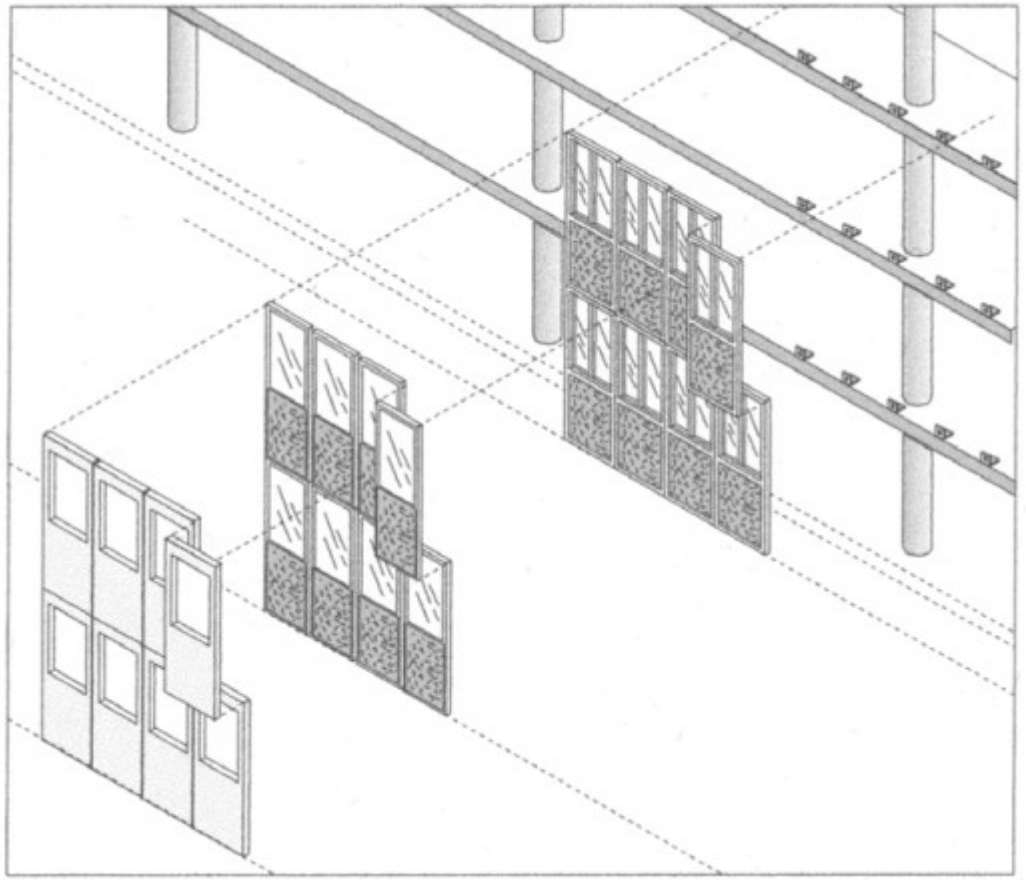
Facciate montanti e traversi a fissaggio puntuale



Facciate montanti e traversi a moduli strutturali

Unitised facades (unitised system, panel system)

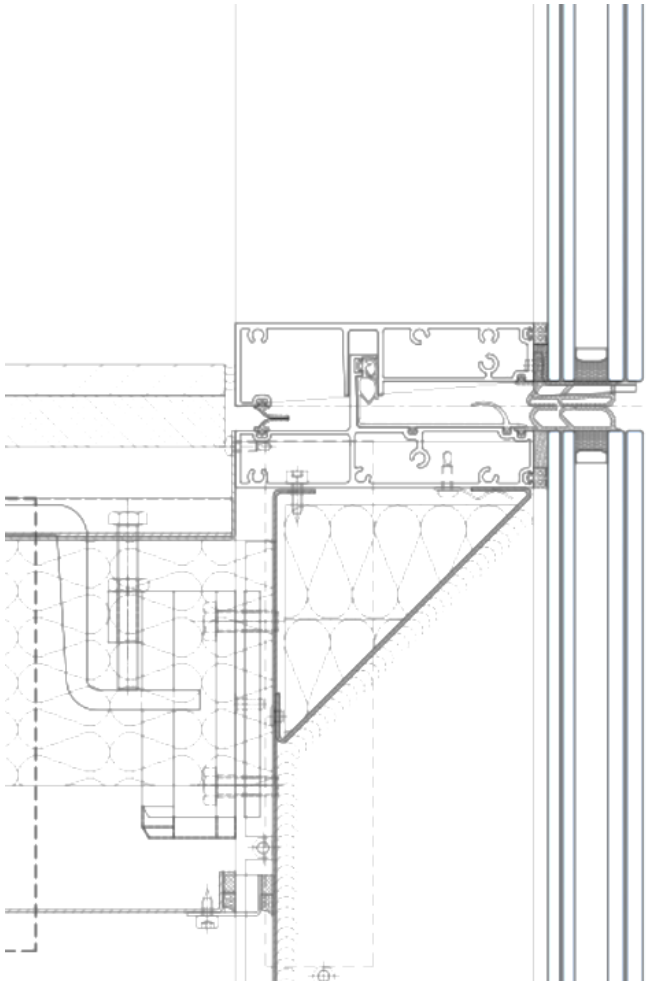
- consist of prefabricated units
- the panel elements comprise both the metal profiles (extruded aluminium profiles) and the infill
- gaskets ensure the system is sealed



PROS & CONS:

- prefabrication
- the pre-assembled units are transported directly to the construction site
- fixing brackets are used, ensuring rapid and precise installation





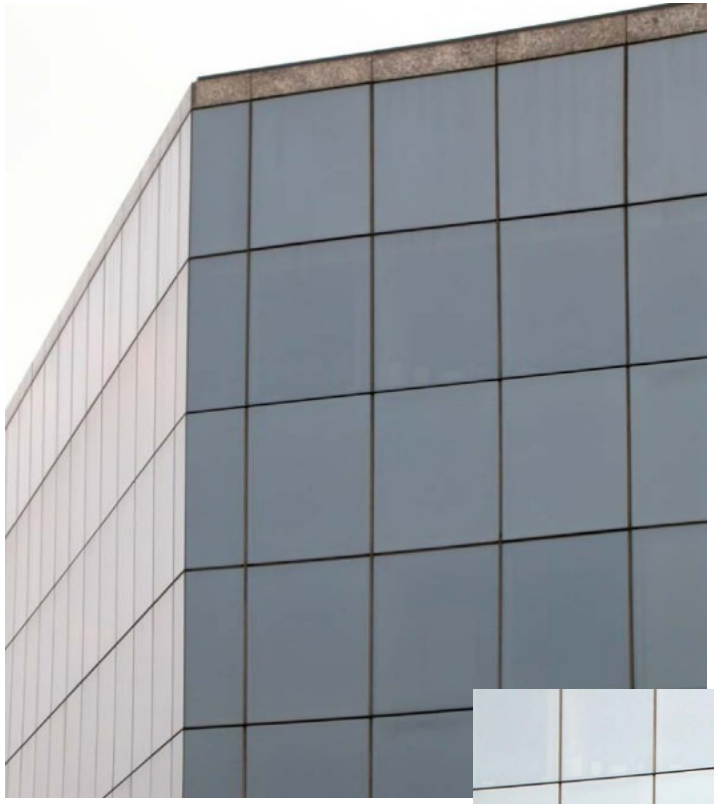


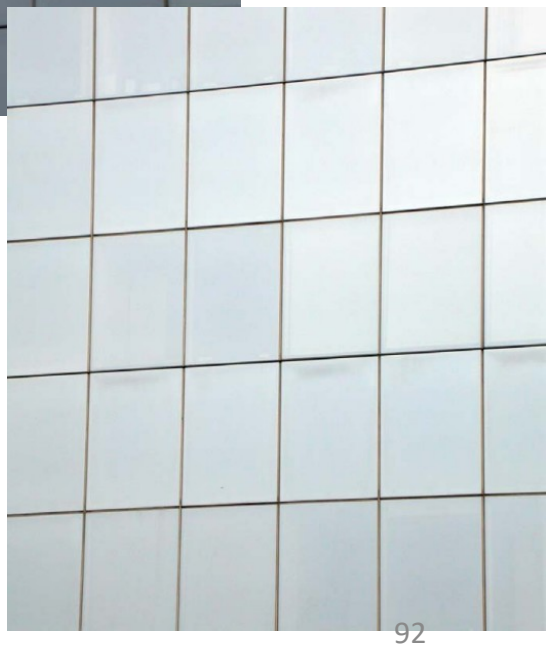
Structural glazing facades

- consisting of metal framing and infill panels
- the panels are bonded to the metal framework using structural silicone adhesives
- typically, special two-component silicones are used
- in use since the 1960s

PROS & CONS:

- the metal framework can be completely or partially concealed
- reduced transmission of heat and vibrations





Point-fixed facades

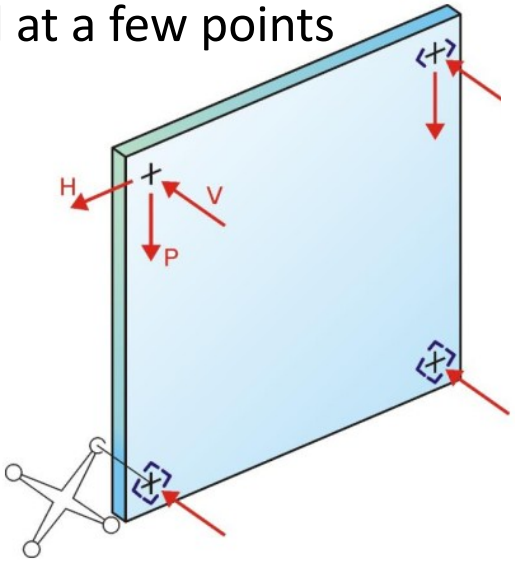
- The panels are supported by special fixings
- The fixing systems ensure that loads are transferred to the main structure

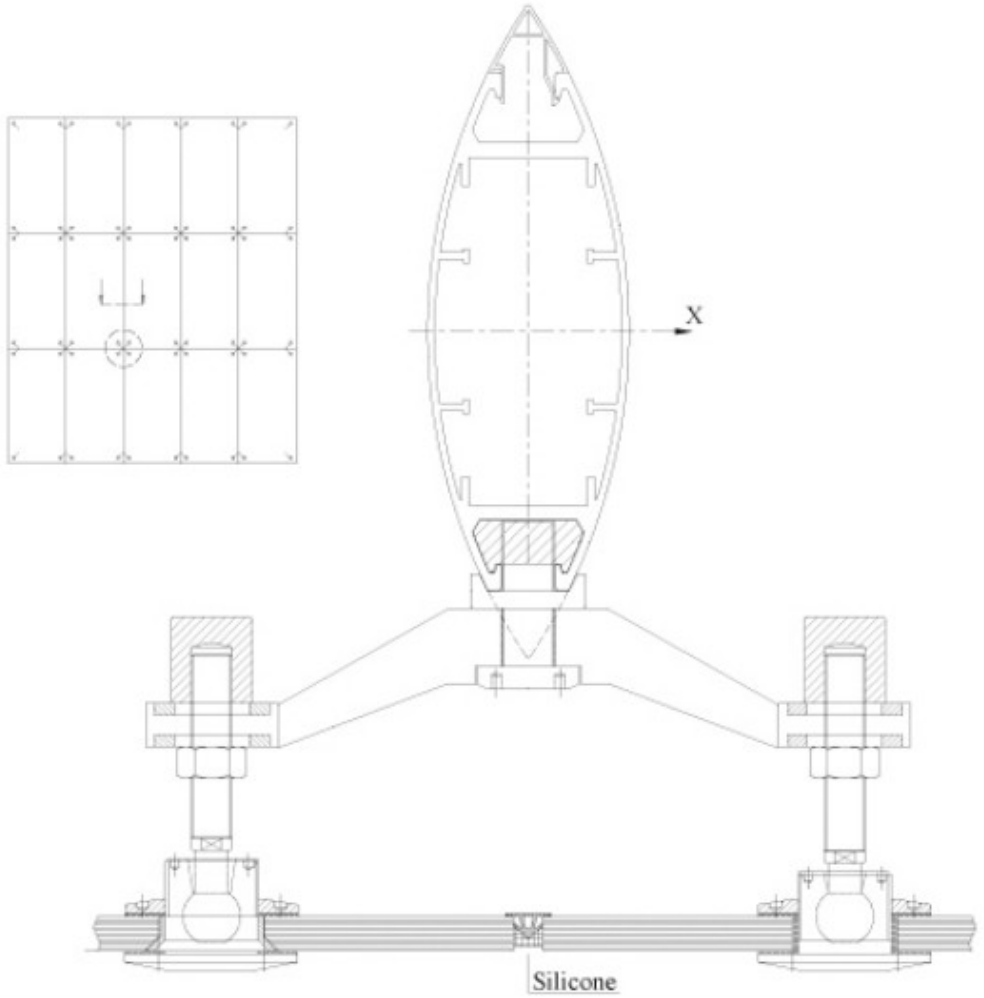
PROS & CONS:

- The metal framework is reduced to a minimum
- Maximum stresses are concentrated at a few points on the panels







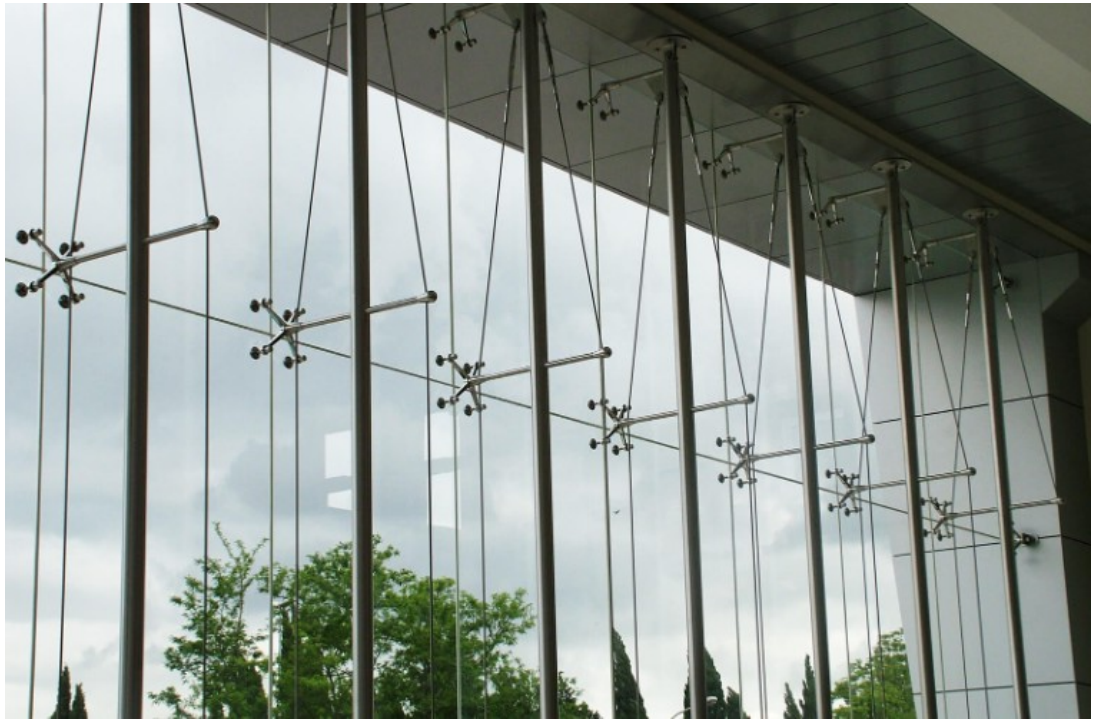






Point-fixed facades

- The fittings (rotules) act as actual hinges
- The system is granted a certain capacity for deformation
- The presence of a rigid joint is avoided
- The panels are able to undergo thermal deformation and accommodate movements of the building





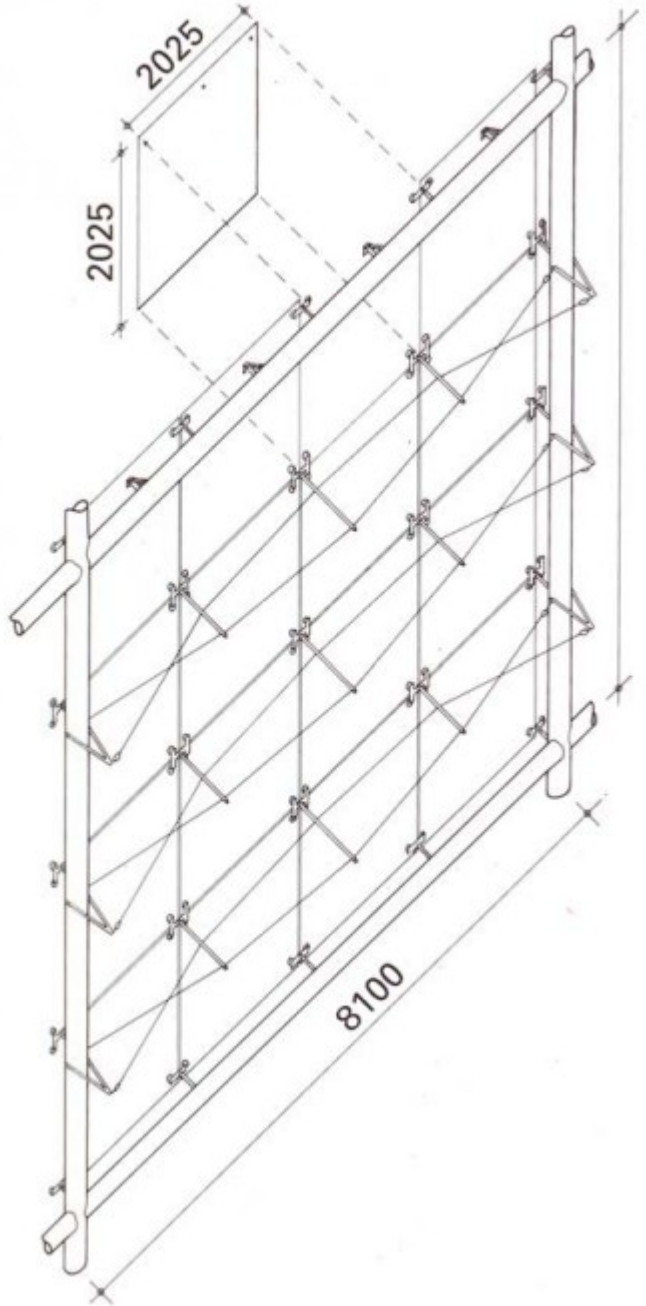


Point-fixed facades

- Such facades require an adequate bracing system
- This can consist of a system of cables or metal profiles
- It is also necessary to provide a sealant between the glass panels








faraone
MENU
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Point-fixed facades

- The spider fittings (rotules) available on the market are suitable for monolithic glass, laminated glass, and insulated glass units

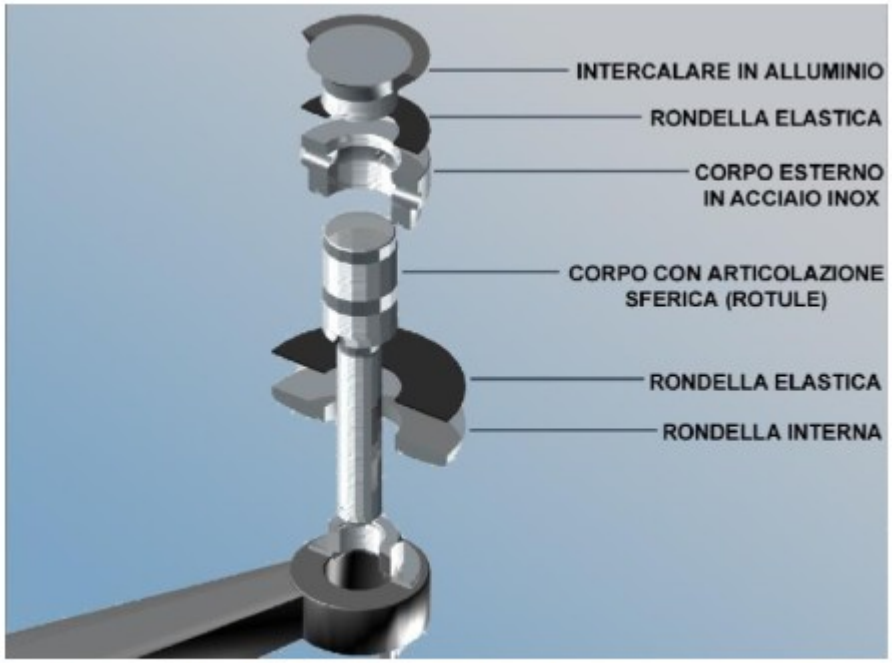
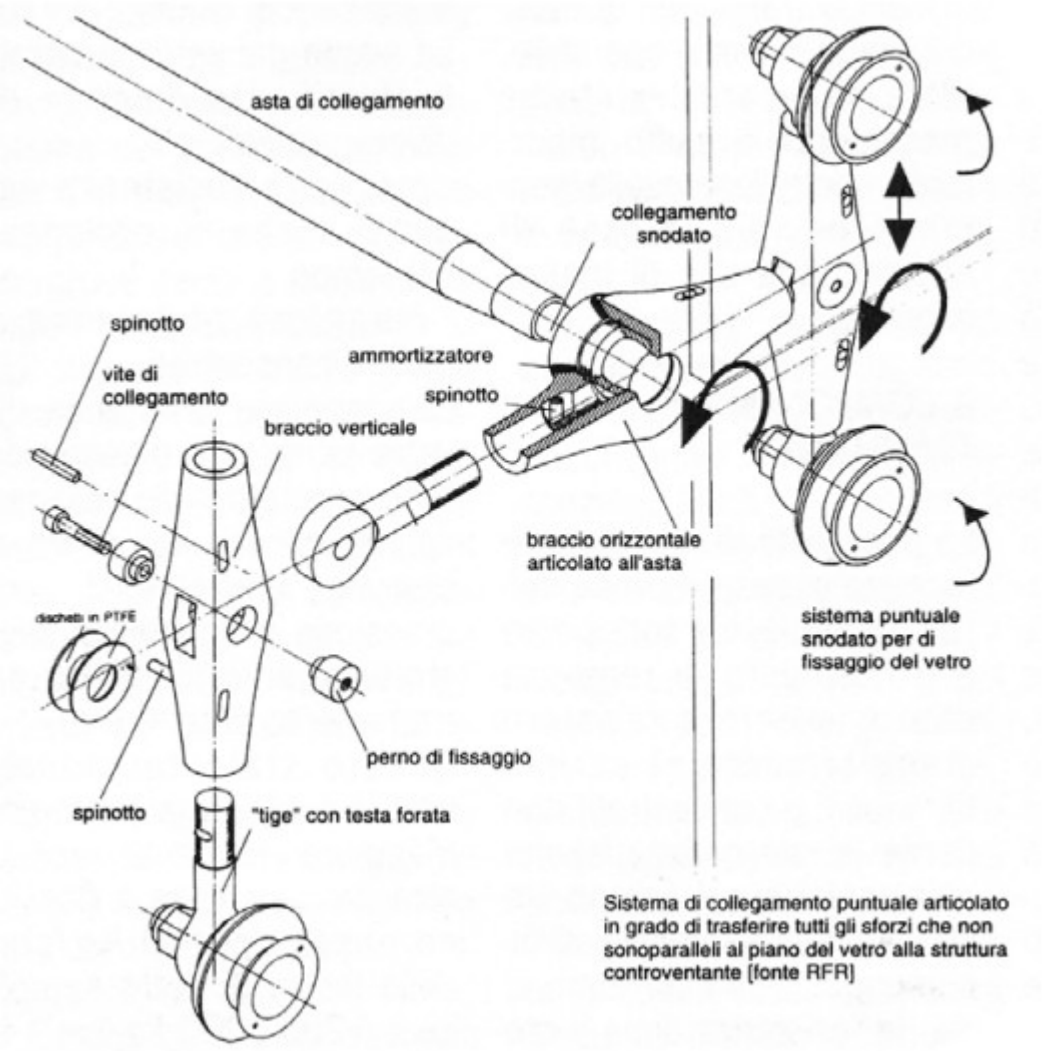
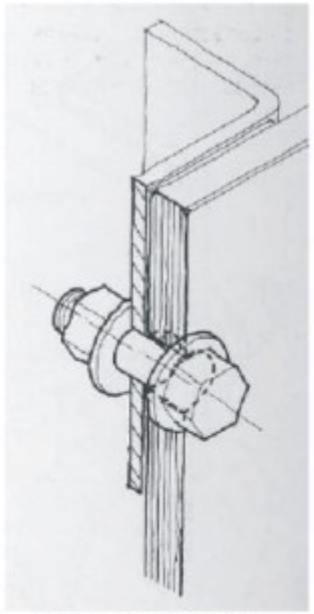


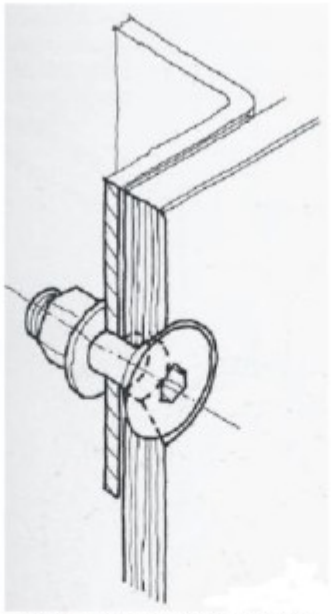
Figura 8.25. Assonometria esplosa di un sistema a rotule.



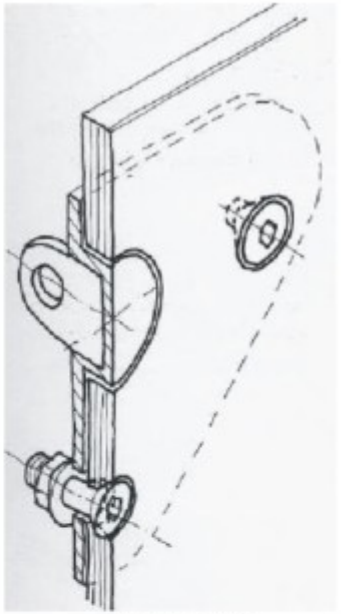
Sistema di collegamento puntuale articolato in grado di trasferire tutti gli sforzi che non sonoparalleli al piano del vetro alla struttura controventante [fonte RFR]



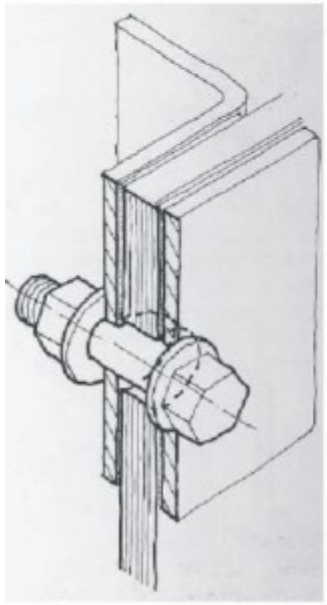
Bullonatura standard



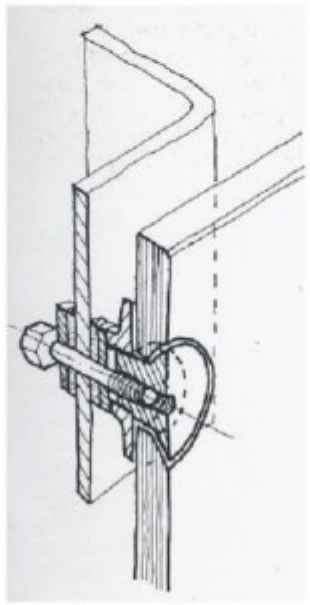
Bullonatura a testa svasata



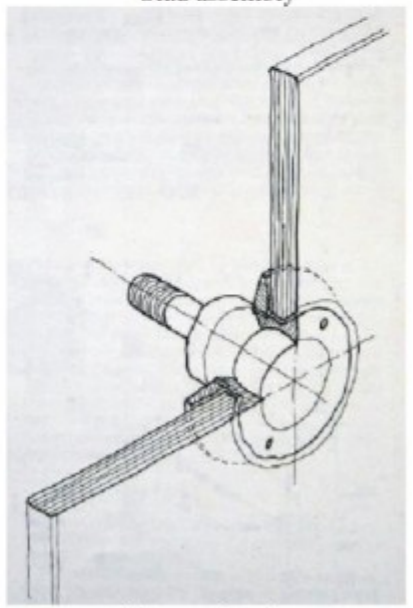
Stud assembly



Piastra e contropiastra



Sistema Planar
(articolazione fissa)



Sistema Rotulle
(articolazione mobile)

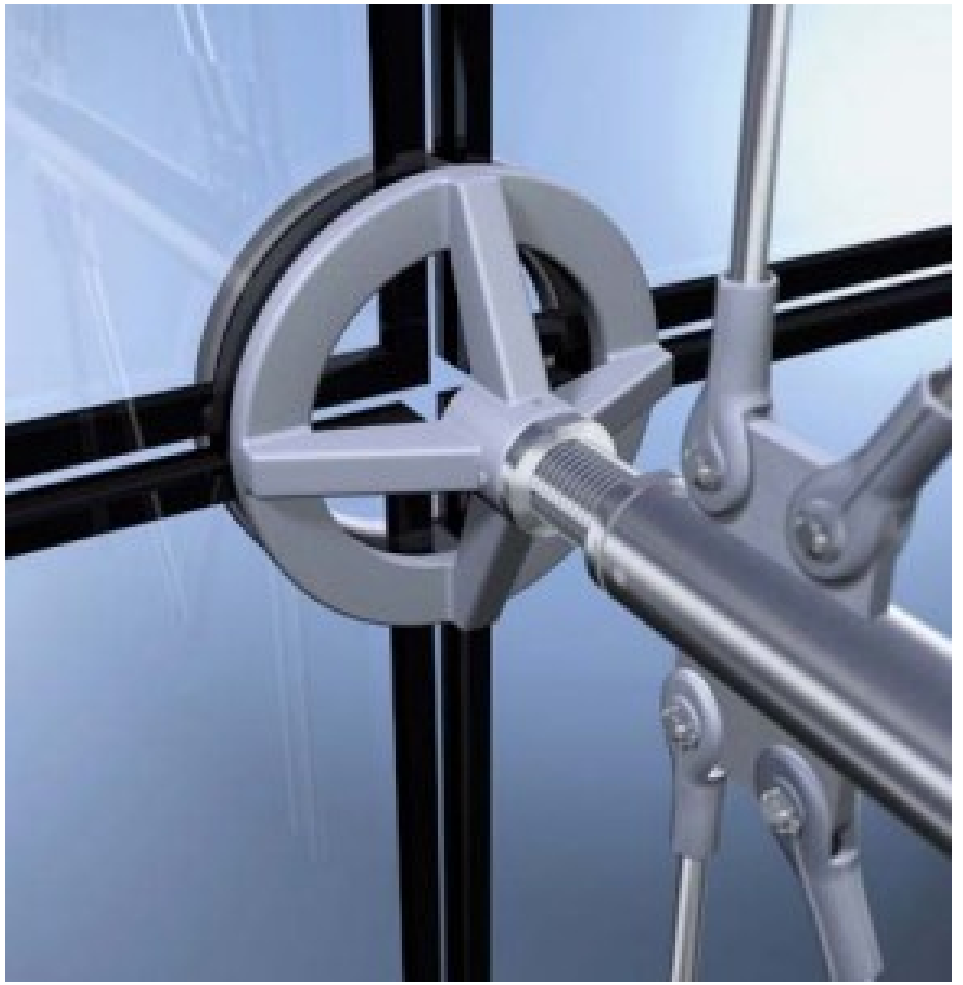
Figura 8.21. Tipi di sistemi di fissaggi puntuali [Rice & Dutton, 1995].

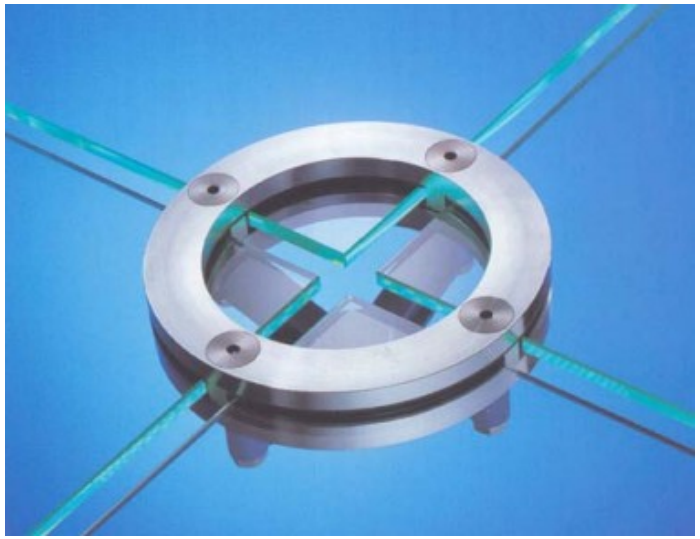


Figura 8.24. Particolari di fissaggi puntuali tipo Planar con supporti "a ragno".

Point-fixed facades:

- instead of traditional spider fittings (rotules), there are more advanced alternatives known as "glass-net" systems;
- the mechanism is similar to that of traditional spider fittings;
- they eliminate the need to drill holes in the glass











Point-fixed facades

- As a further evolution of point-fixed systems, a single-pane (monolithic) glass skin solution can sometimes be employed.
- Special point-fixing systems are used.
- Drilling of the glass panels is not required.
- The visual impact of the fixing systems is reduced.







Aspects to Consider

- Production and On-Site Assembly Phases
- In-Service Maintenance
- Durability
- Costs

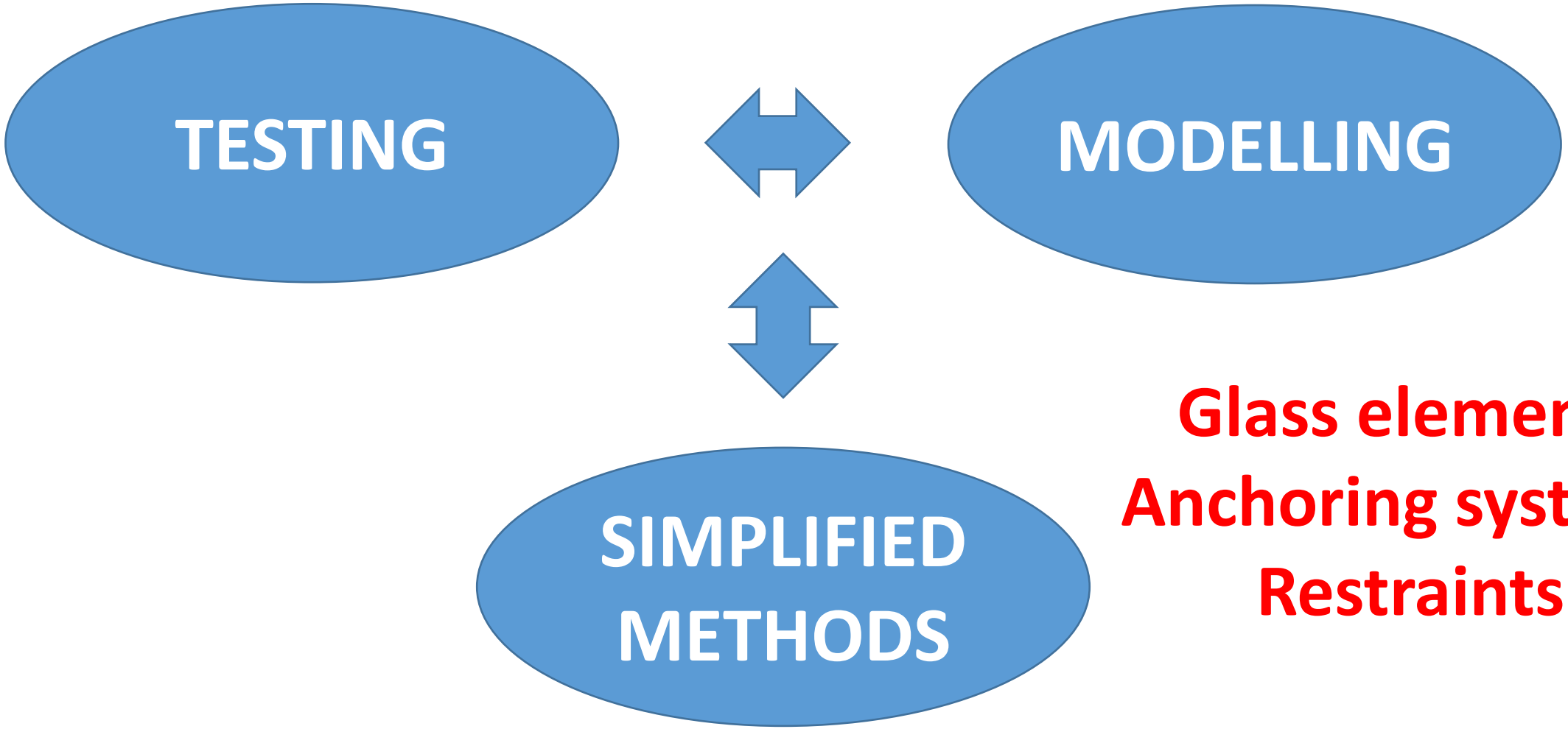







Modelling

Modelling



Glass elements
Anchoring systems
Restraints

Modelling

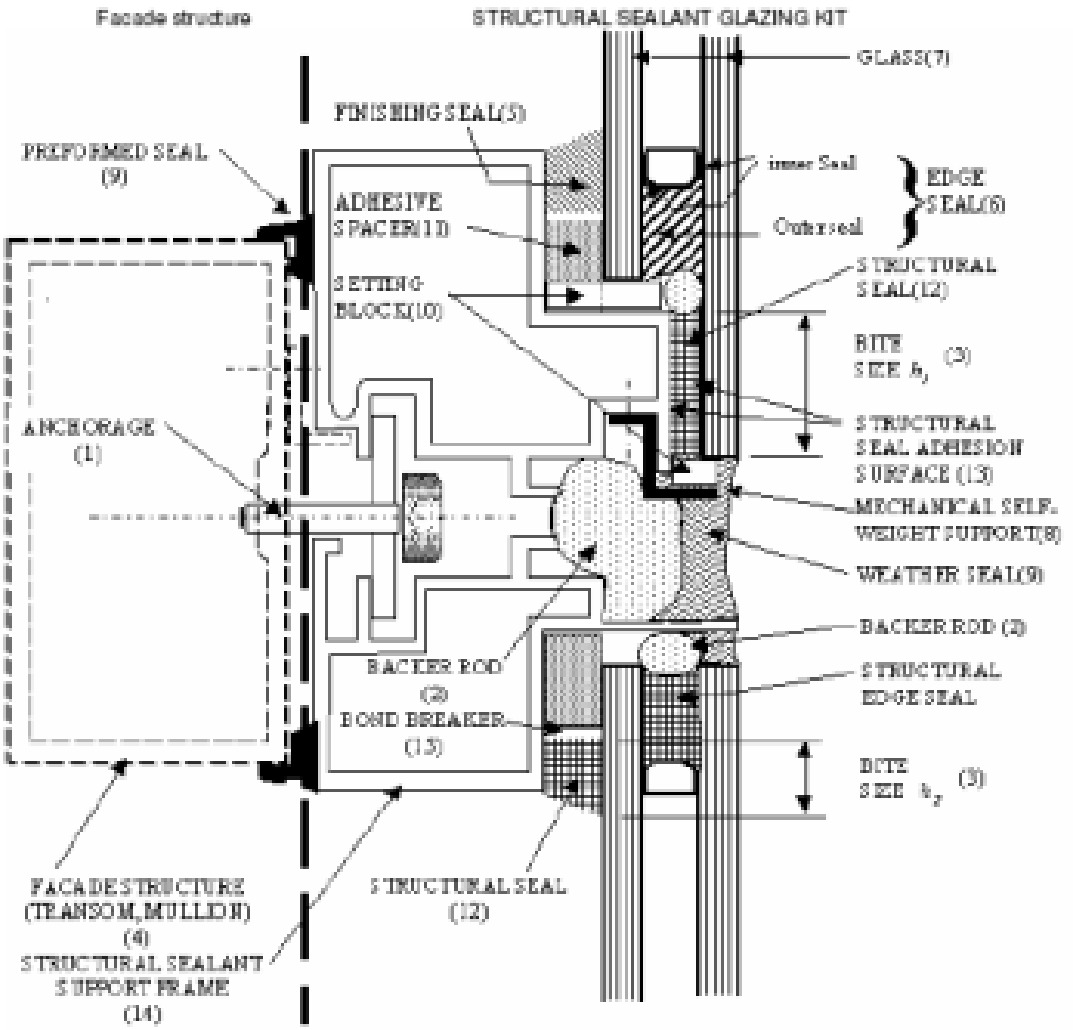


Figura 6.3. Esempio di giunti siliconici. [ETAG 002- Part 1]

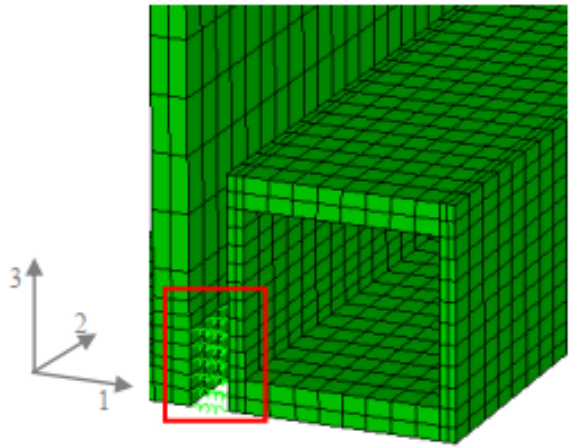
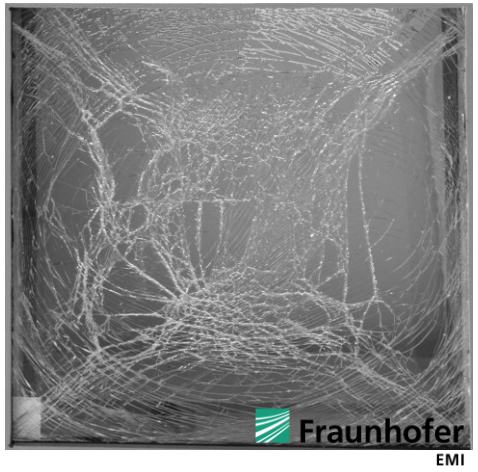


Figura 6.5. Esempio di modellazione di un giunto siliconico mediante molle equivalenti.

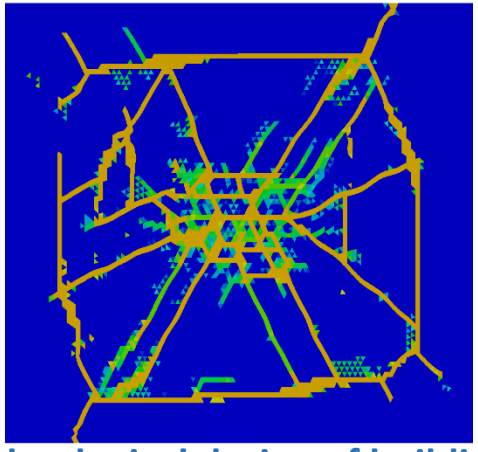
Example of numerical simulation

Experiment

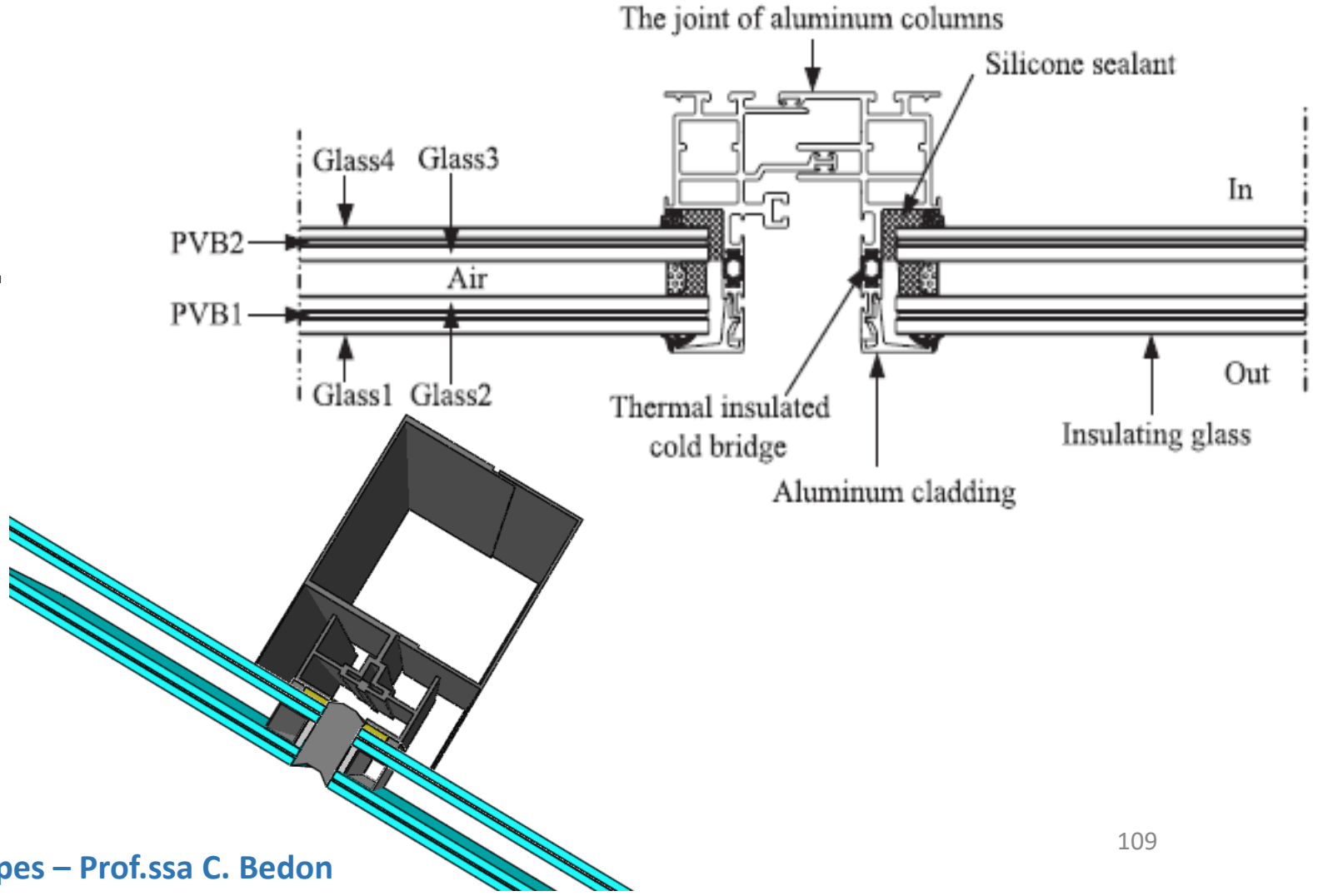


[Kranzer et al. 2005]

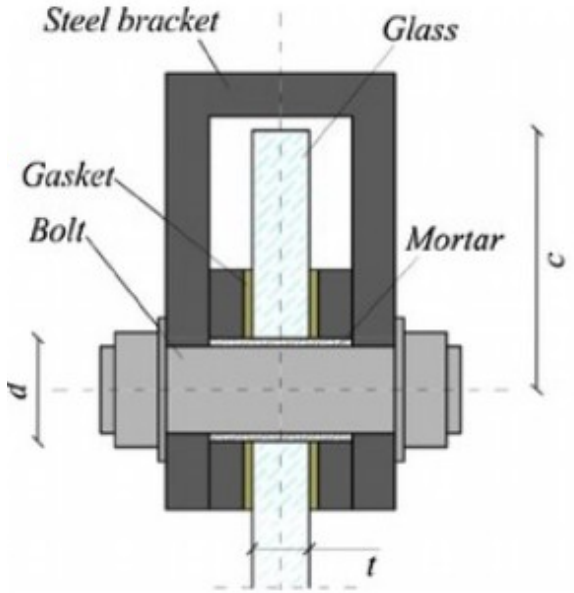
Numerical Simulation

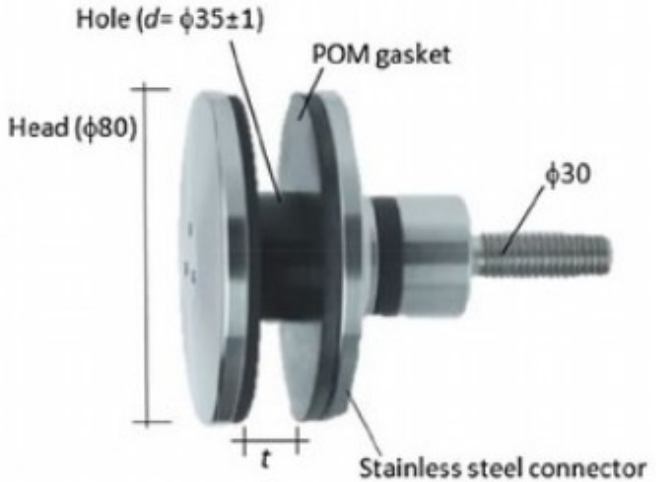


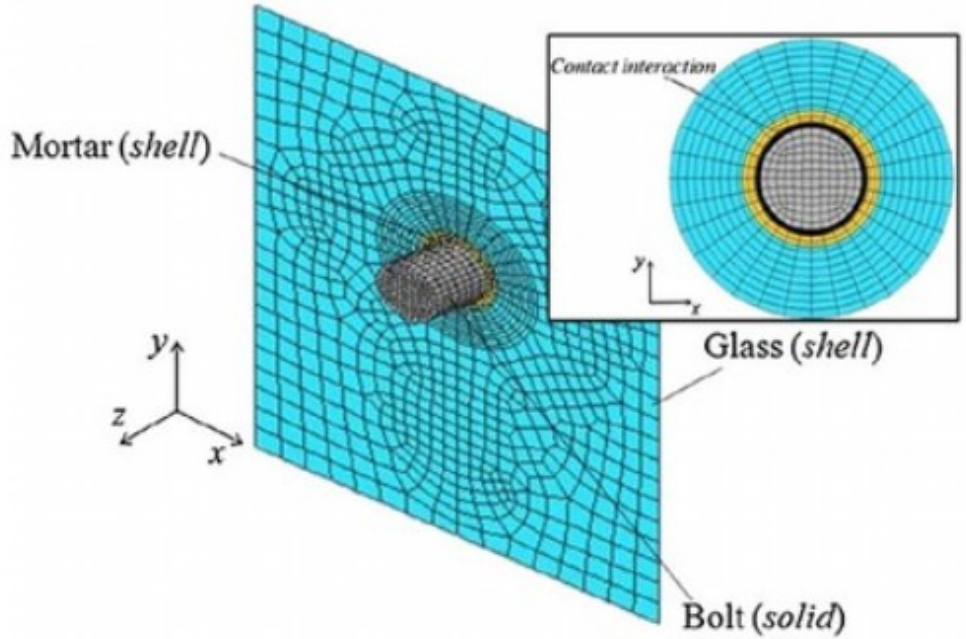
Window frame system

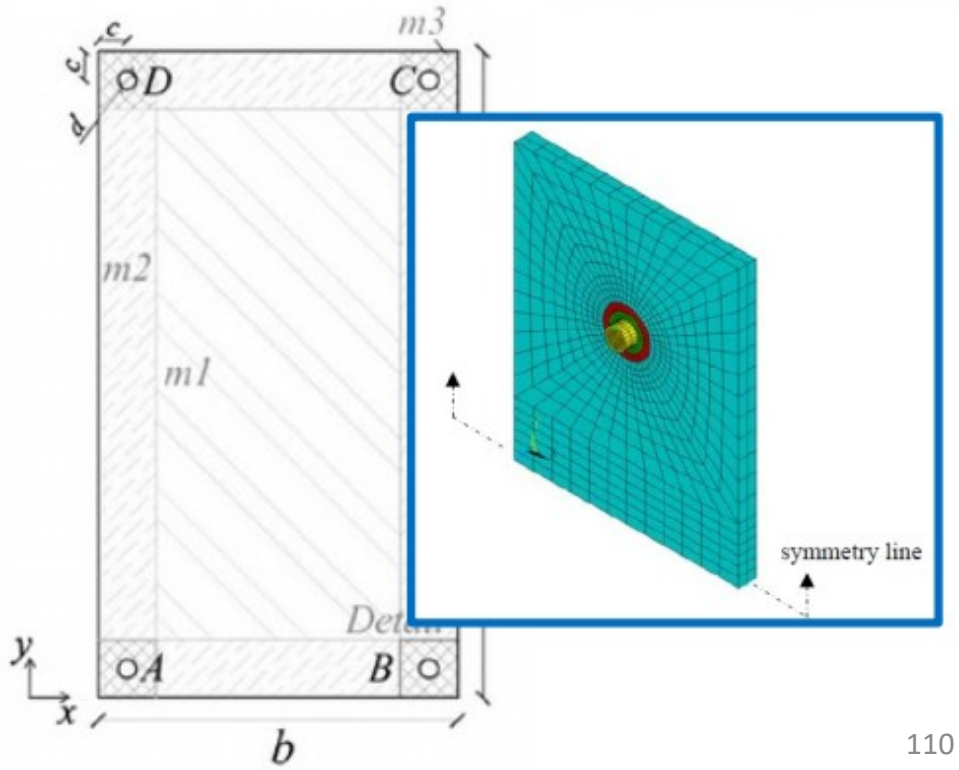


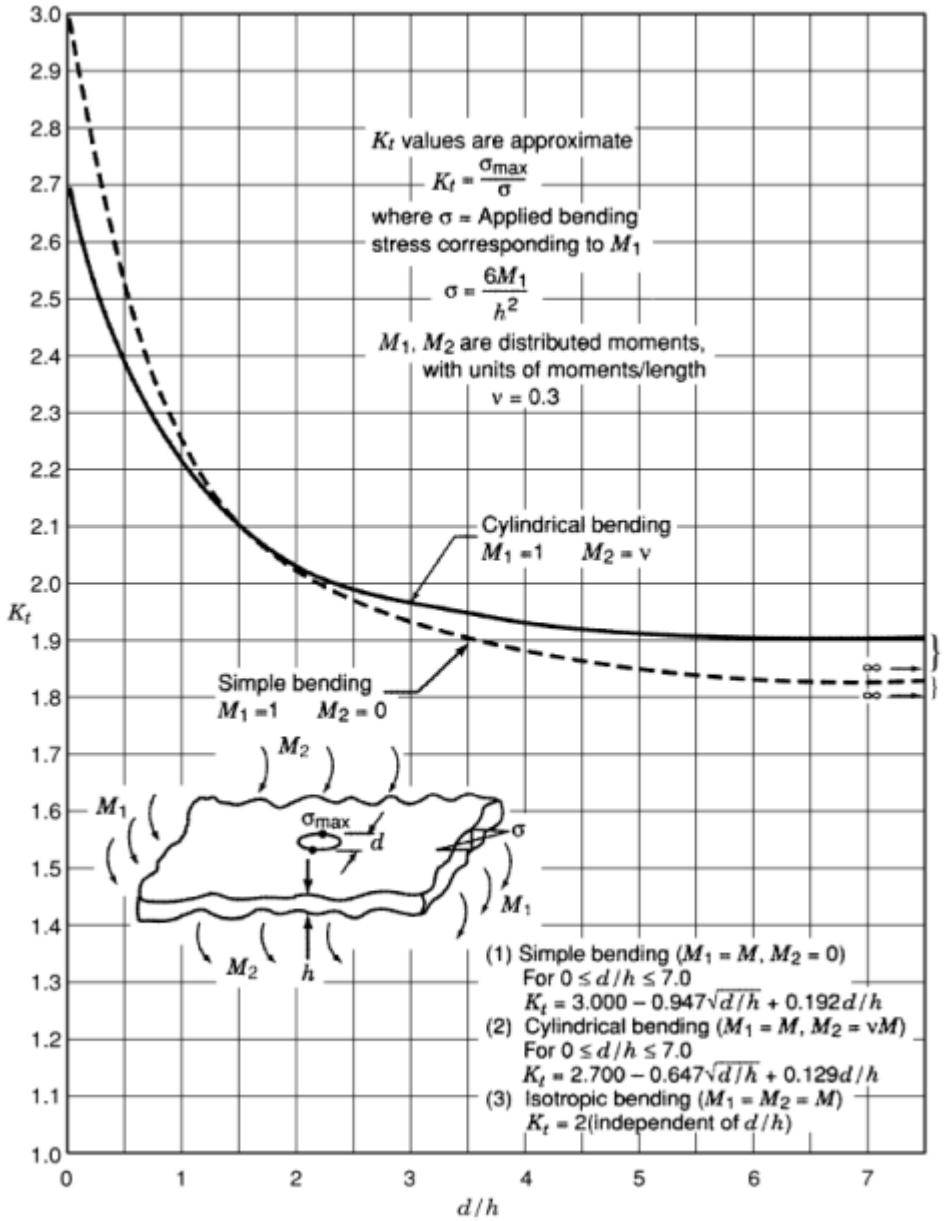
Modelling


Steel bracket
Glass
Gasket
Bolt
Mortar
c
d
t


Hole (d= ϕ35±1)
POM gasket
Head (ϕ80)
ϕ30
t
Stainless steel connector


Mortar (shell)
Contact interaction
Glass (shell)
Bolt (solid)
y
z
x


m3
D
C
m2
m1
A
B
b
symmetry line



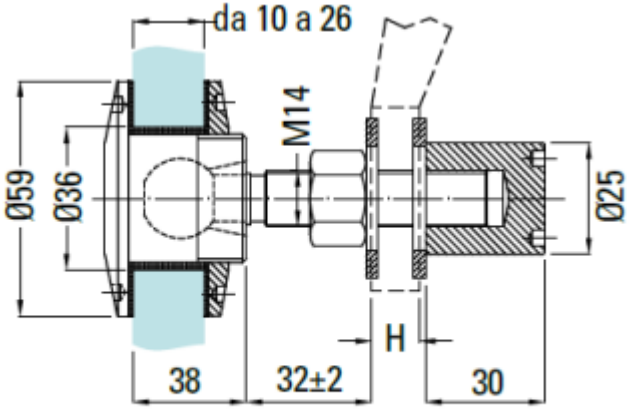
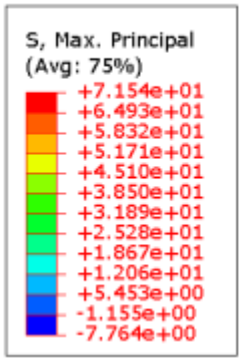
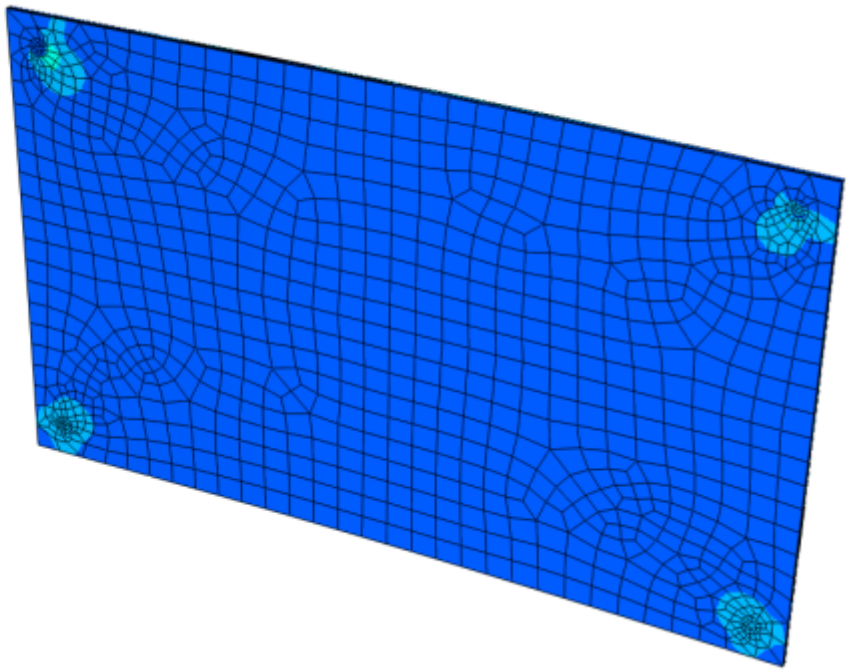
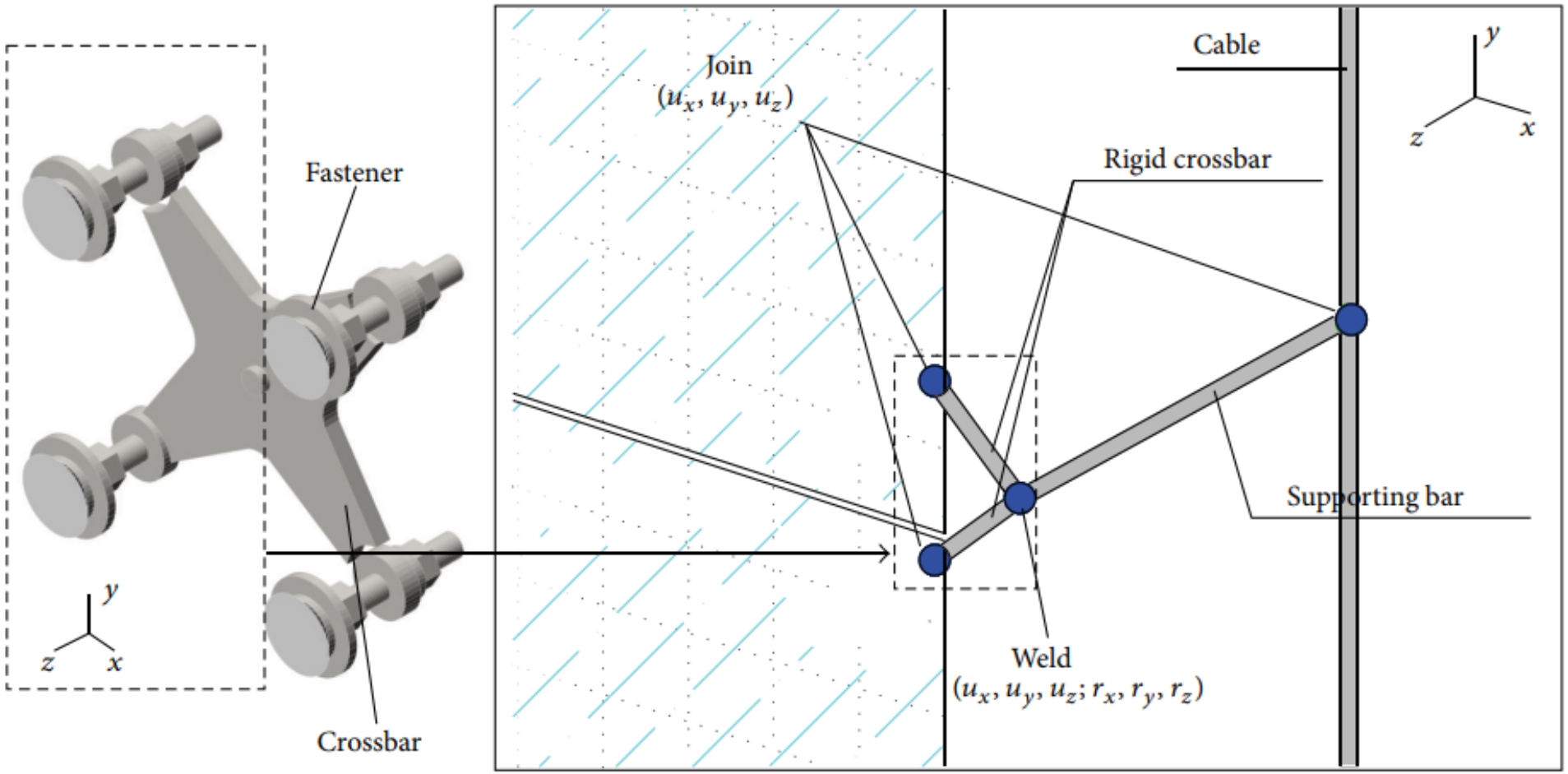


Figura 8.35. Sistema a rotule utilizzato nell'esempio.

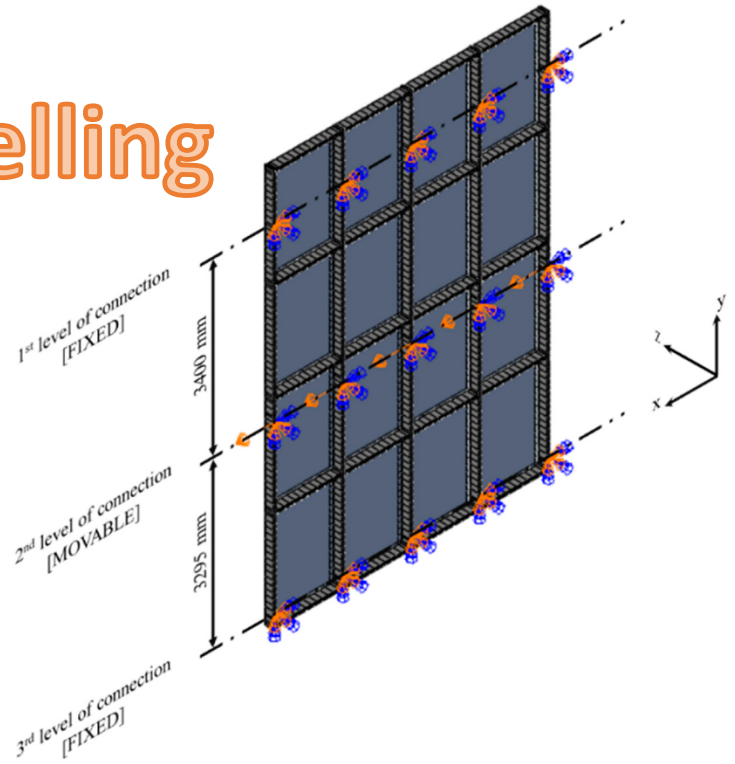




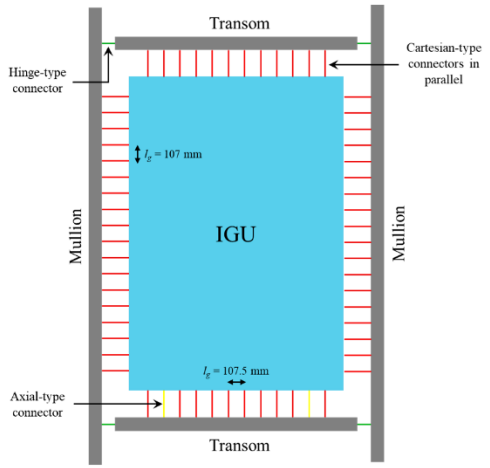
Modelling


Fastener
Crossbar
y
z
x
Join
(u_x, u_y, u_z)
Cable
Rigid crossbar
Supporting bar
Weld
$(u_x, u_y, u_z; r_x, r_y, r_z)$

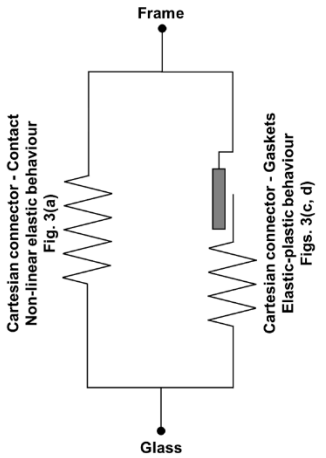
Modelling



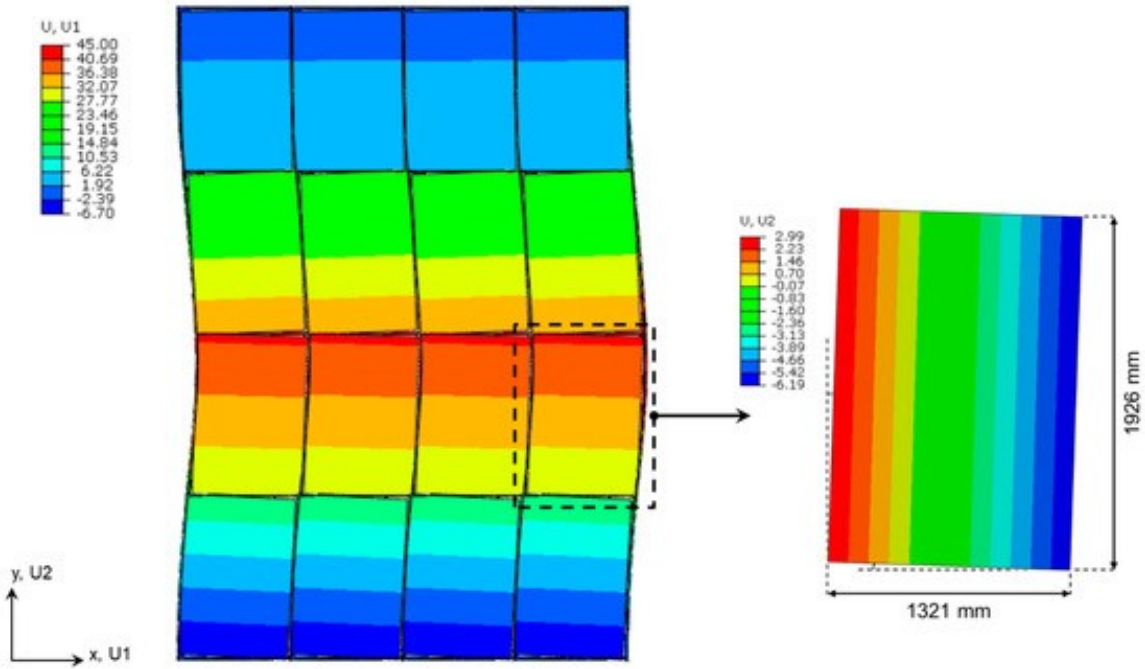
(a)



(b)



(c)



https://www.mdpi.com/2075-5309/14/12/3863

Practical example: New facade

Design recommendations – CNR DT210/2013

- Consequence class for pre- and post-failure verifications of glass
- Connectors and restraints must be also verified
- Clearance (gaps)

Element	CC_n (pre-F)	CC_n (post-F)
Vertical (linear restraints)	1	1/n.a.
Vertical (point fixings)	2/1	1/n.a.
Roofs	2	2/1
Fins	2	2/1
Railings (fall danger)	2	2/1
Floors, beams	2	2
Pillars	3	2 (pre-F loads)

Seismic design

- the distinction is between (a) **"secondary" structural elements** or (b) **glass elements that have a relevant structural role under seismic events**

- **(a)=** disregarded in the global analysis of the primary system. However, they are required to accommodate the main deformation and seismic performance of the primary

- **(b)=** glass systems and components that have a relevant stiffness / resistance contribution, or consist of stand-alone / special glass structures. They all fall in **CC3**, and damage /cracking must be avoided. Dedicated experiments can be also required, in support of design (for glass and /or joints and restraints)

V_N (years)	Examples
10	Temporary structures [2]
10-25	Replaceable parts
15-30	Agricultural structures
50	Buildings, common structures
100	Monumental buildings, bridges, other

[1] Post-F V_N= 10 for CC1 and CC2; from specific studies for CC3

[2] Excluded structures / parts that can be dismantled / reused

	Importance class			
Limit State	I	II	III	IV
SLO	-	-	ND_{45}	ND_{60}
SLD	SD_{35}	SD_{50}	SD_{75}	SD_{100}
SLV	HD_{333}	HD_{475}	HD_{713}	HD_{950}
SLC	-	-	F_{1463}	F_{1950}

Performance level	Description
ND	No damage in glass; no replacement; watertightness preserved
SD	Partial loss of functionality; usable building; no risk for users
HD	High degree (and cost) of functionality loss; still no risk for users
F	Severe damage; evidence of failure; risk for users

Local analysis

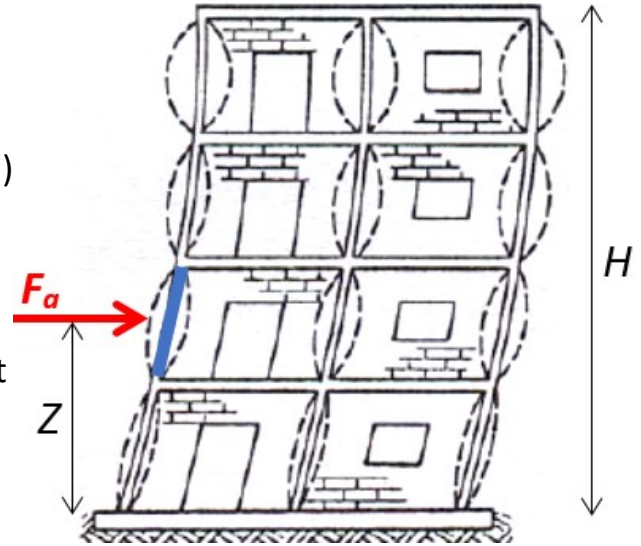
$$F_a = \frac{S_a W_a}{q_a}$$

Z height of centre of gravity of the glass element to verify (from the foundation)

H height of the full assembly / building (from the foundation)

T_a fundamental period of the glass element to verify

T_1 fundamental period of the full assembly / building, in the direction of interest



W_a is the weight of the element,

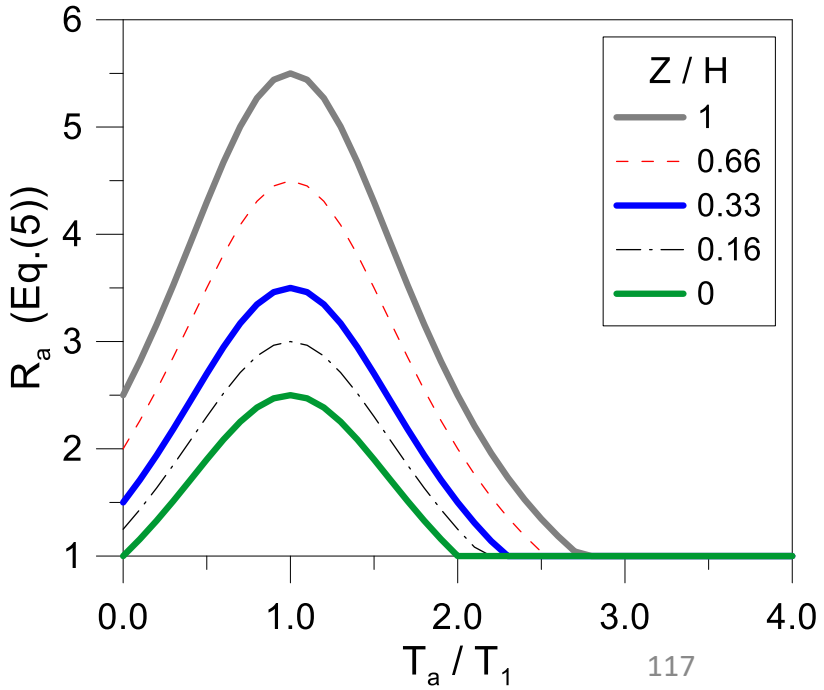
q_a is the behaviour factor of the glass element / system to verify

S_a is the peak acceleration if interest

$$S_a = \frac{a_g}{g} \cdot S \cdot R_a$$

$$R_a = max \begin{cases} \dfrac{3(1 + Z/H)}{1 + (1 - T_a/T_1)^2} - 0.5 \\ 1 \end{cases}$$

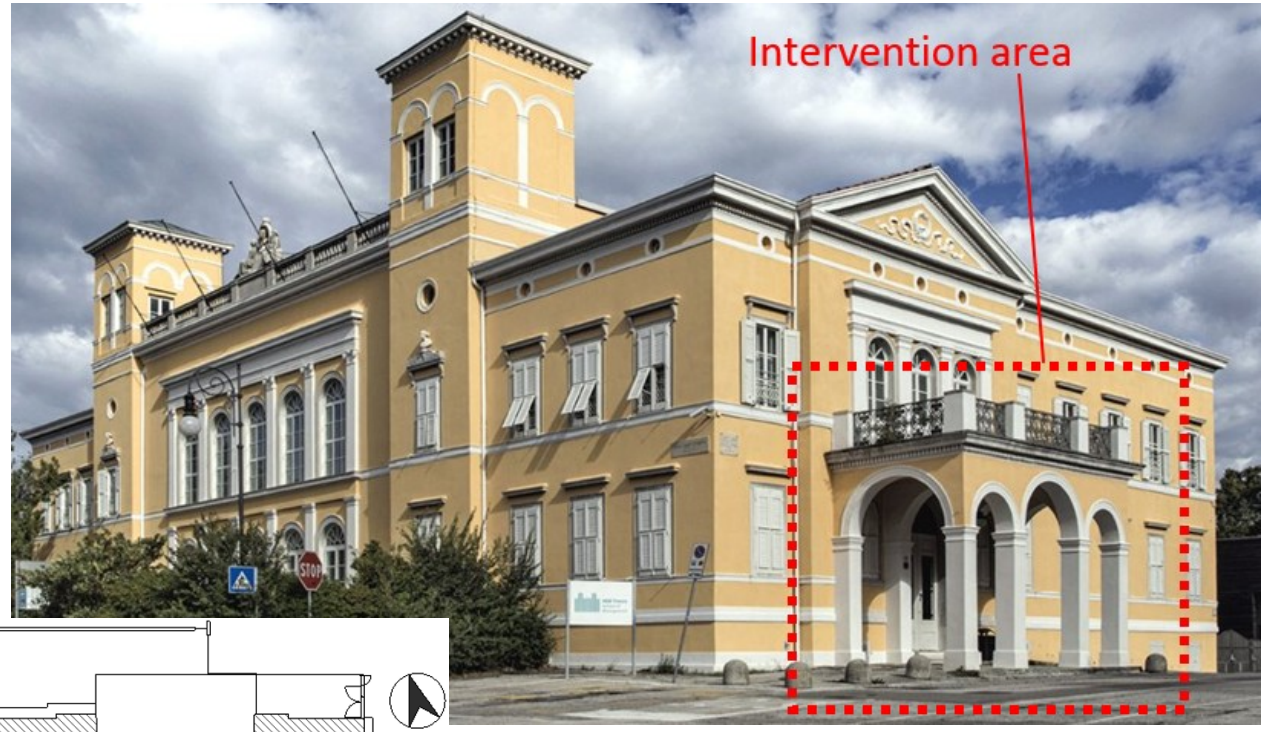
S accounts for soil category and topographical conditions

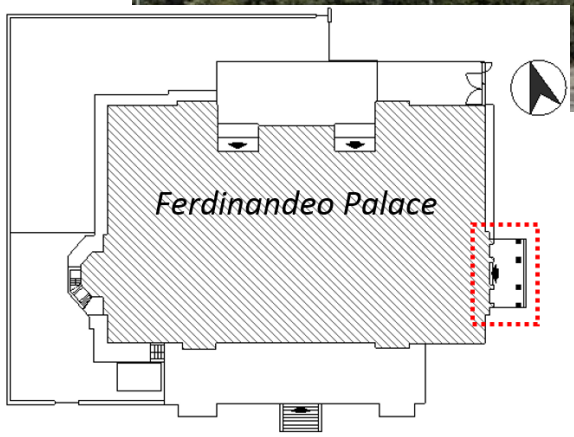


Case study system

- Glass partition wall

- Trieste (wind)
- Historical building (Ferdinandeo Palace)
- Strategic building (offices and private school)
- Emergence exit









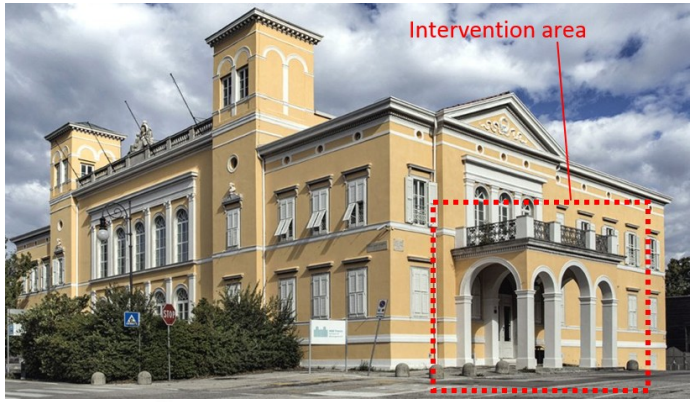
Case study system

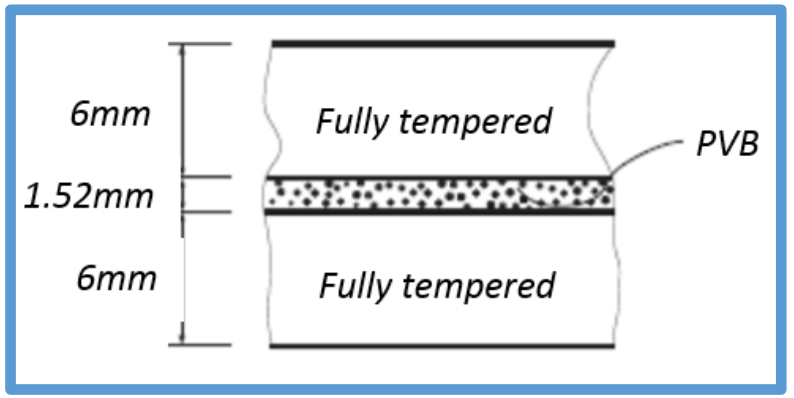
- Laminated glass panels
- Point-fixings (with holes)
- Friction clamps

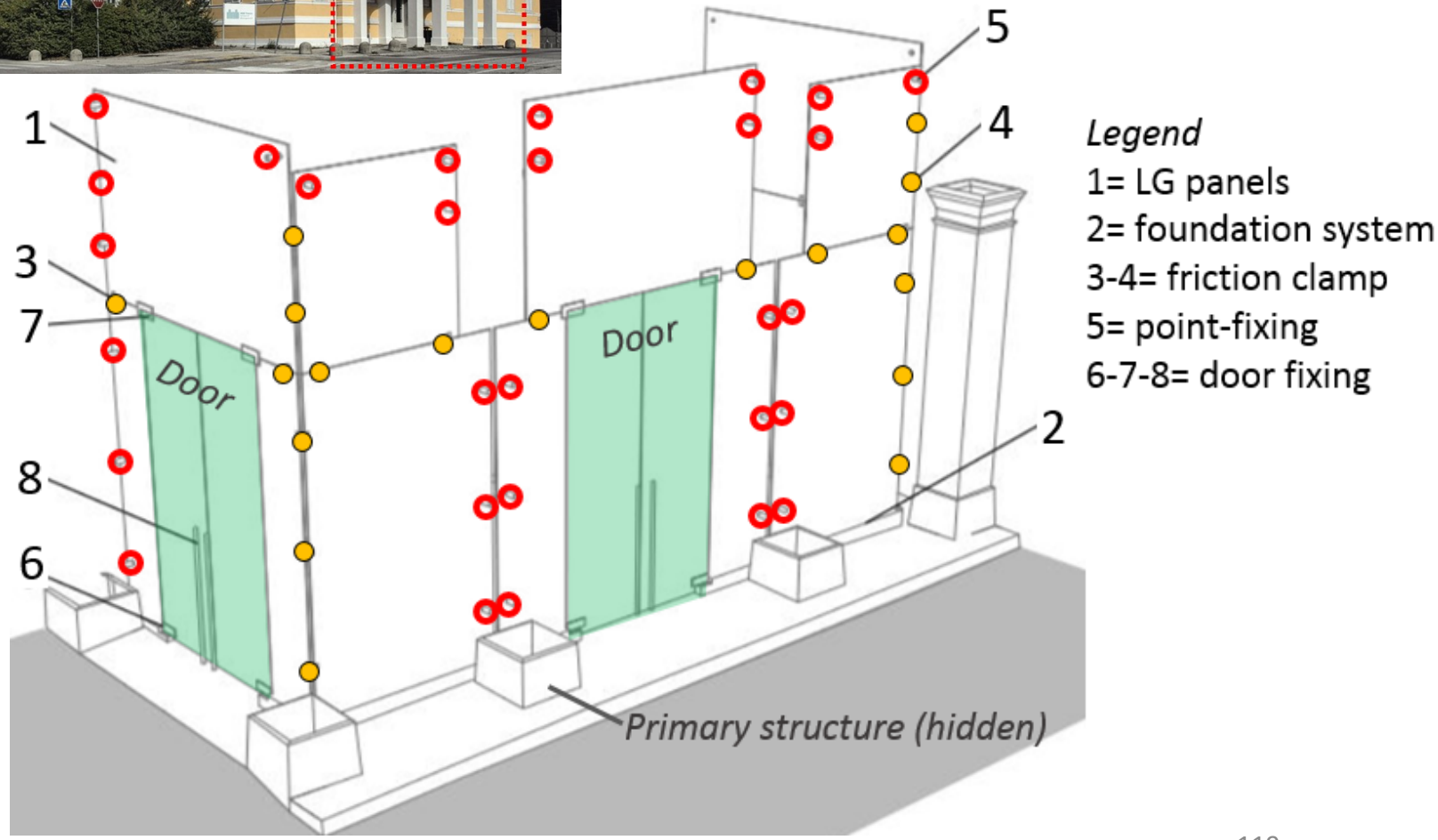
- Reversible intervention
- Bearing members minimized

Size

- **50 square meters of glass**
- **1.8 – 2.5m wide panels**
- **Top height= 4.65m**

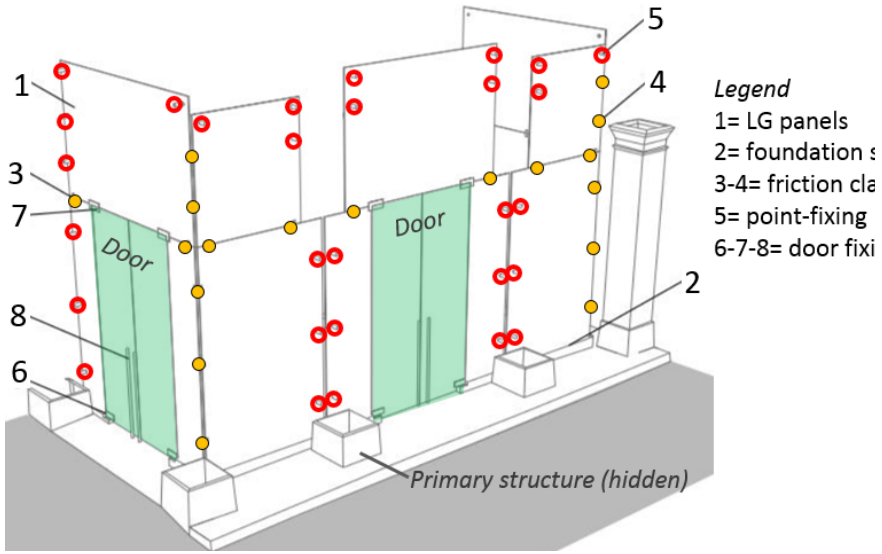


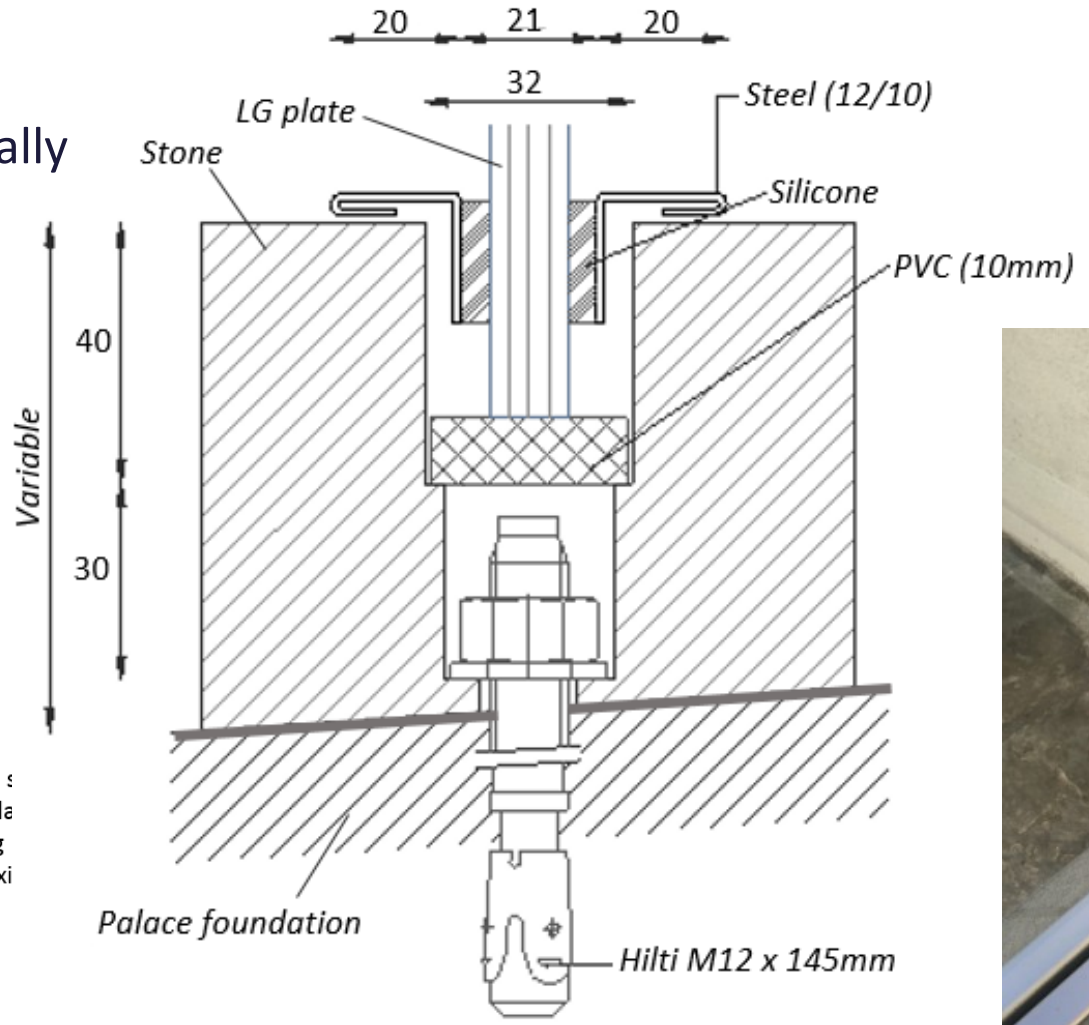




Foundation

- Bespoke stone rails, with geometrically irregular base foundation
- Avoidance of stress peaks in glass
- Relative in-plane displacements allowed

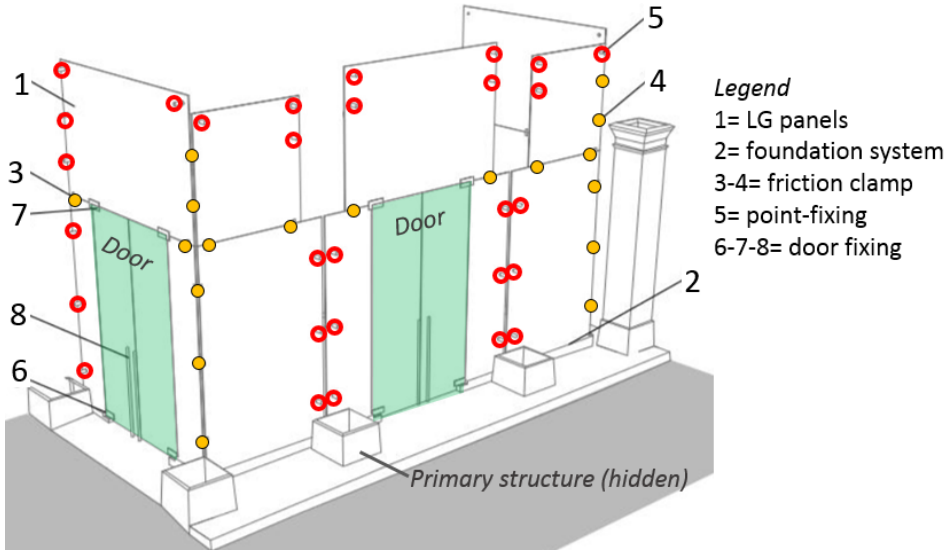






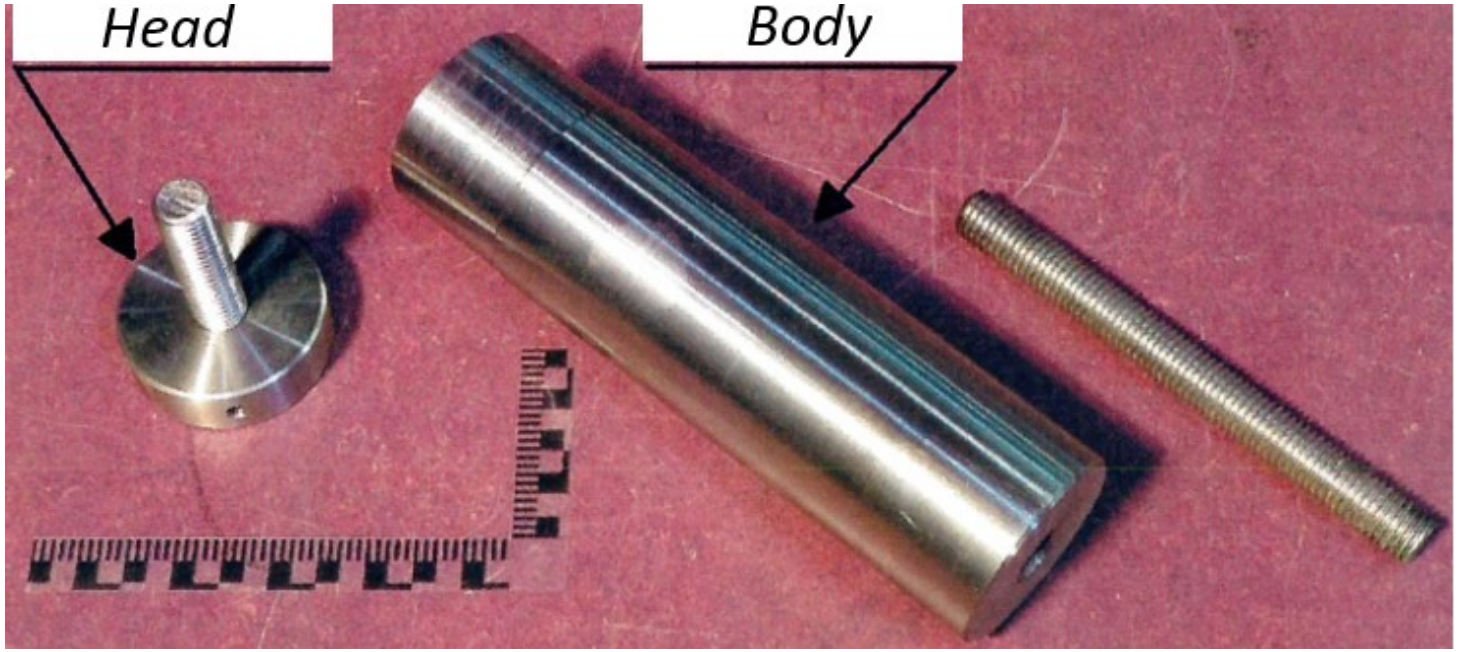
Elevation restraints

- Bespoke steel joints
- Solid section (42mm diameter)
- M12 screw
- Variable body length, to accommodate the primary building (mean 160mm)





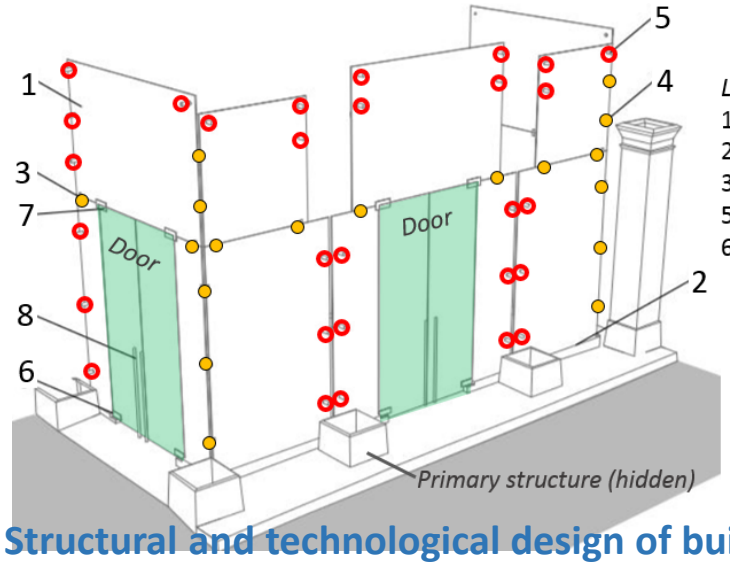
Type A
Point fixings with holes



Type B
Friction clamps
(corners)



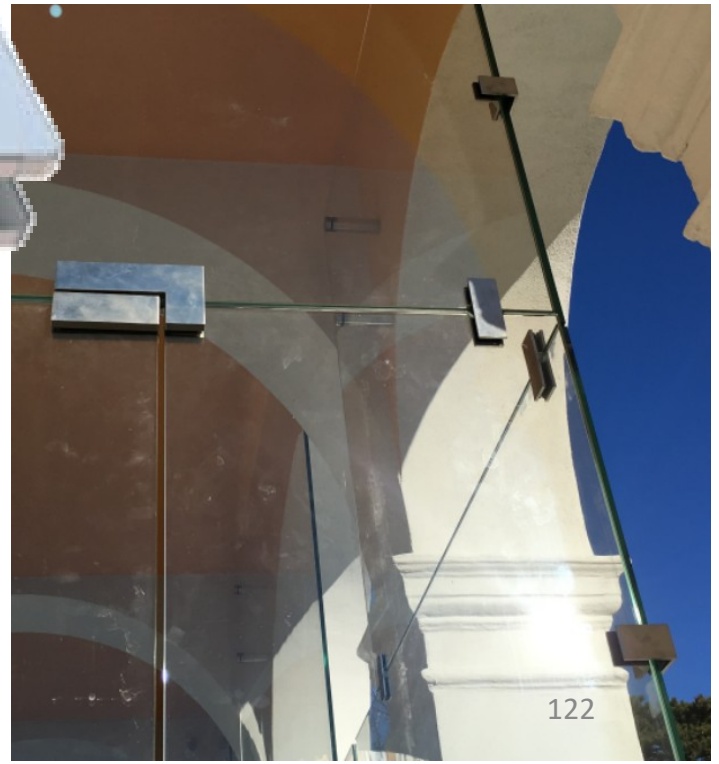




Legend
1= LG panels
2= foundation system
3-4= friction clamp
5= point-fixing
6-7-8= door fixing

Type C
Friction clamps
(overlapping plates)

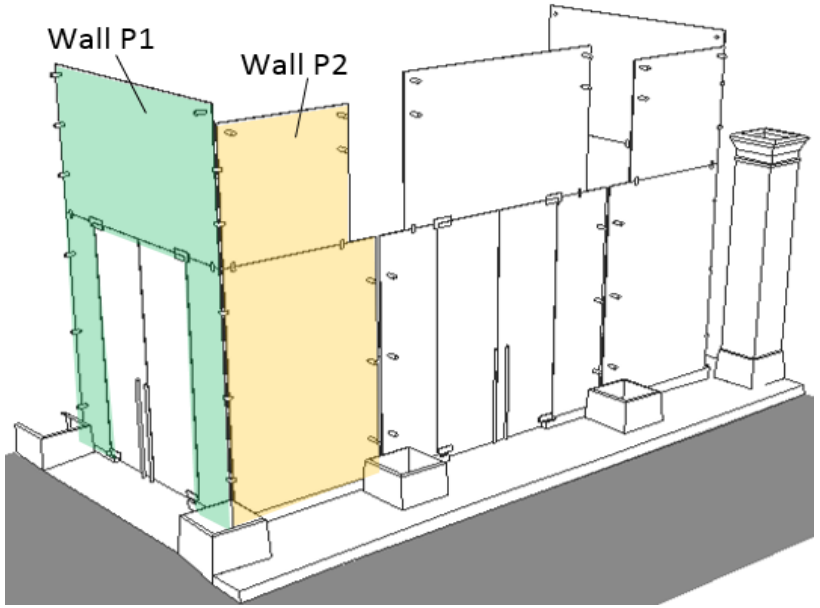


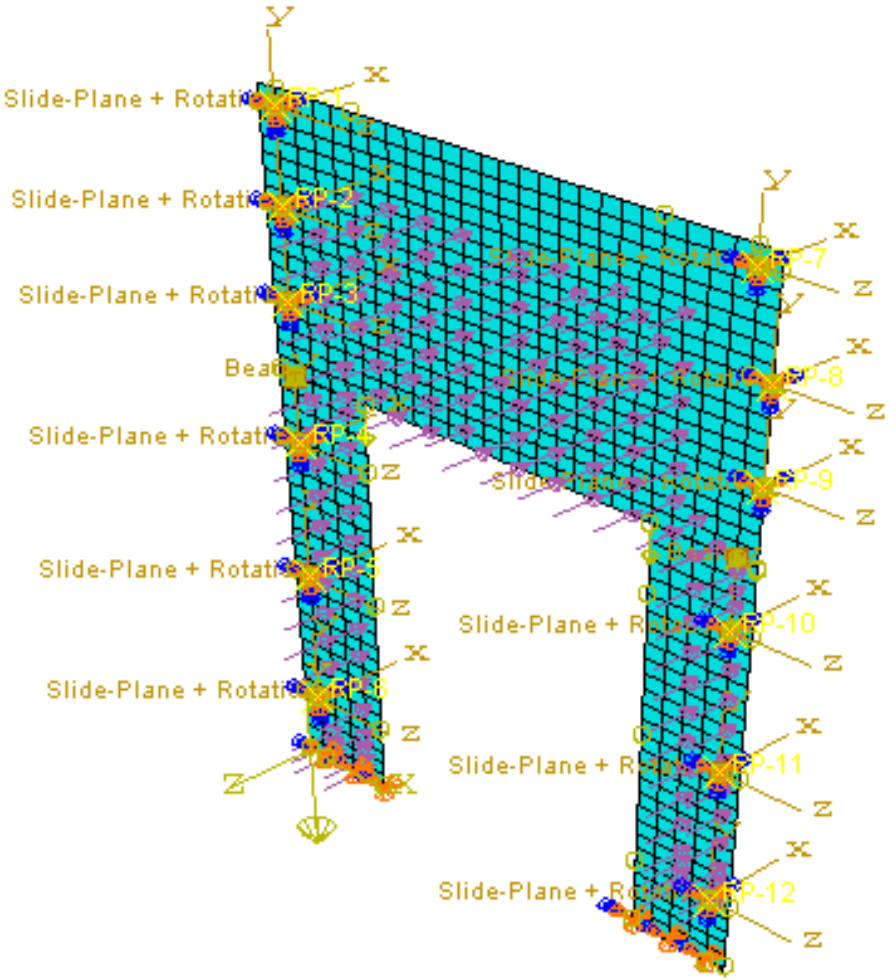


Design and analysis

Separate local analysis of:

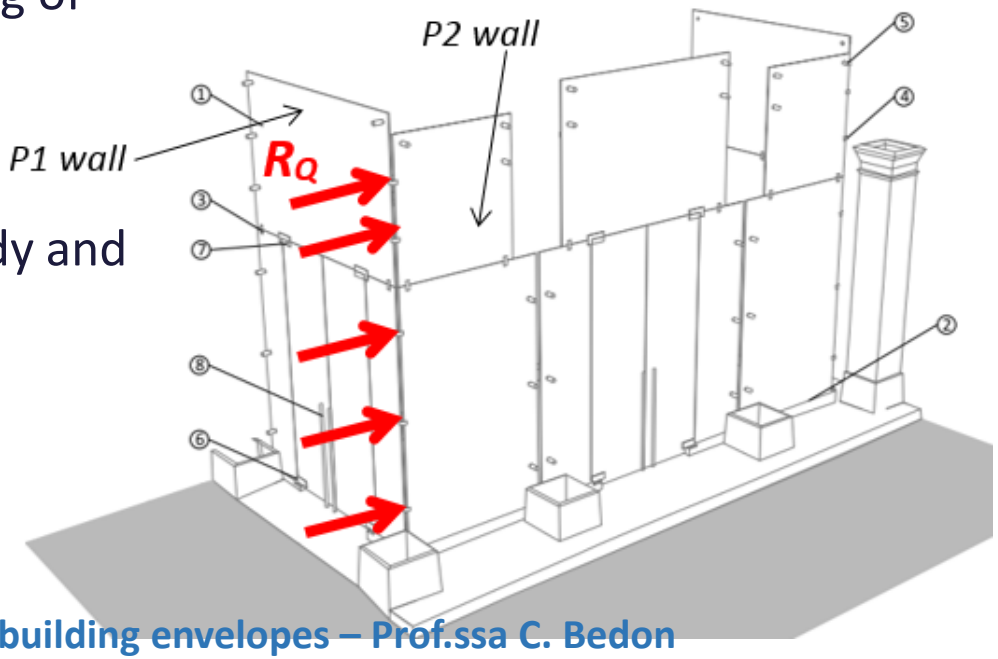
- Out-of-plane, and
- In-plane seismic loads



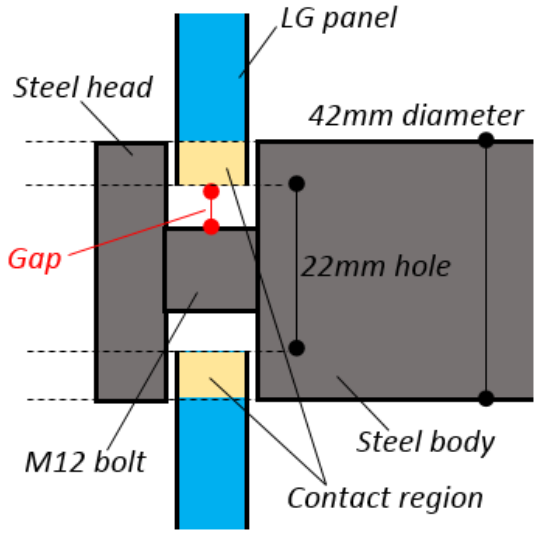


Key role of numerical modelling of point fixings:

- out-of-plane
- In-plane
- gaps between the steel body and the glass hole





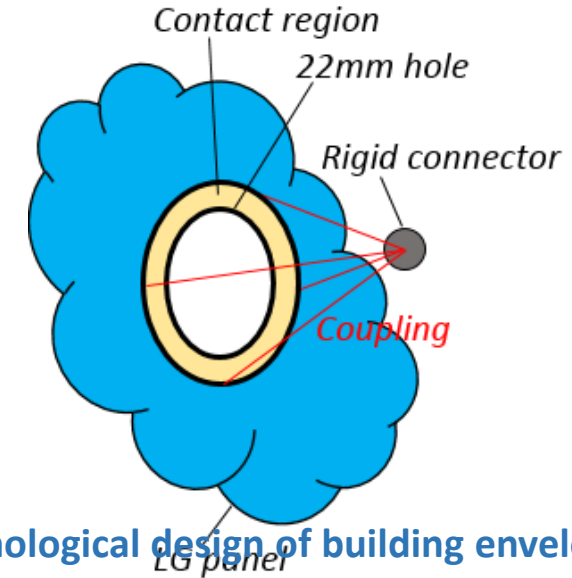


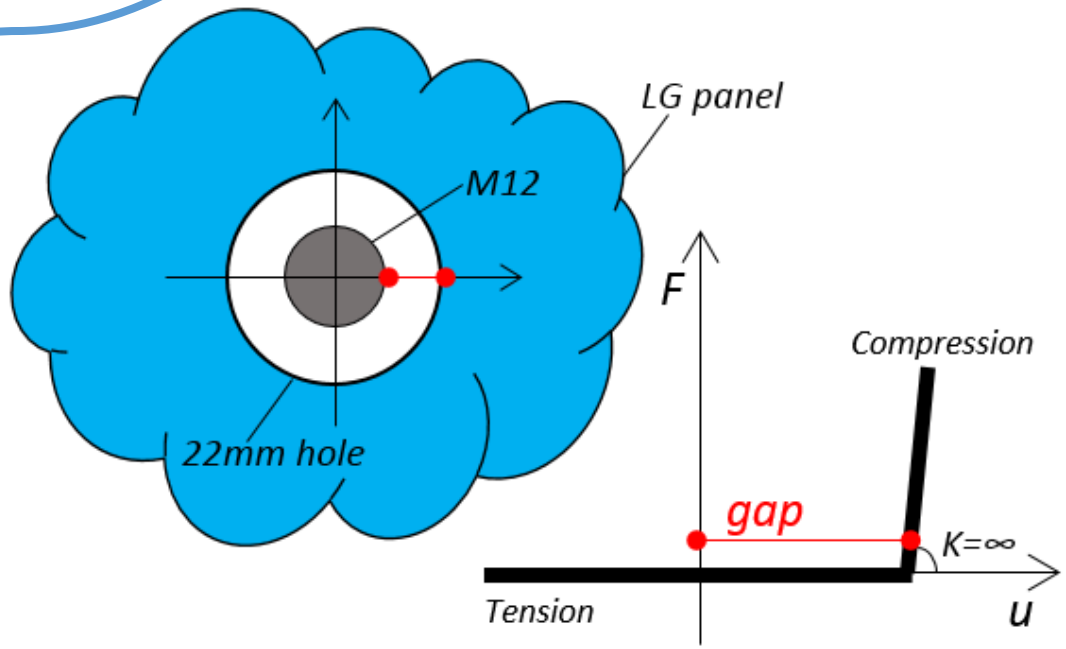
In-plane

- Unilateral restraint
- Contact in compression only

Out-of-plane

- Distributed rotational constraint (contact region)
- Infinite axial / longitudinal stiffness

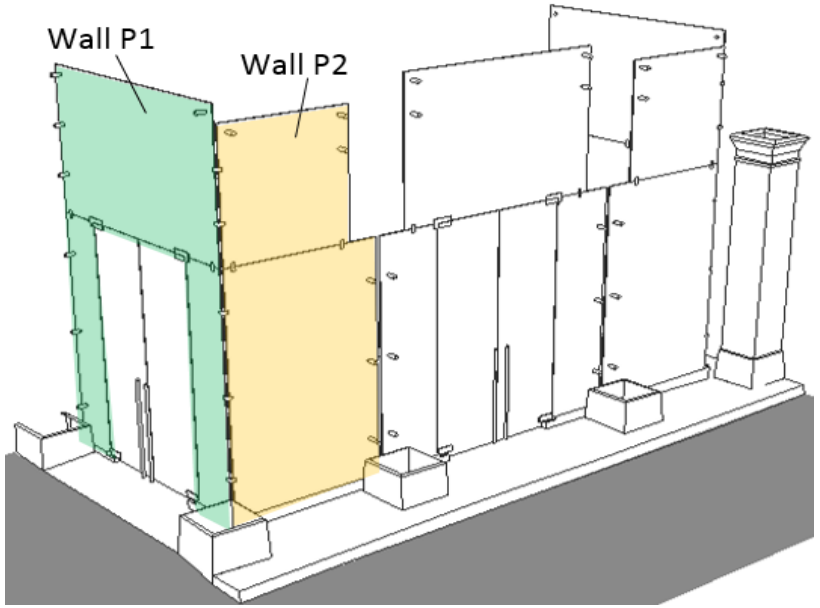


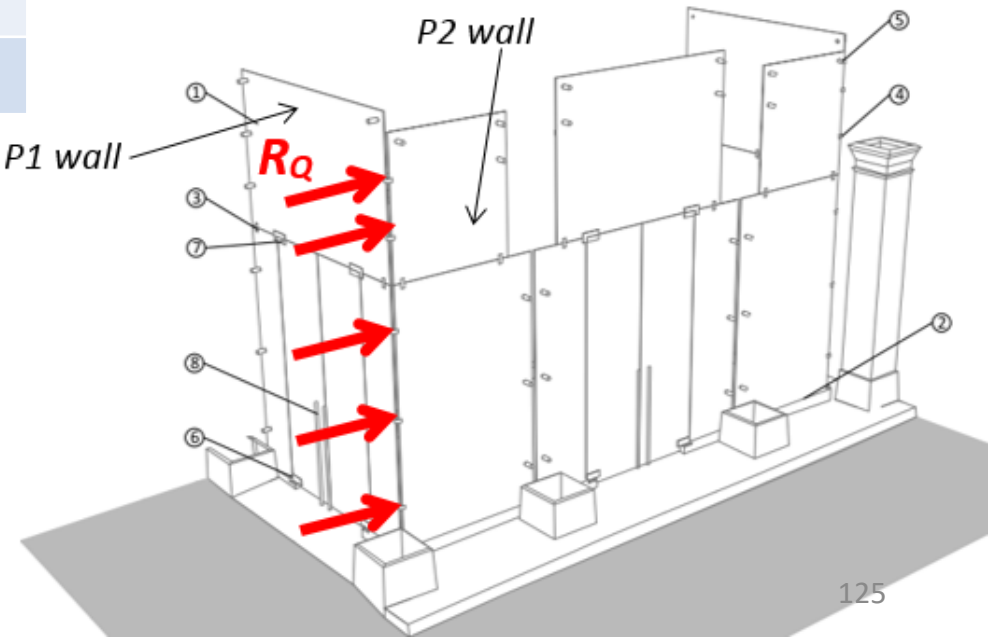


Design and analysis

$$F_a = \frac{S_a W_a}{q_a}$$ *with q_a= 1*

R_a= 1				
Limit State	$a_{g,max}$ [g]	S_a [g]	F_a [kN]	**Q_a [kN/m²]**
SLO	0.128	0.154	0.385	**0.049**
SLD	0.167	0.201	0.503	**0.064**
SLV	0.442	0.531	1.328	**0.170**
SLC	0.546	0.655	1.638	**0.210**





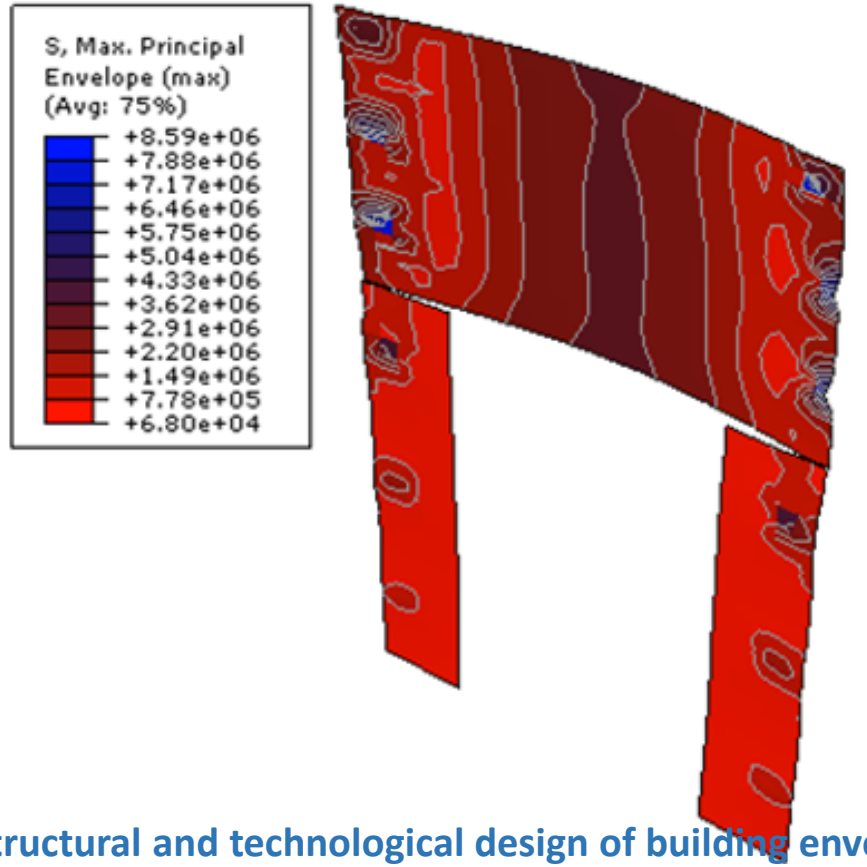
Separate local analysis of:

- Direct seismic effects
- Indirect seismic loads (point-fixings)

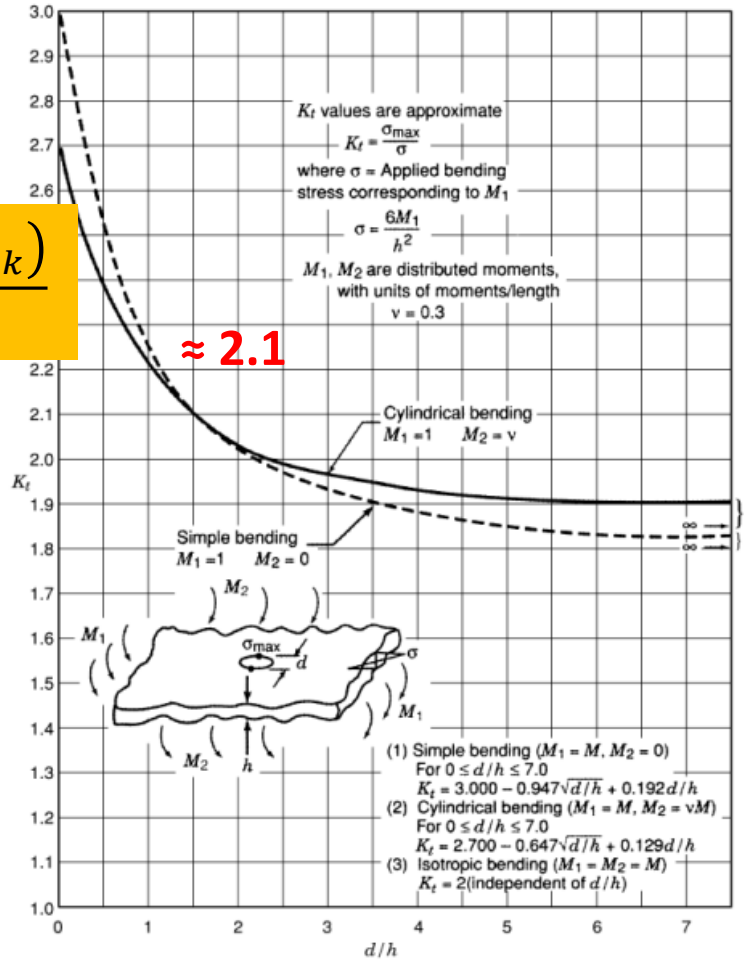
Stress verification

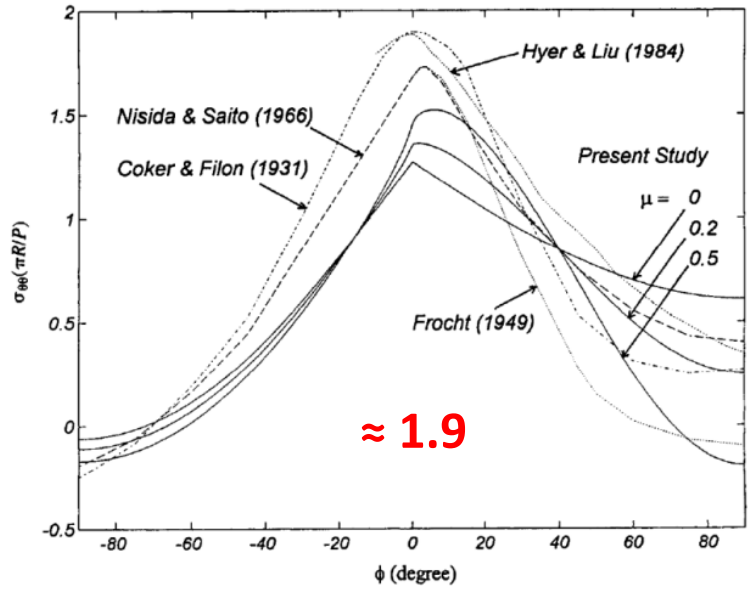
$$\sigma_{max} = \sigma_{FE} K \leq f_{g;d}$$

$$f_{g;d} = \frac{k_{mod} k_{ed} k_{sf} \lambda_{gA} \lambda_{gl} f_{g;k}}{R_M \gamma_M} + \frac{k'_{ed} k_v (f_{b:k} - f_{g;k})}{R_{M;v} \gamma_{M;v}}$$



Coefficient for out-of-plane (bending) loads



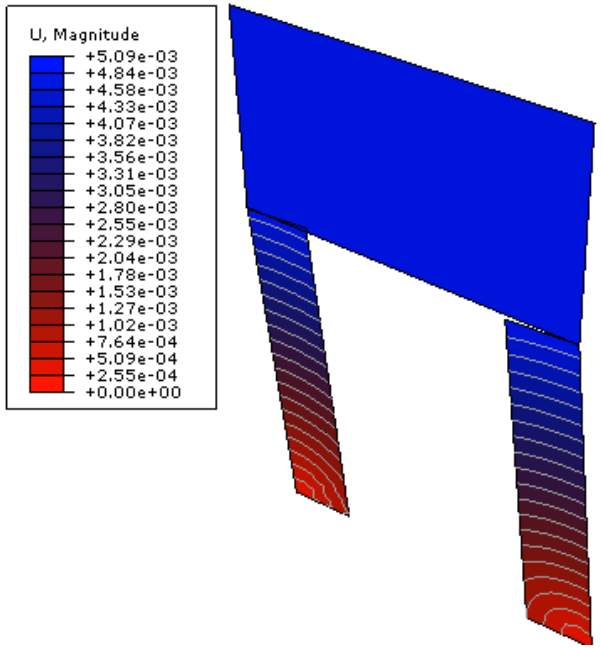


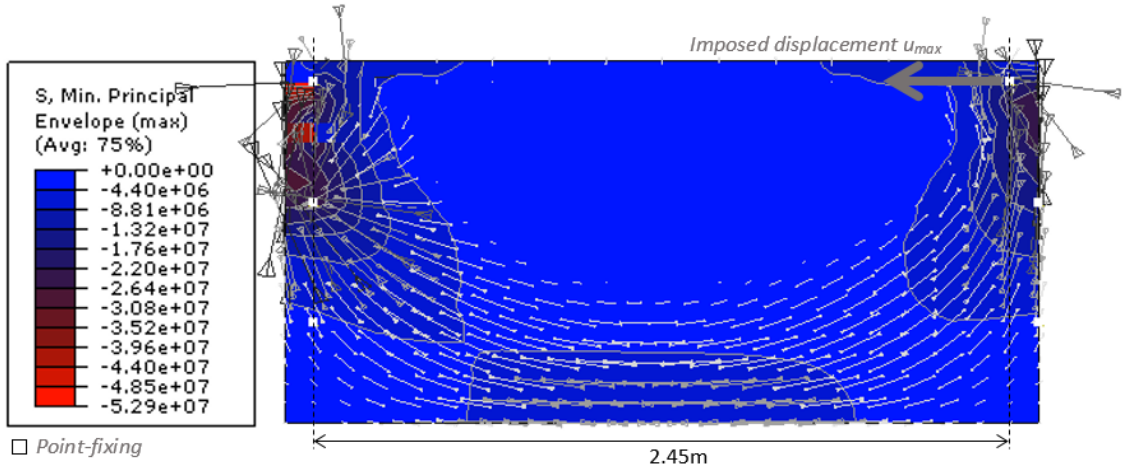
Coefficient for in-plane loads

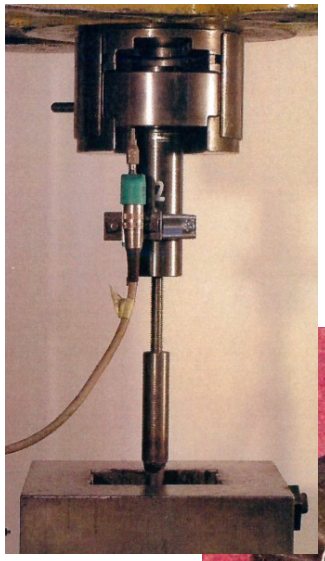
Fully tempered panels, “near holes”, “short term loads”

$f_{g;d}$ ≈65MPa

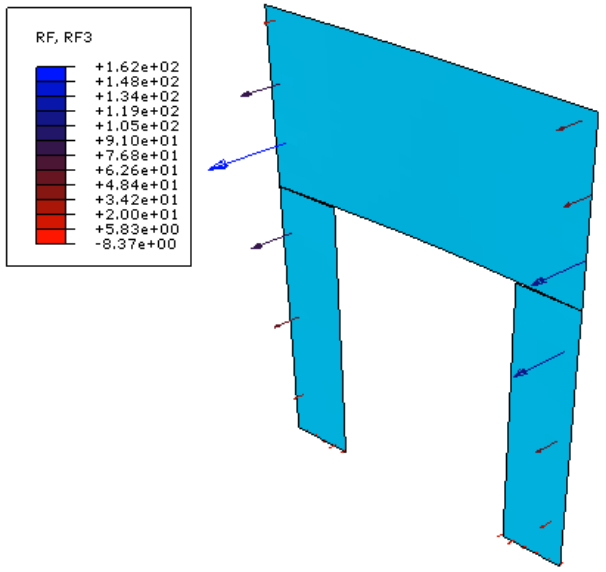
Deformations and reaction forces in the restraints









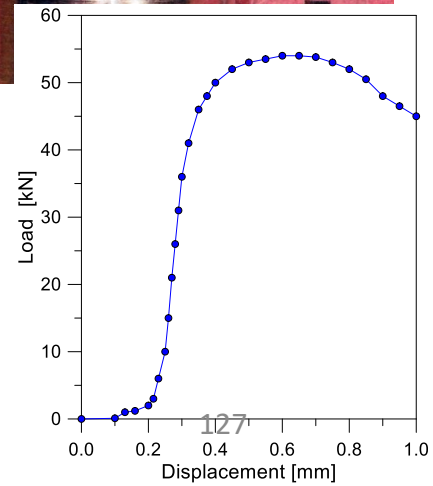


Allowable drift?

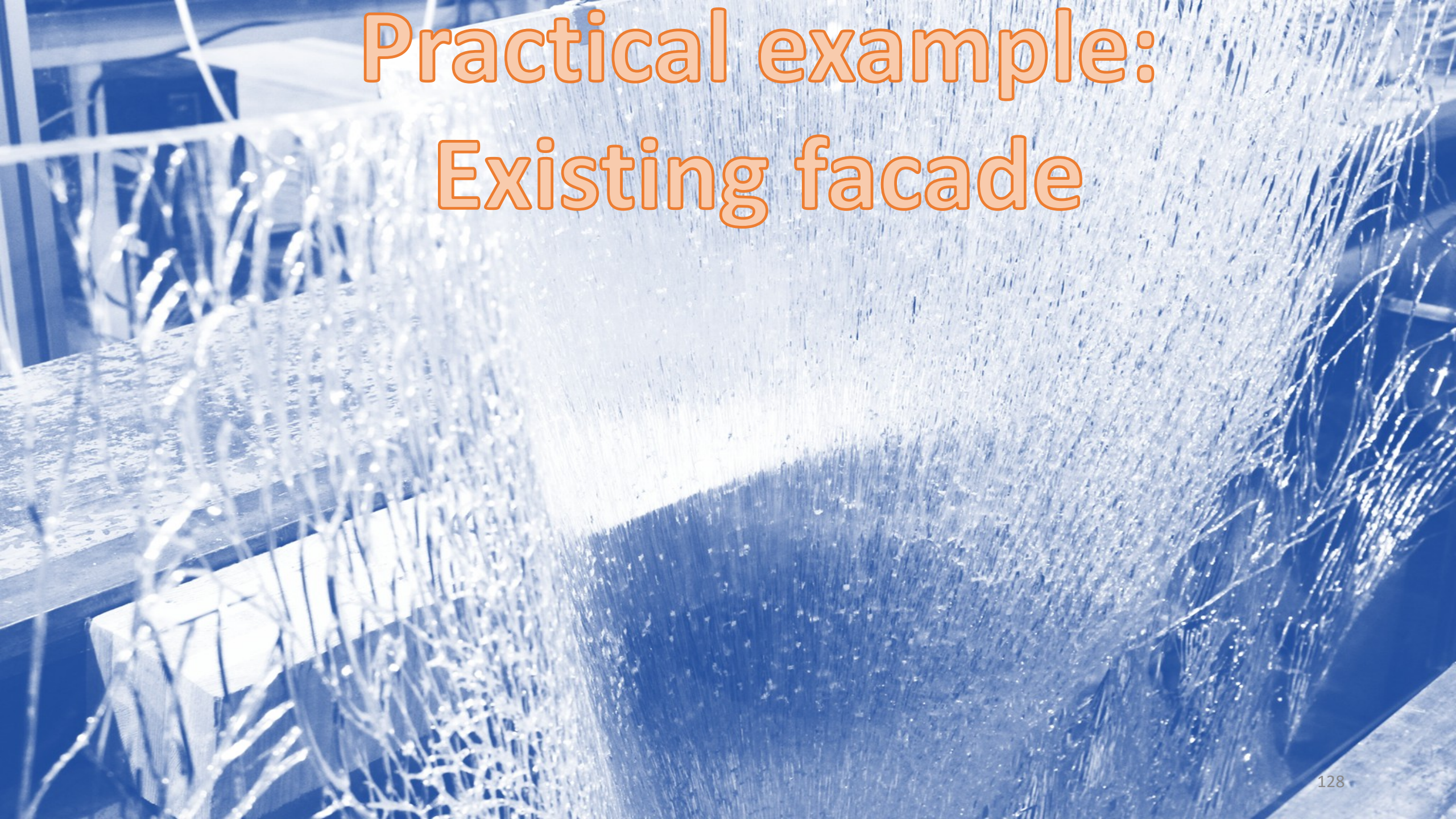
Imposed deformation? Force?

0.002H = 9.3mm

with 0.002 for ordinary masonry buildings
and *H*= 4.65m the maximum height of the glass partition



Practical example: Existing facade

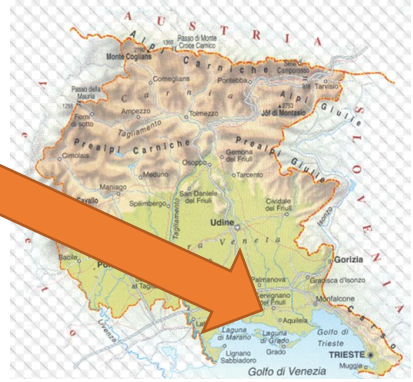




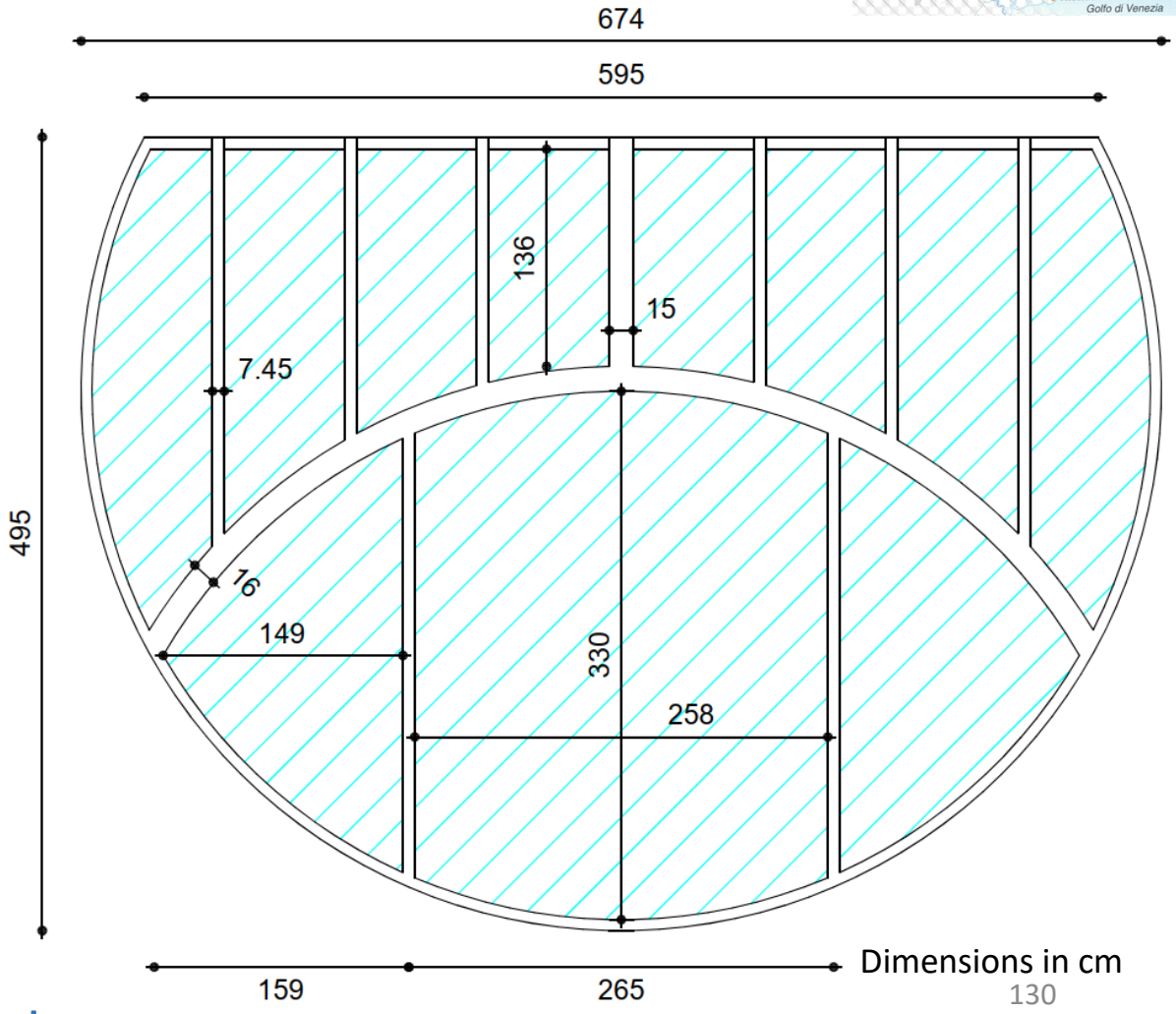


Glass facade
Case-study system

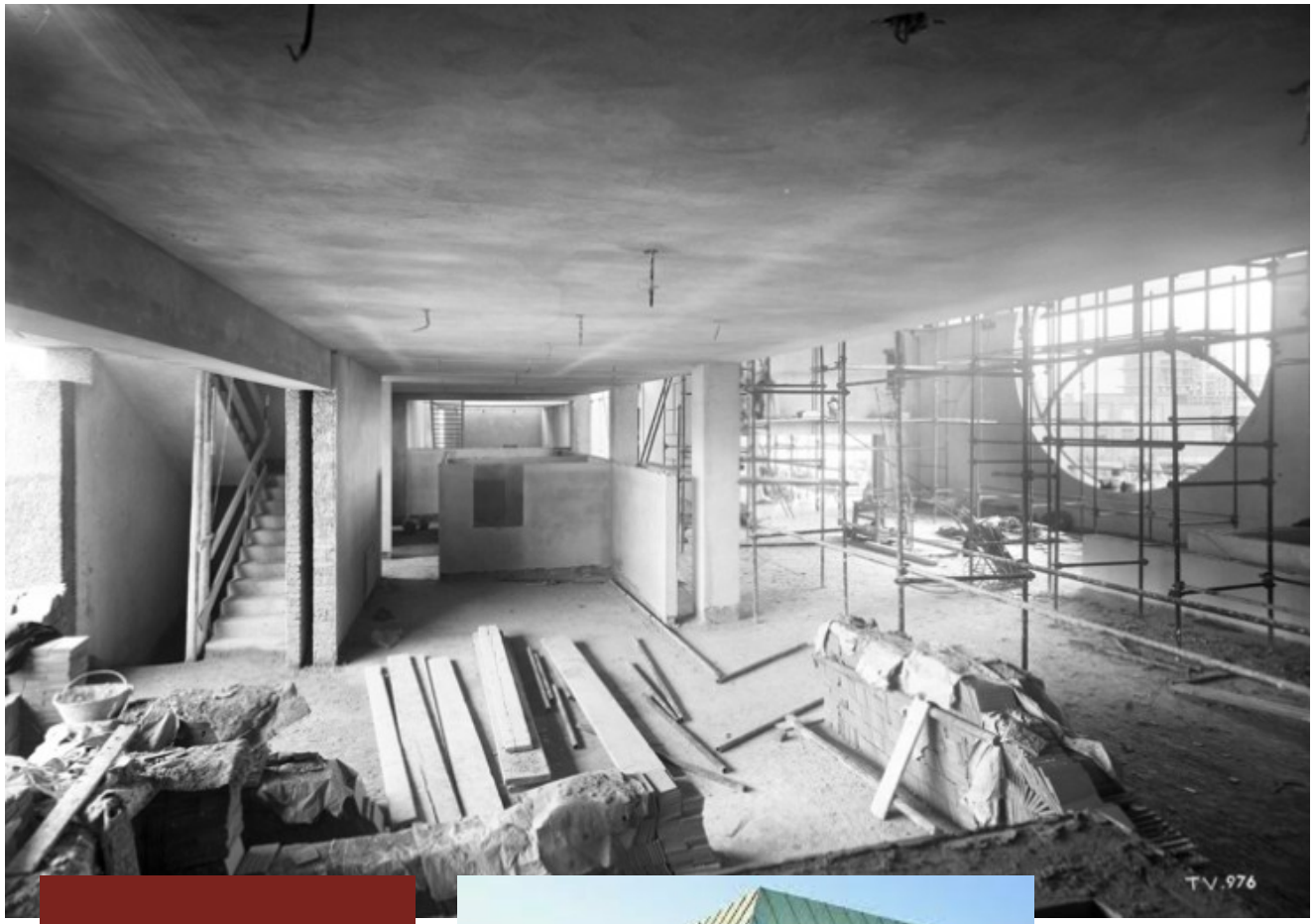
- Large-size steel-glass envelope
- Construction in 1961 in Torviscosa (Udine)
- Museum building / strategic building subjected to crowd







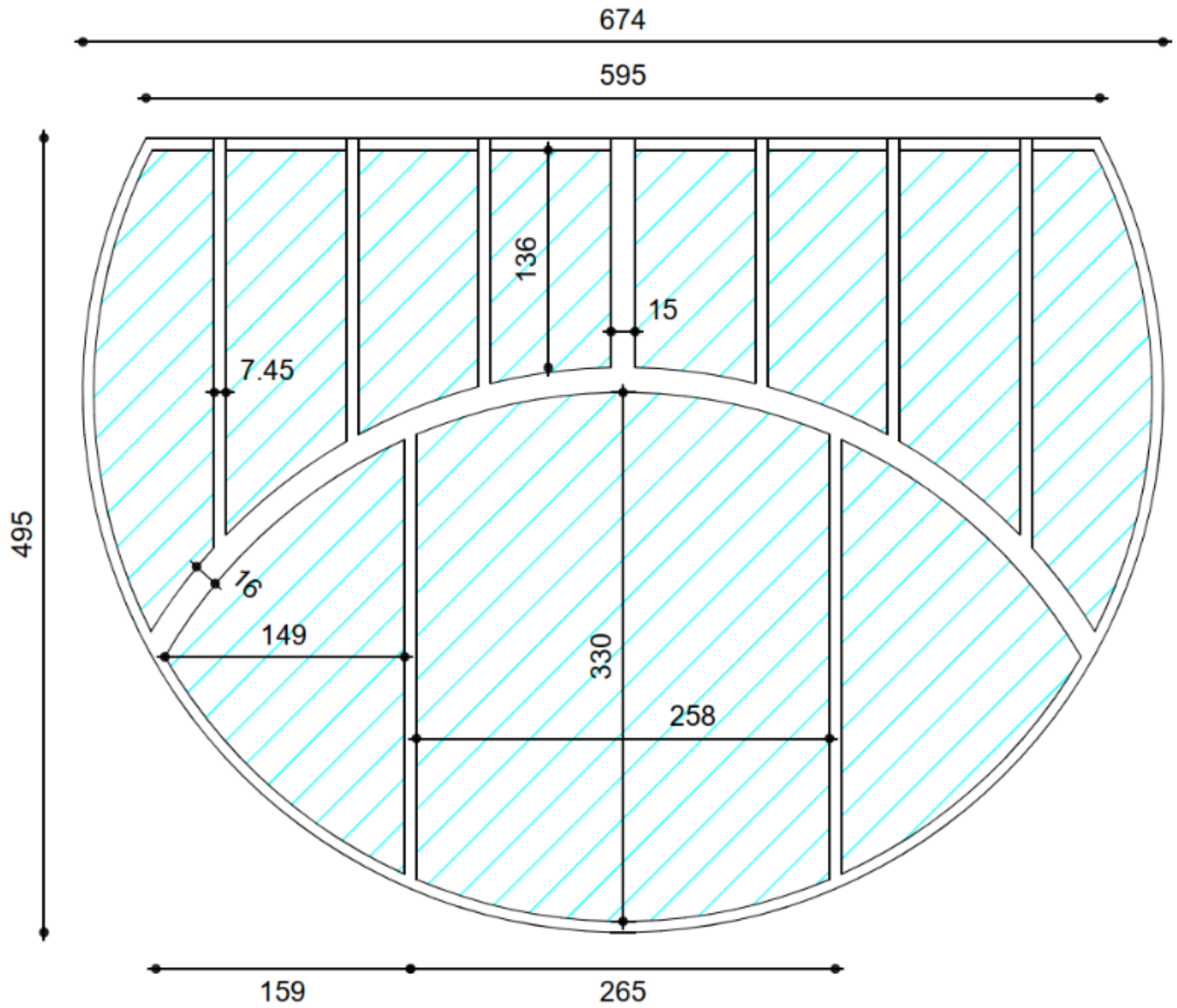
Case-study system

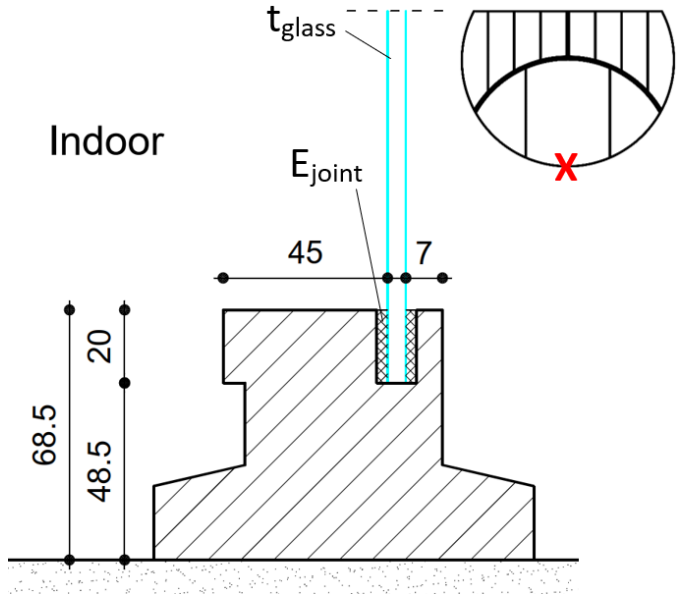


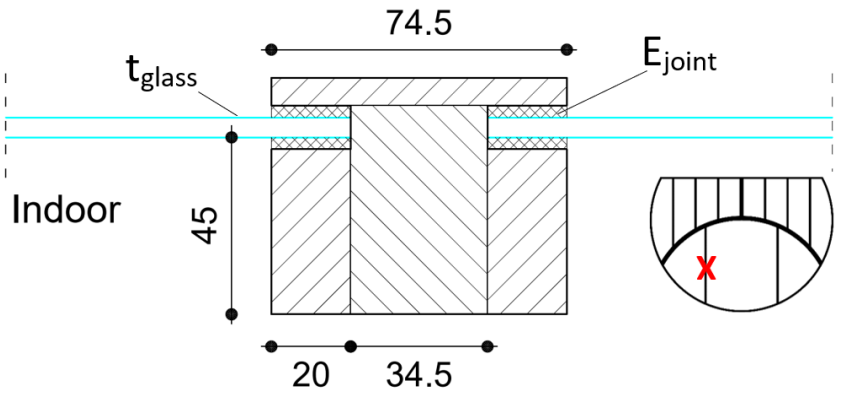


- Lack of design standards and regulations for glass load-bearing members
- Lack of technical drawings, etc.
- Fully monolithic annealed glass panels **(5 mm!!)**
- Material degradation



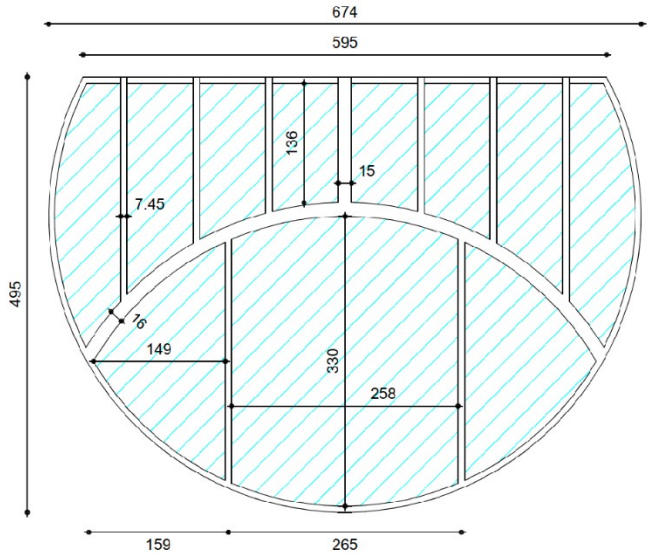

674
595
495
136
15
7.45
76
149
330
258
159
265


t_{glass}
Indoor
E_{joint}
45
7
20
68.5
48.5


74.5
t_{glass}
E_{joint}
Indoor
45
20
34.5

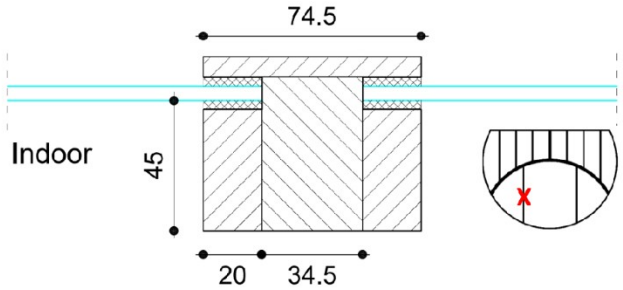
Seismic capacity?



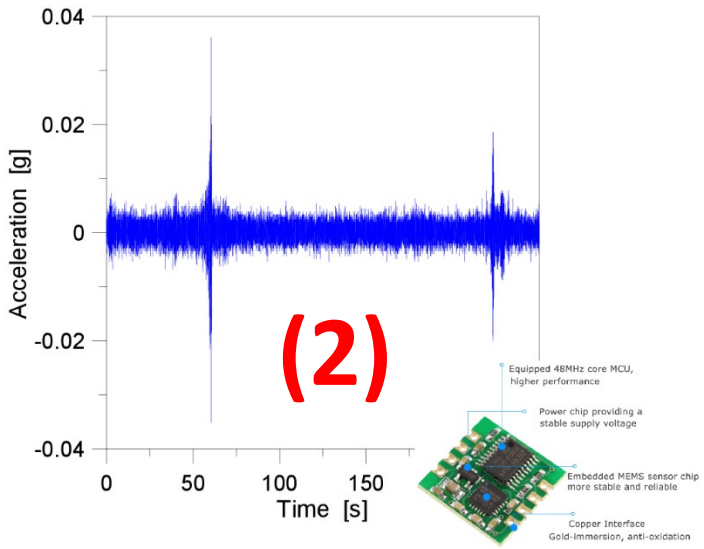




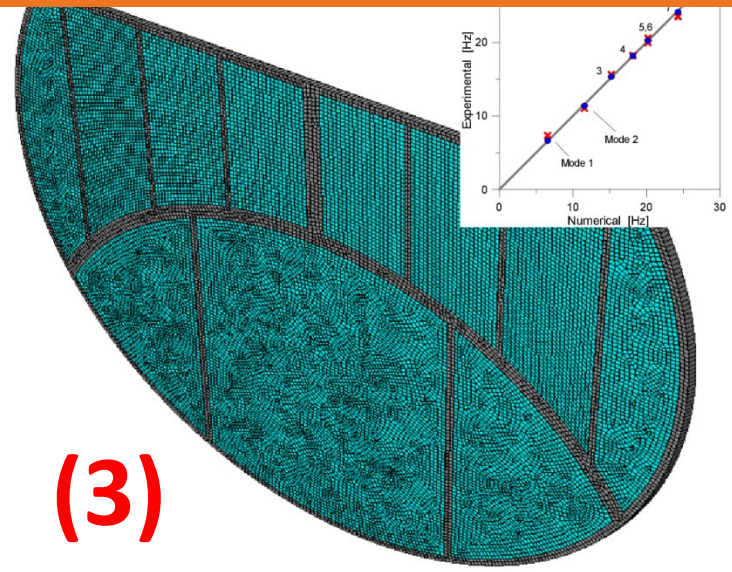
Optimized steps



(1)

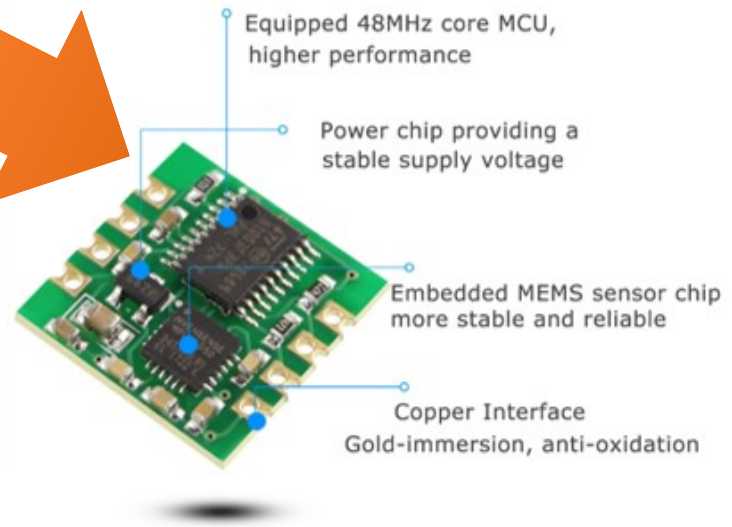


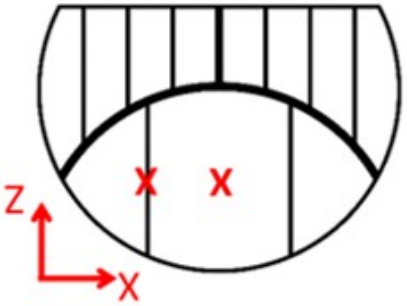
(2)



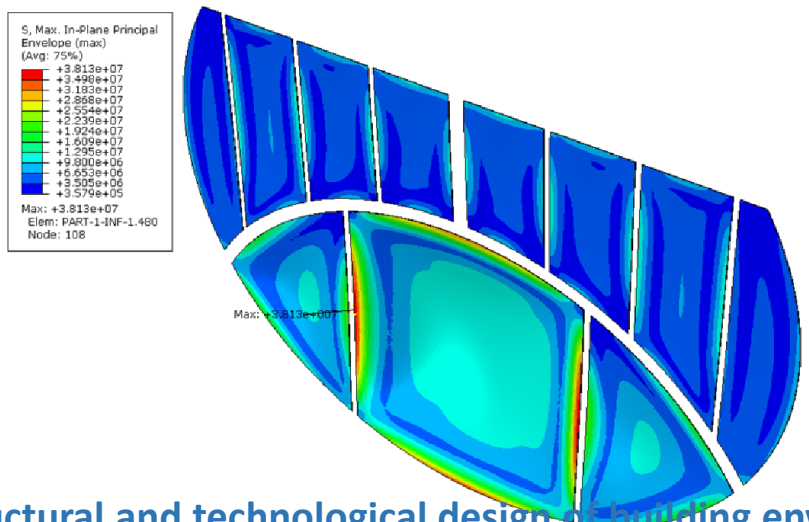
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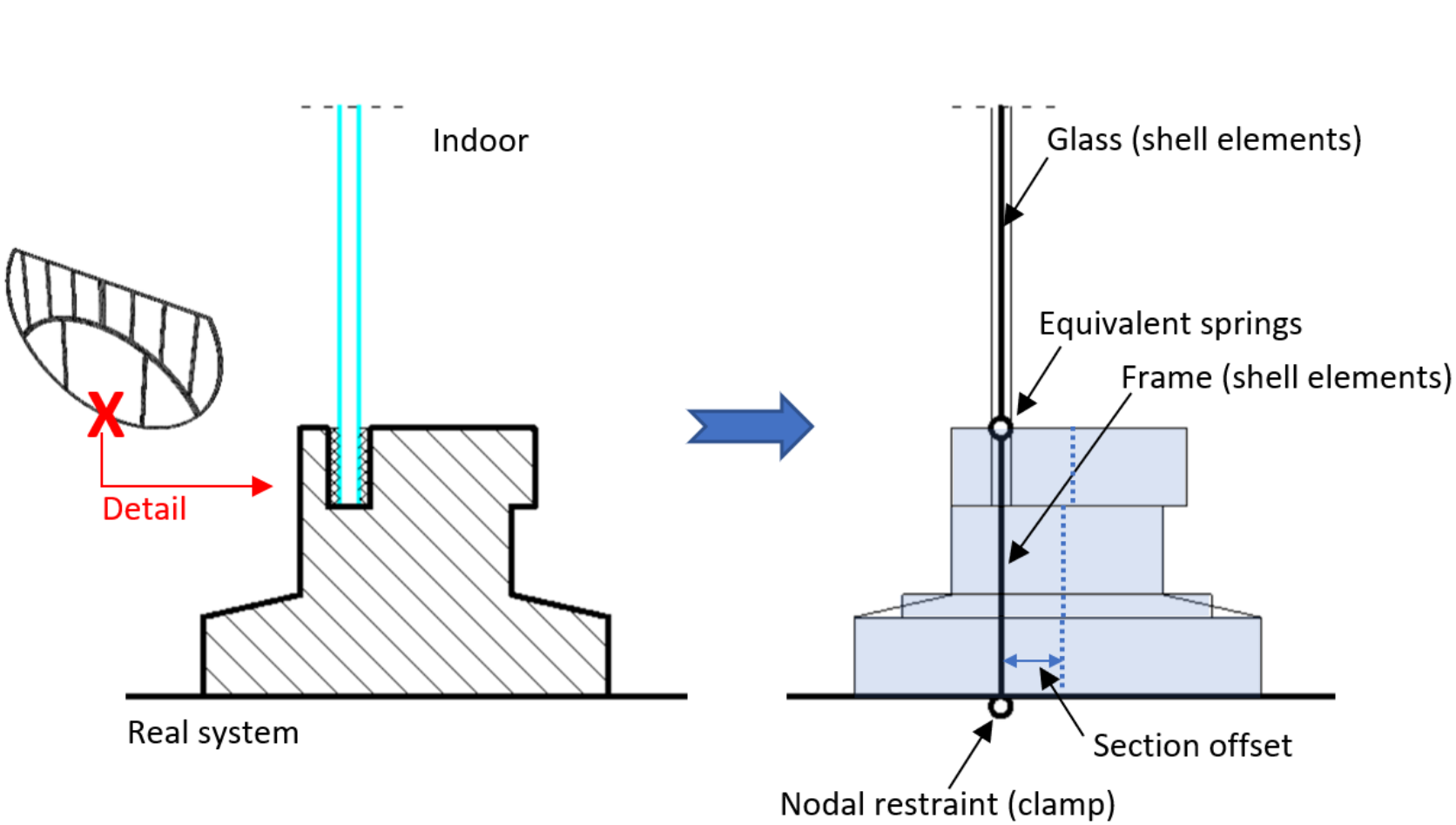

Equipped 48MHz core MCU,
higher performance
Power chip providing a
stable supply voltage
Embedded MEMS sensor chip
more stable and reliable
Copper Interface
Gold-immersion, anti-oxidation

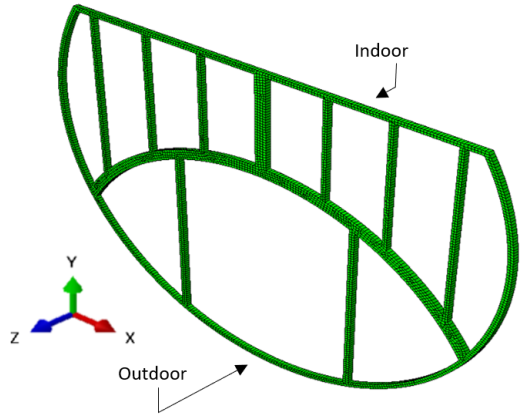

Z
X
X
X

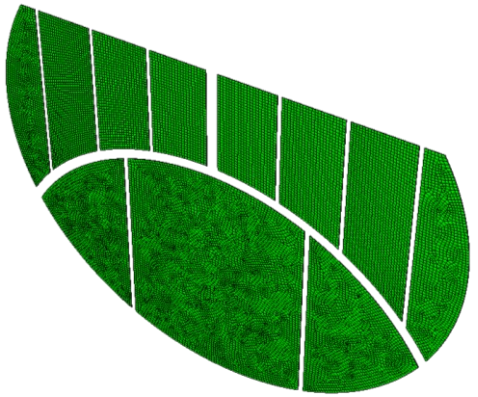

X
Z


S, Max. In-Plane Principal
Envelope (max)
(Avg: 75%)
+3.813e+07
+3.498e+07
+3.183e+07
+2.868e+07
+2.554e+07
+2.239e+07
+1.924e+07
+1.609e+07
+1.295e+07
+9.800e+06
+6.652e+06
+3.505e+06
+3.579e+05
Max: +3.813e+07
Elem: PART-1-INF-1.480
Node: 108

Modelling


Indoor
Detail
Real system
Glass (shell elements)
Equivalent springs
Frame (shell elements)
Section offset
Nodal restraint (clamp)

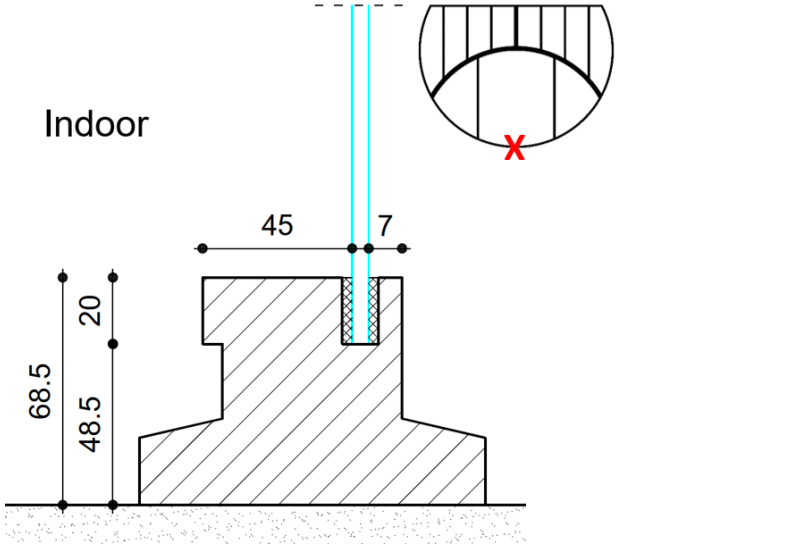

Indoor
Y
Z
X
Outdoor

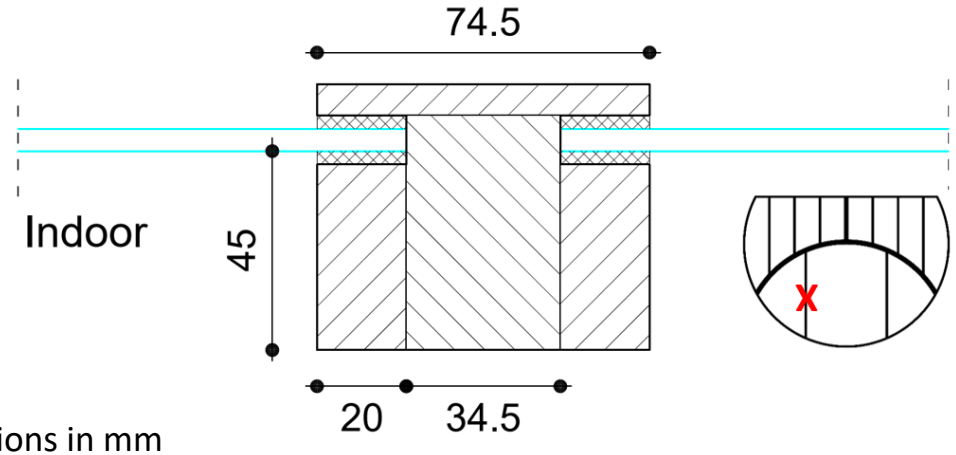


In-field experimental analysis

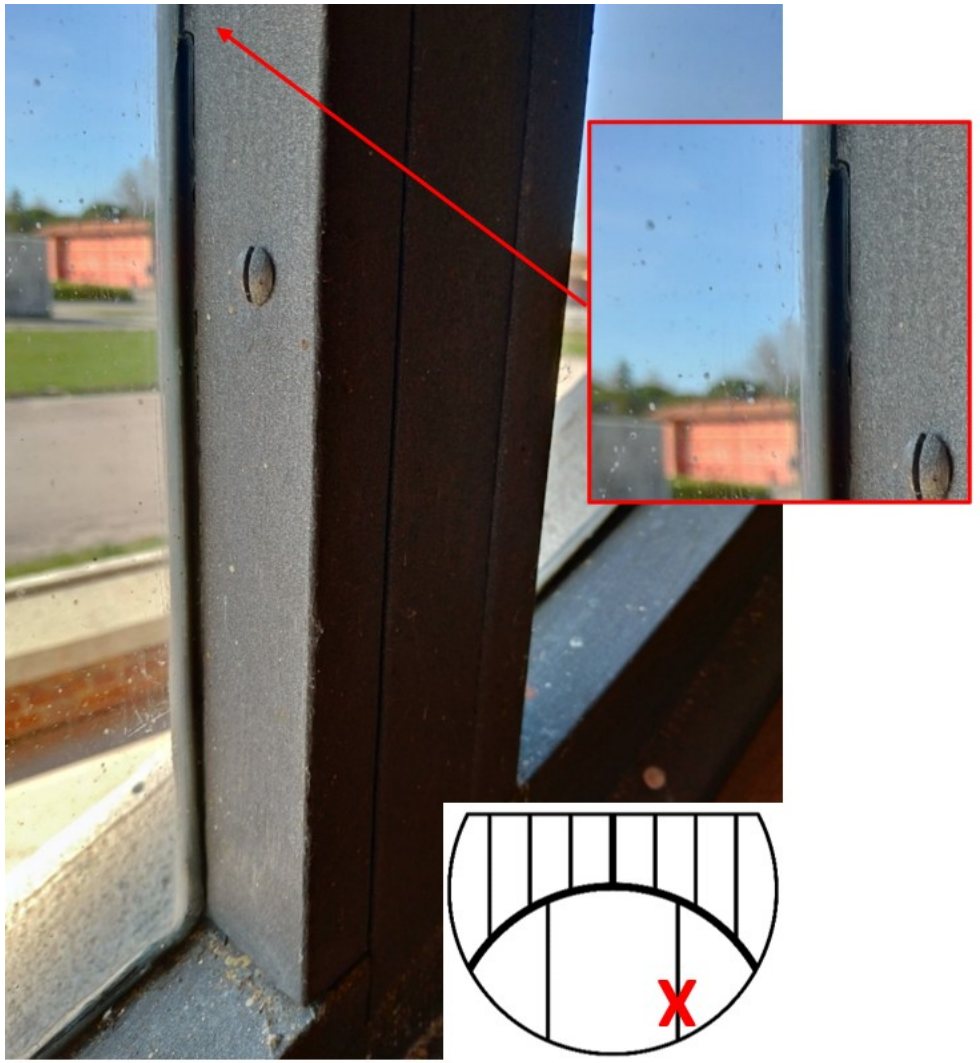
(1)

On-side inspection and diagnostic investigation

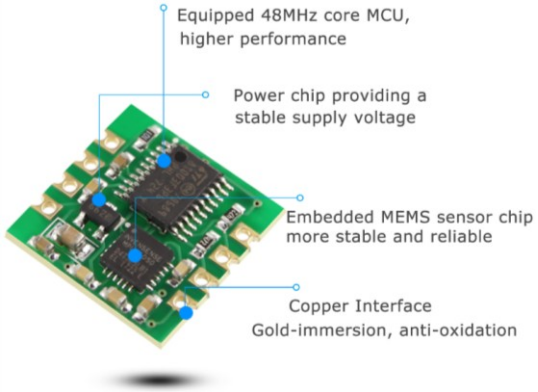


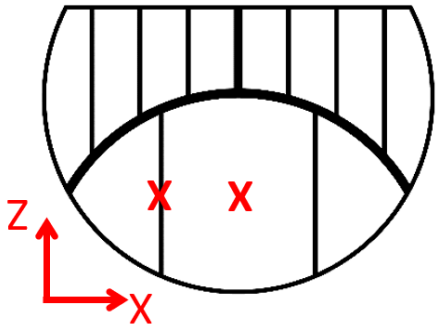


Dimensions in mm



In-field experimental analysis (2)

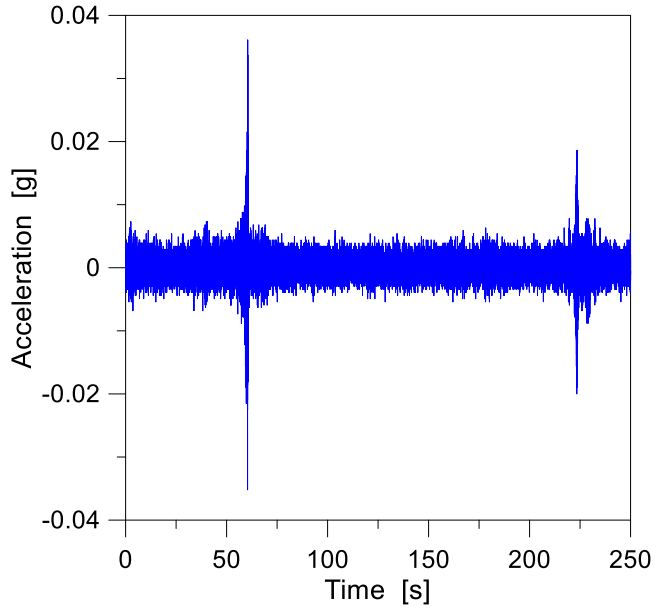




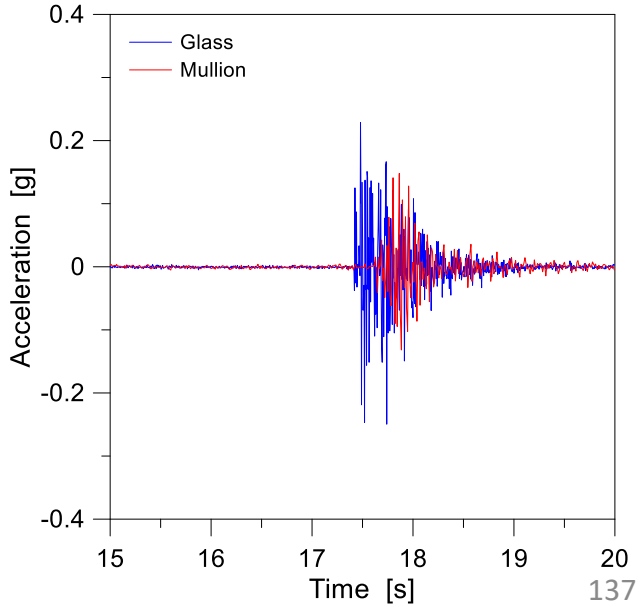


- Wi-Fi triaxial MEMS accelerometers
- Multiple acquisitions on glass and on frame
- 200 Hz sampling rate

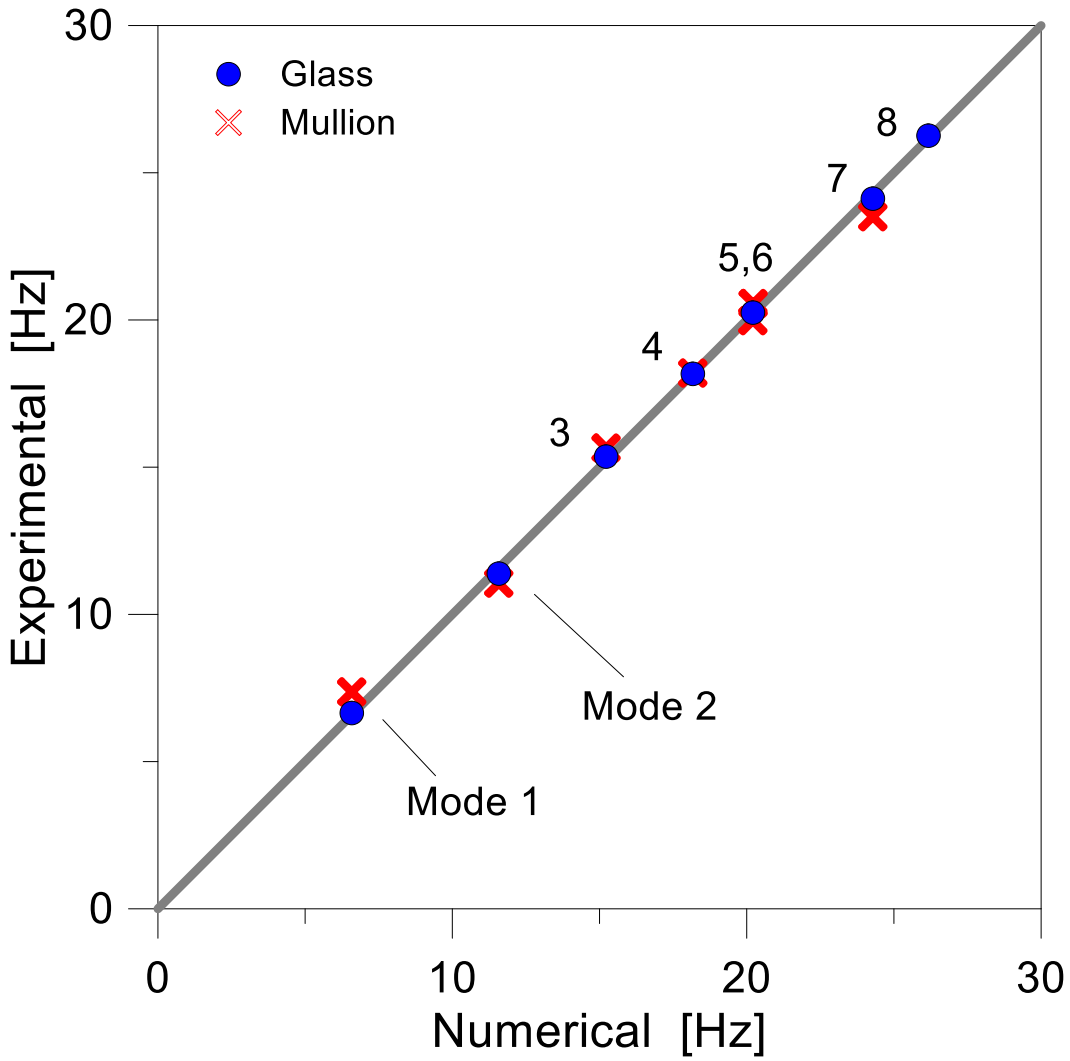
Ambient vibrations



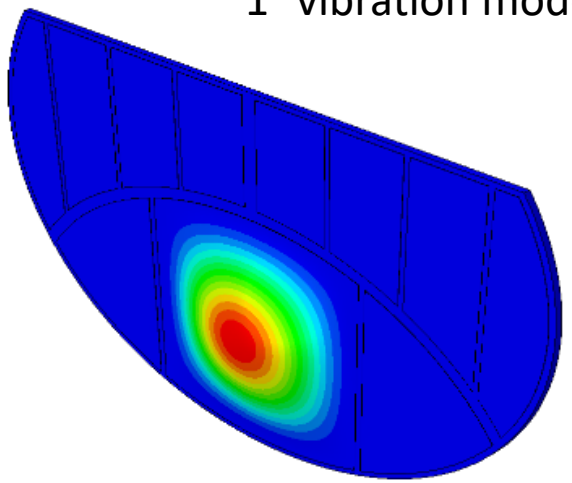
Soft-body impact



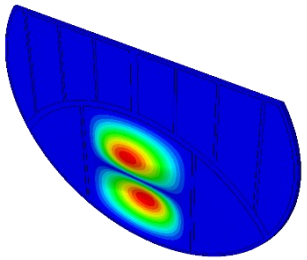
In-field experimental analysis & dynamic identification (3)



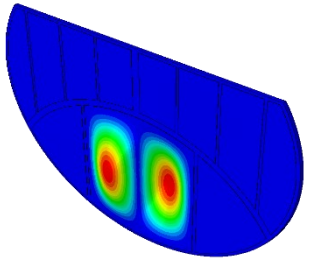
Finite Element numerical analysis in ABAQUS/Standard



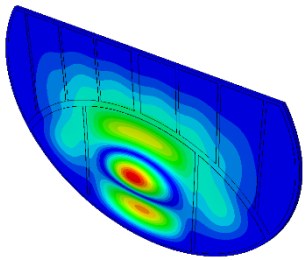
1° vibration mode



2° vibration mode

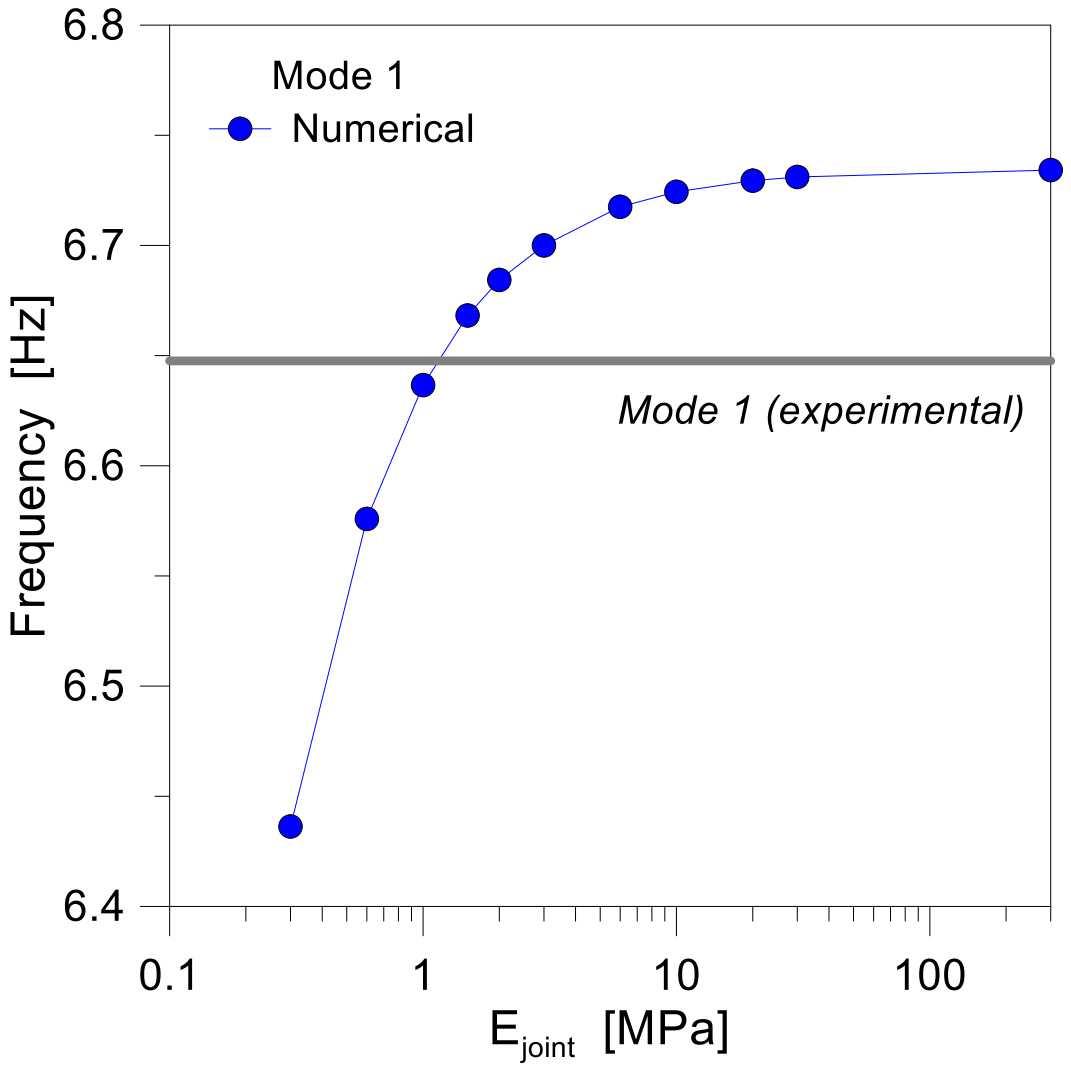


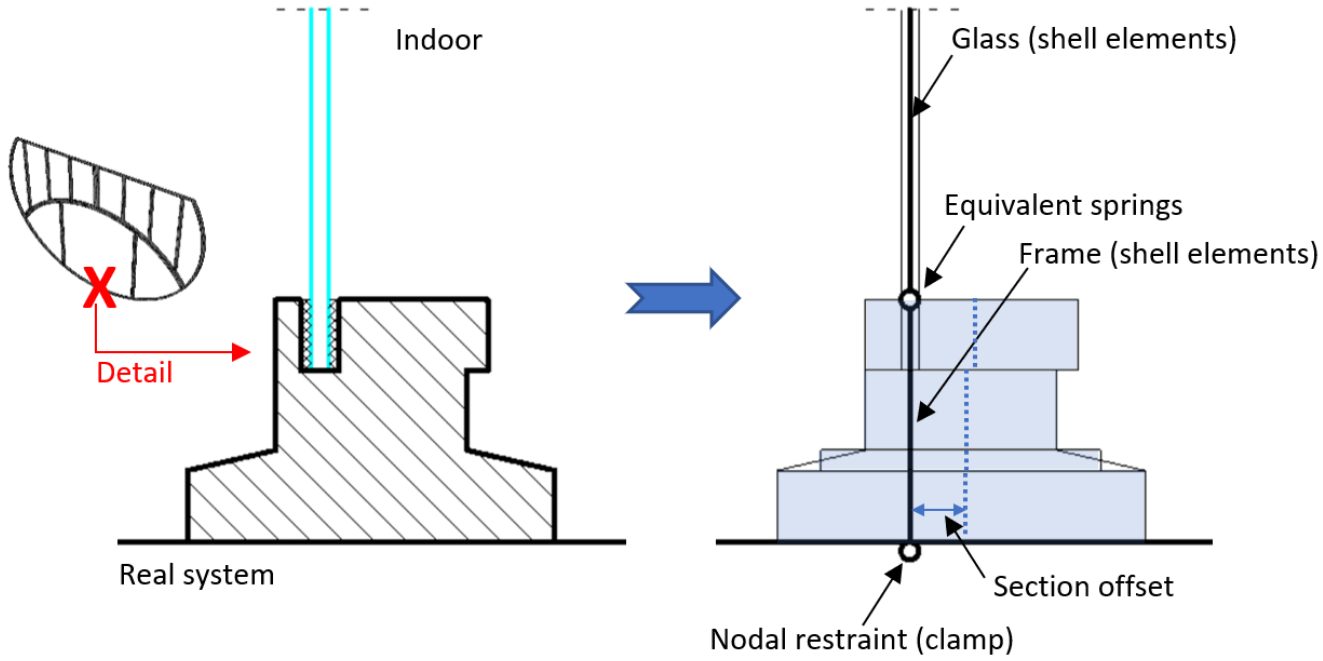
3°



4°

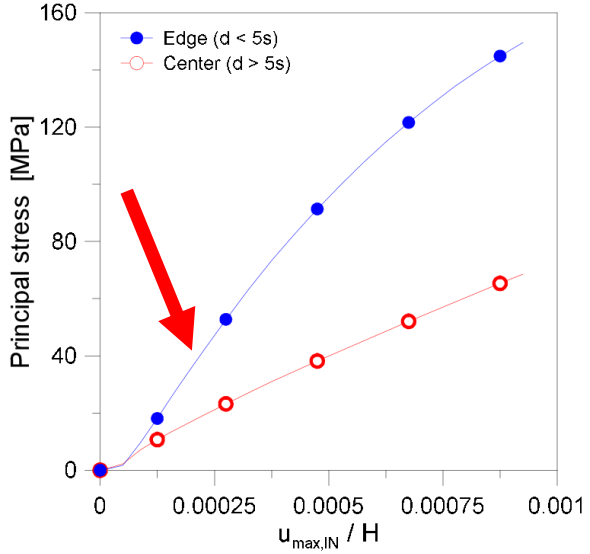
In-field experimental analysis & dynamic identification



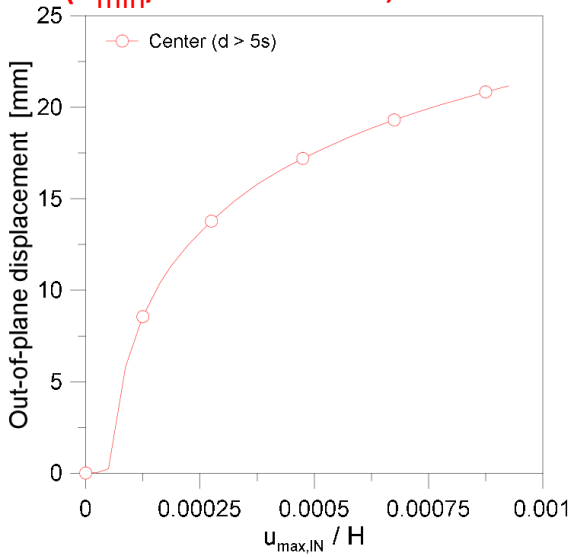


Seismic analysis

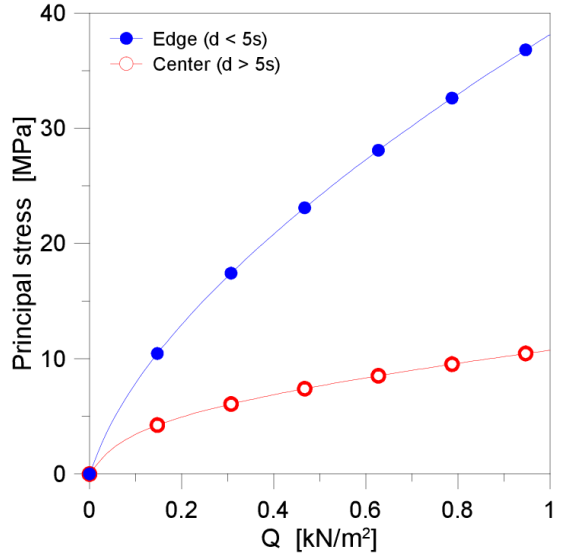
Min(L_{min}/60= 43 mm; or 30 mm)



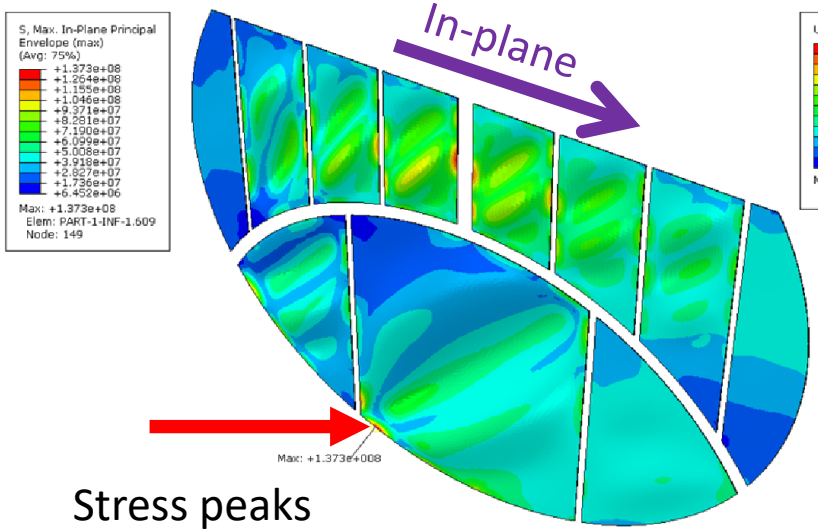
(a)



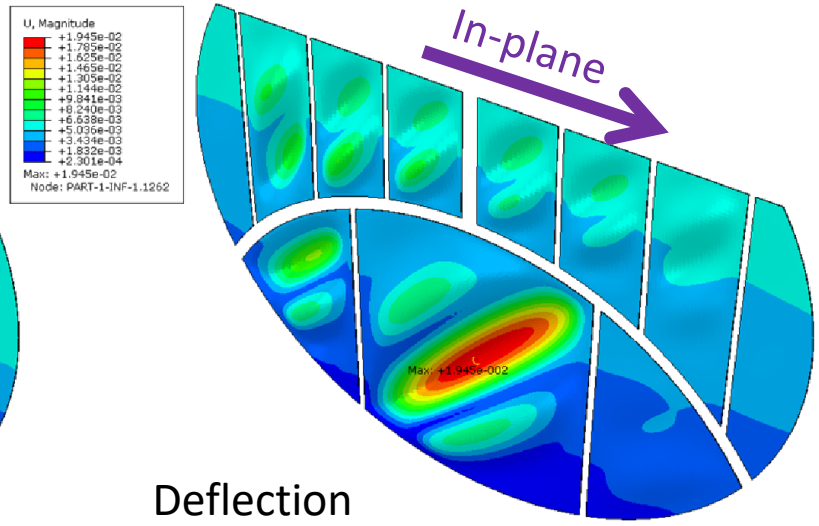
(b)



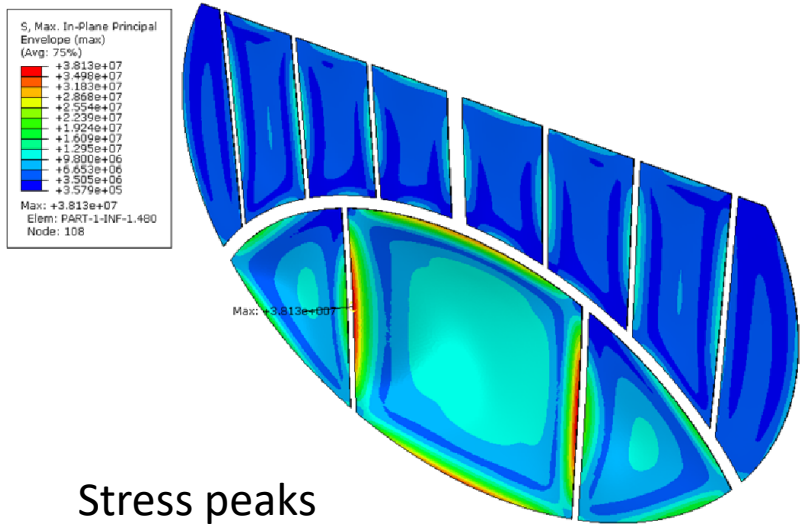
(c)



Stress peaks

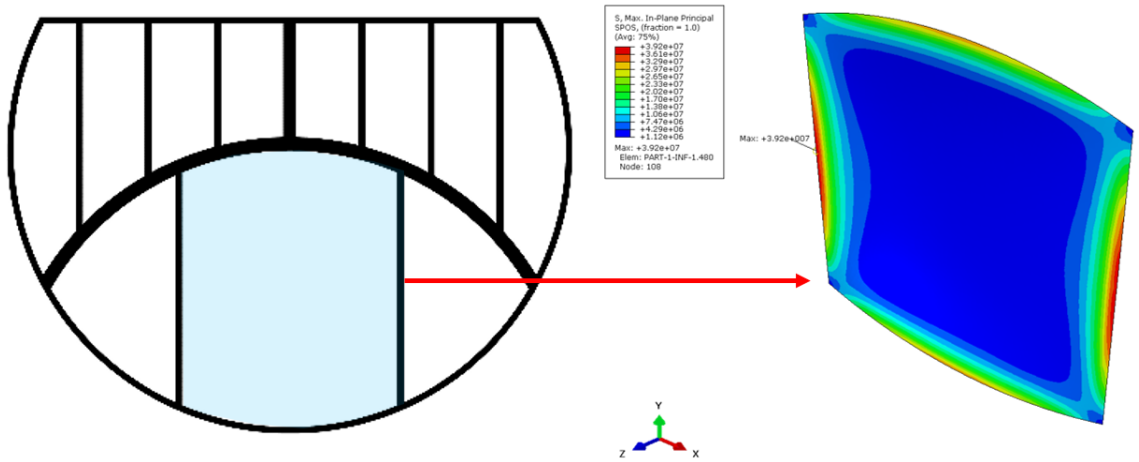


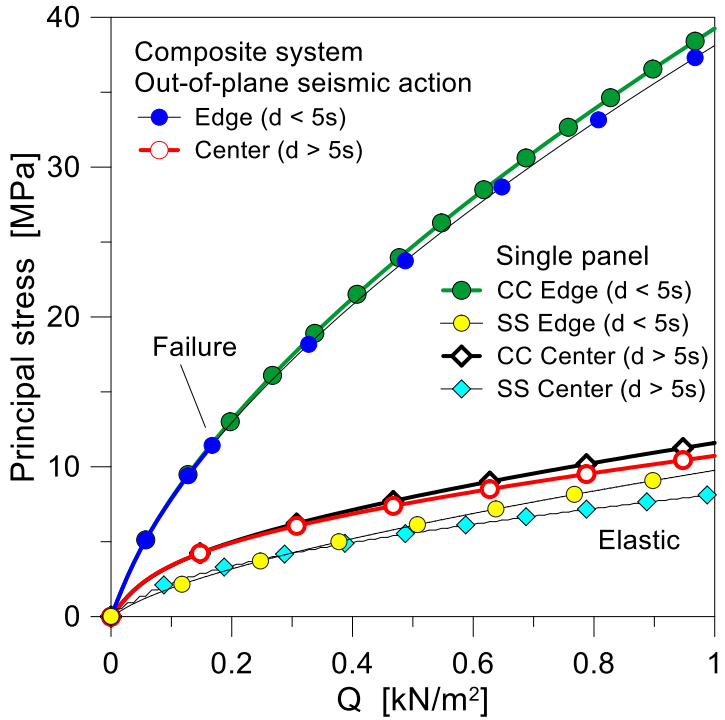
Deflection

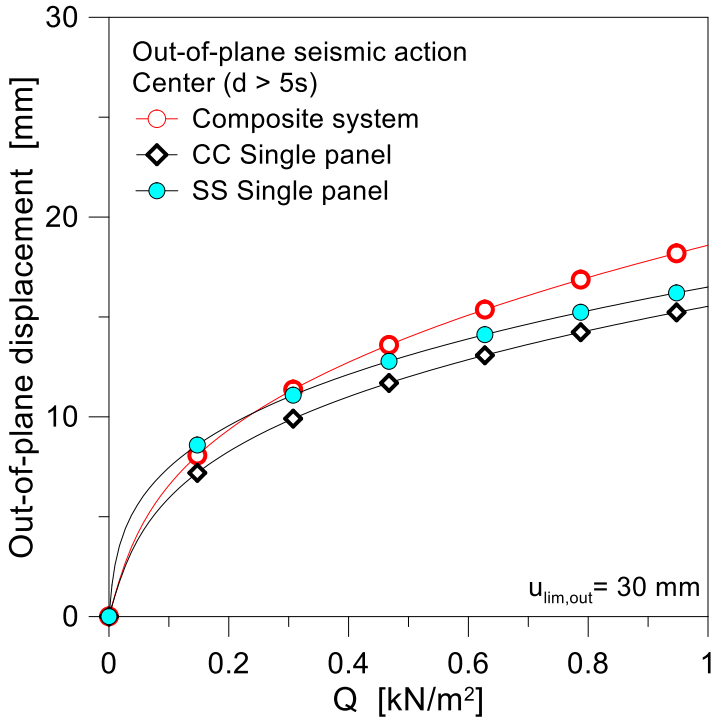


Stress peaks

Analysis and verification







Analysis and verification

Table 2
Summary of stress and deflection verifications for the central glass panel under out-of-plane seismic action (ABAQUS/Standard).

FE model	Stress				Deflection	
	$d < 5s$		$d > 5s$			
	Failure	$\sigma_{Ed,max}/f_{g;d}$	Failure	$\sigma_{Ed,max}/f_{g;d}$	Failure	$u_{max}/u_{lim,out}$
Composite glass-steel envelope	Yes	1 for Q = 0.148 kN/m^2	No	0.755 for Q = 1 kN/m^2	No	0.619 for Q = 1 kN/m^2
Single glass panel (SS restraint)	No	0.965 for Q = 1 kN/m^2	No	0.586 for Q = 1 kN/m^2	No	0.550 for Q = 1 kN/m^2
Single glass panel (CC restraint)	Yes	1 for Q = 0.130 kN/m^2	No	0.837 for Q = 1 kN/m^2	No	0.510 for Q = 1 kN/m^2

