FIRE RESISTANT LAMINATED STRUCTURAL GLASS BEAMS

P5 Graduation Presentation
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7th of November 2018

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Deligate Examiner: Dr. Nelson Mota

PRESENTATION CONTENT

1. INTRODUCTION TO STRUCTURAL GLASS
2. CURRENT BUILDING REGULATIONS
3. RELEVANT RESEARCH
4. EXPERIMENTAL TESTING
5. CONCLUSIONS
6. DESIGN RECOMMENDATION & APPLICATION
7. RECOMMENDATIONS

DEMATERIALISATION OF BUILDING SKIN & MATERIAL

First glass windows (79 AD)

Figure: Cast glass window pane fragments from Pompeii Naples - Archaeological Museum

Source: https://www.flickr.com/photos/70125105@N06/7682216182

Full glass skin (1887)

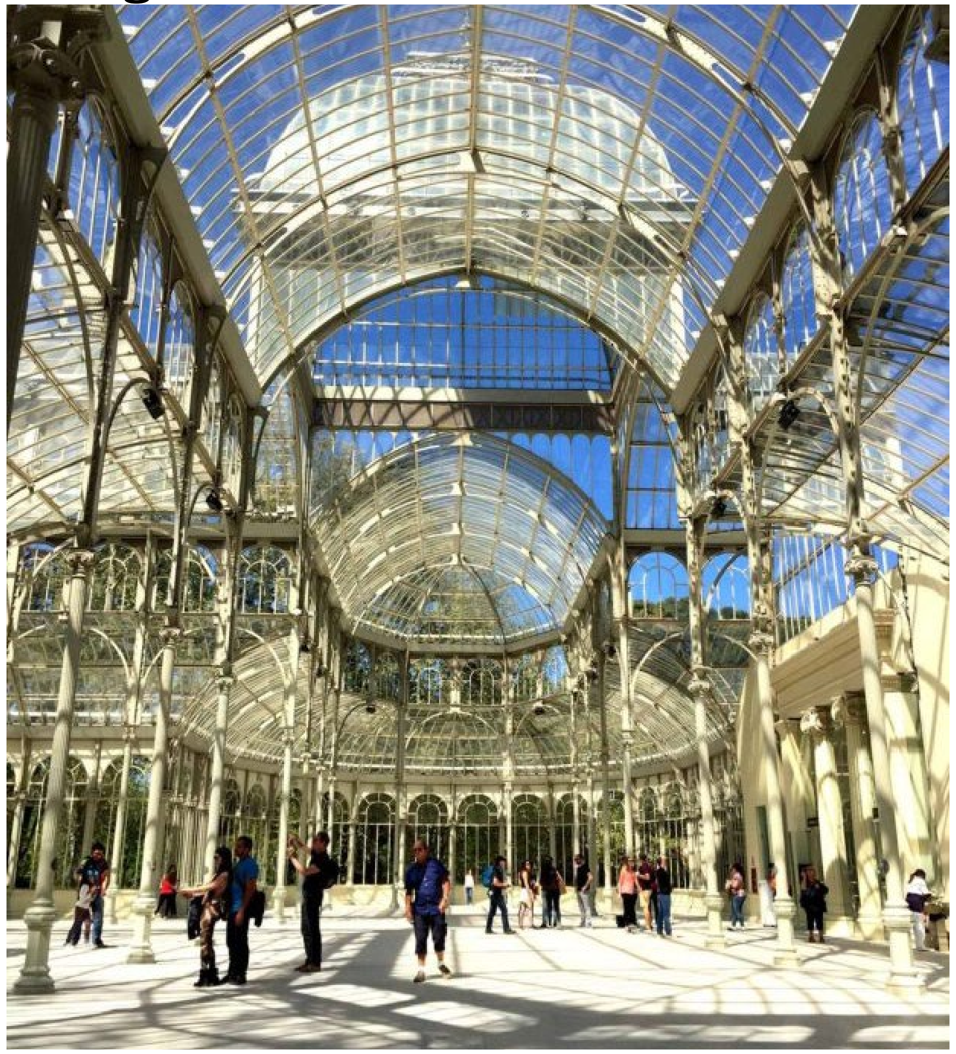


Figure: Crystal Palace - Madrid

Source: https://i0.wp.com/theweekendguide.com/wp-content/uploads/2017/07/crystal-palace-madrid-e1507126389143.jpg?w=619&h=825&crop

Structural glass (2005)

Figure: Laminated glass column - Danfoss - New York

Source: http://www.annebagger.dk/CustomerData/Files/Images/Gallery/glass-columns-danfoss-2005_2891/6_2297.jpg

GLASS AS STRUCTURAL MATERIAL

Cast structural glass

Figure: Chanel Amsterdam Boutique - Amsterdam
https://www.deingenieur.nl/artikel/glazen-pui-aan-de-pc-hooft

Laminated structural glass

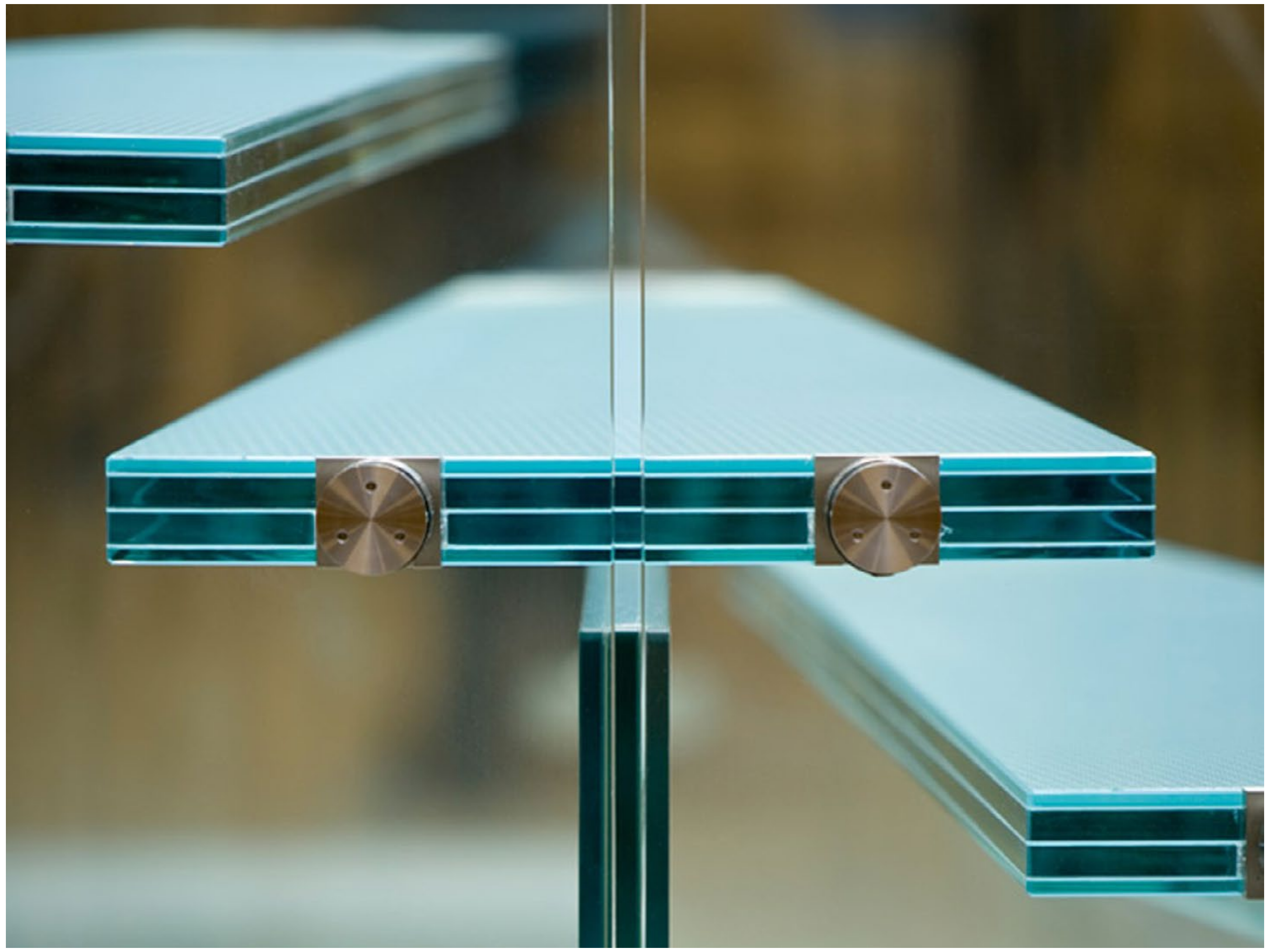


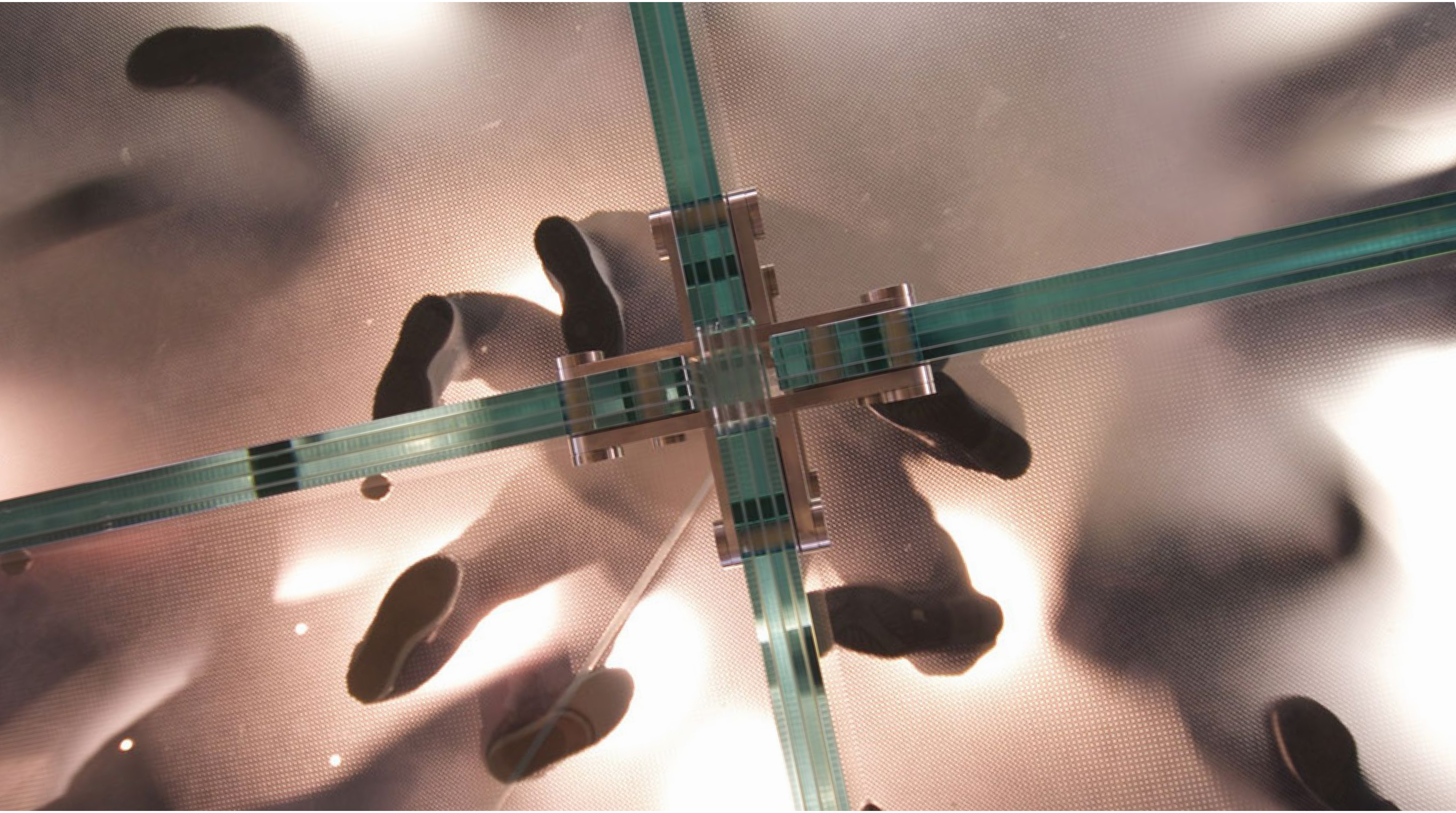
Figure: Apple Retail Store 5th Avenue - New York
http://architizer-prod.imgix.net/mediadata/projects/212011/e093cba1.jpg?q=60&auto=format,compress&cs=strip&w=1680

LAMINATED STRUCTURAL GLASS

Source: Peter Aaron - Apple Cube II, Manhattan

VISION

MY VISION



Source: Eckersley O'Callaghan - Apple, Paris

MAIN RESEARCH QUESTION

*“ In what way can a laminated structural glass beam be **detailed** in such a way that it keeps the **aesthetic transparency** of glass, while being able to withstand **a fire load** during **30 minutes?**”*

RESEARCH SUB-QUESTIONS

" In what way can a laminated structural glass beam be detailed in such a way that is keeps the aesthetic transparency of glass, while being able to withstand fire loading of 30 minutes?"

1. ***"What are the requirements set by building regulations?"***
2. ***"What research has been done and what are the conclusions?"***
3. ***"What is the possible explanation for the different behaviour in thermally treated and non-treated glass beams?"***
4. ***"What application presents itself when structural glass can be implemented as fire resistant building component?"***

BUILDING REGULATIONS

FIRE SAFETY AND FIRE RESISTANCE

BOUWBESLUIT 2012

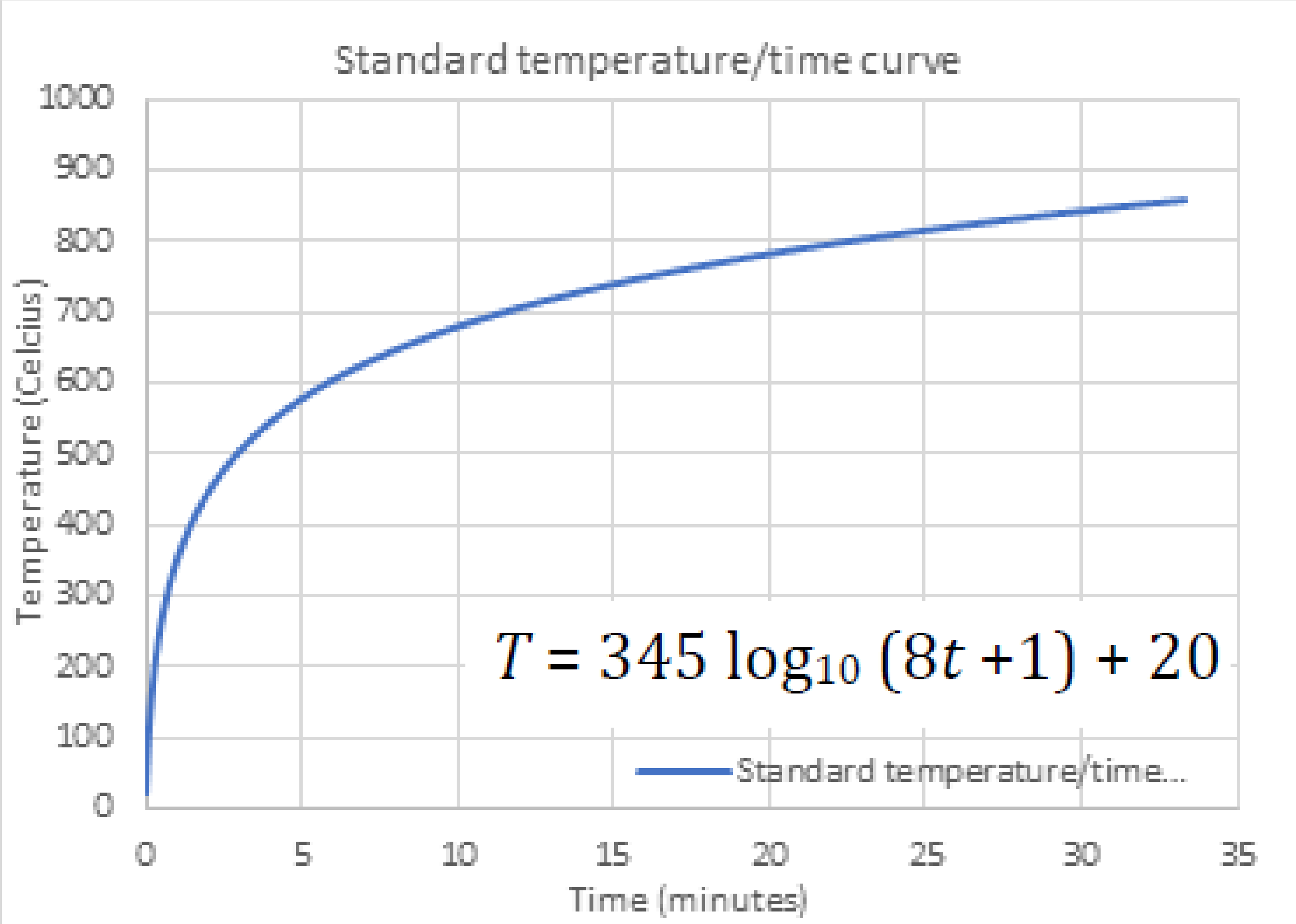
MINIMUM EVACUATION TIME OF BUILDING COMPARTMENTS

INTERNAL FIRE LOAD < 500 MJ/m^2

~ 30 MINUTES

Standard temperature time curve

NEN-EN 13501-2 ;2016



FLEXURAL LOADED ELEMENTS

NEN-EN 1363-A ;2012

FAILURE CRITERIA:

LIMITING DEFLECTION $$D = \frac{L^2}{400\,d}\,mm$$

LIMITING RATE OF DEFLECTION $$\frac{dD}{dt} = \frac{L^2}{9000\,d}\,mm/\mathrm{min}$$

RELEVANT RESEARCH

IMPORTANT & RELEVANT CONCLUSIONS

Christian Louter

*"The **order of failure** is in order of the residual pre-stress from **thermal treatement**. Annealed, heat-strengthened, followed by fully tempered"*

Michaël Debuysser

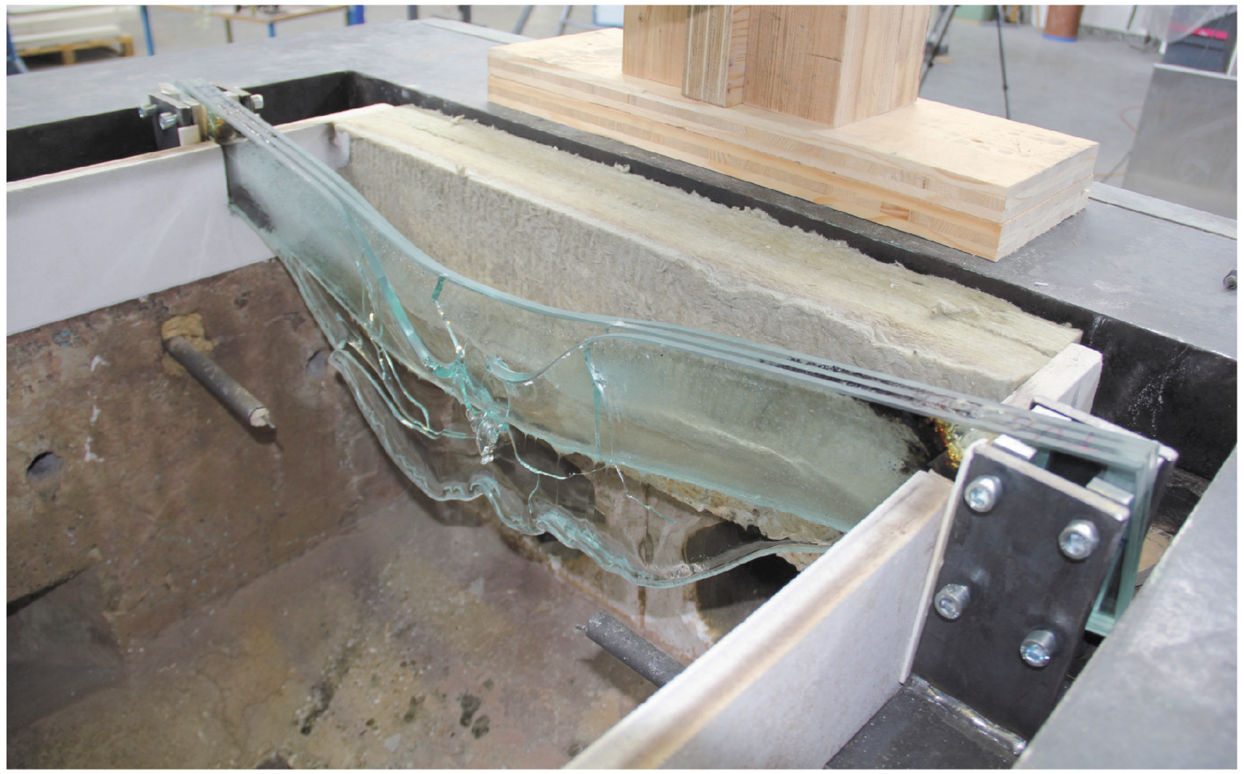
*"In **PVB** laminate gas formation started around 90˚C and for a **SentryGlas** laminate this took place at 150˚C."*

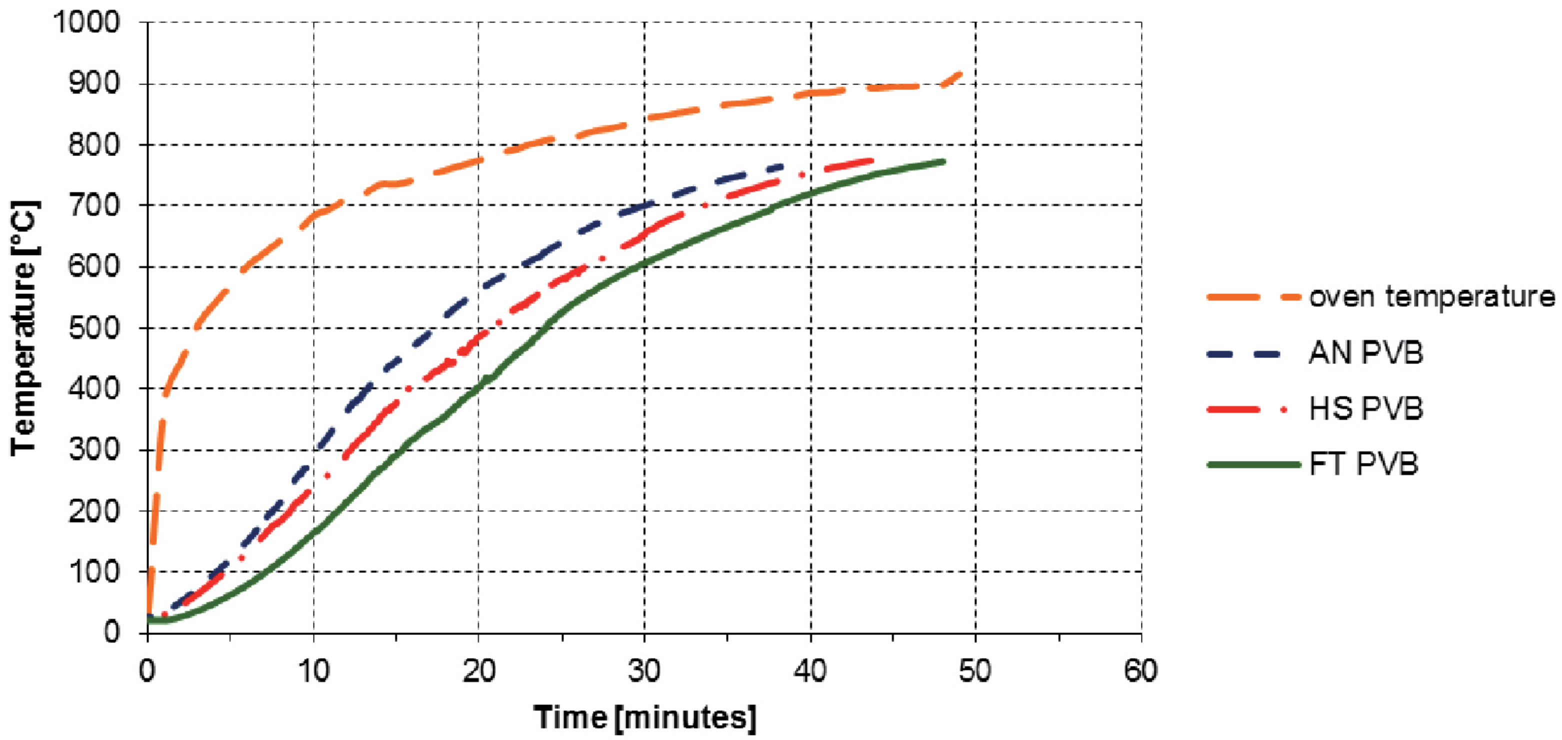
Fred Veer

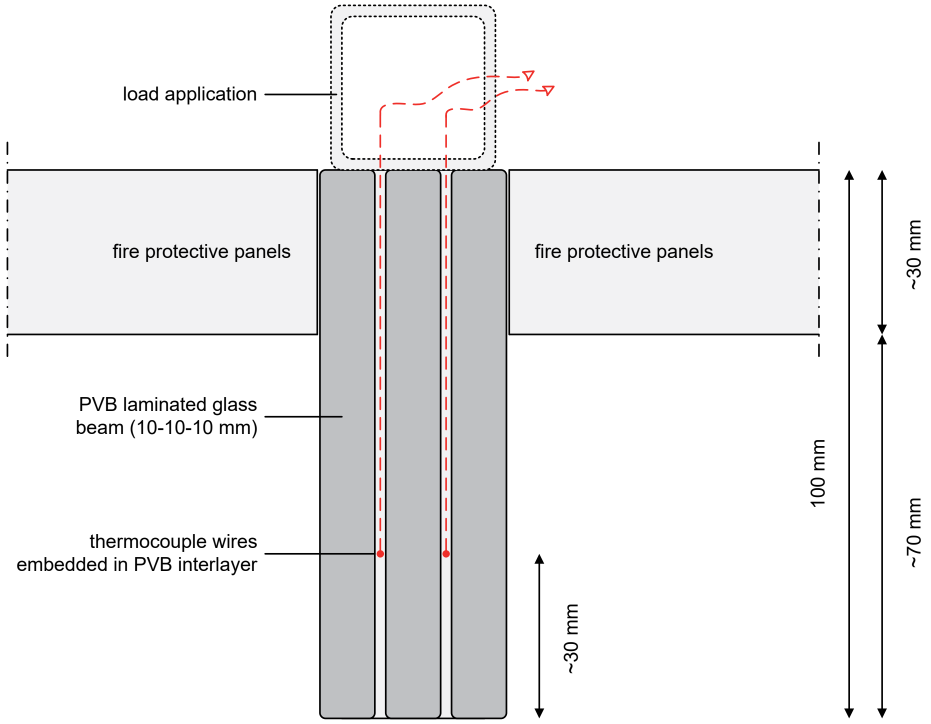
*"The use of **intumescent paint** reduces the heat build-up and thus **slows down** the development of thermal strain in the glass and on the adhesive layer"*

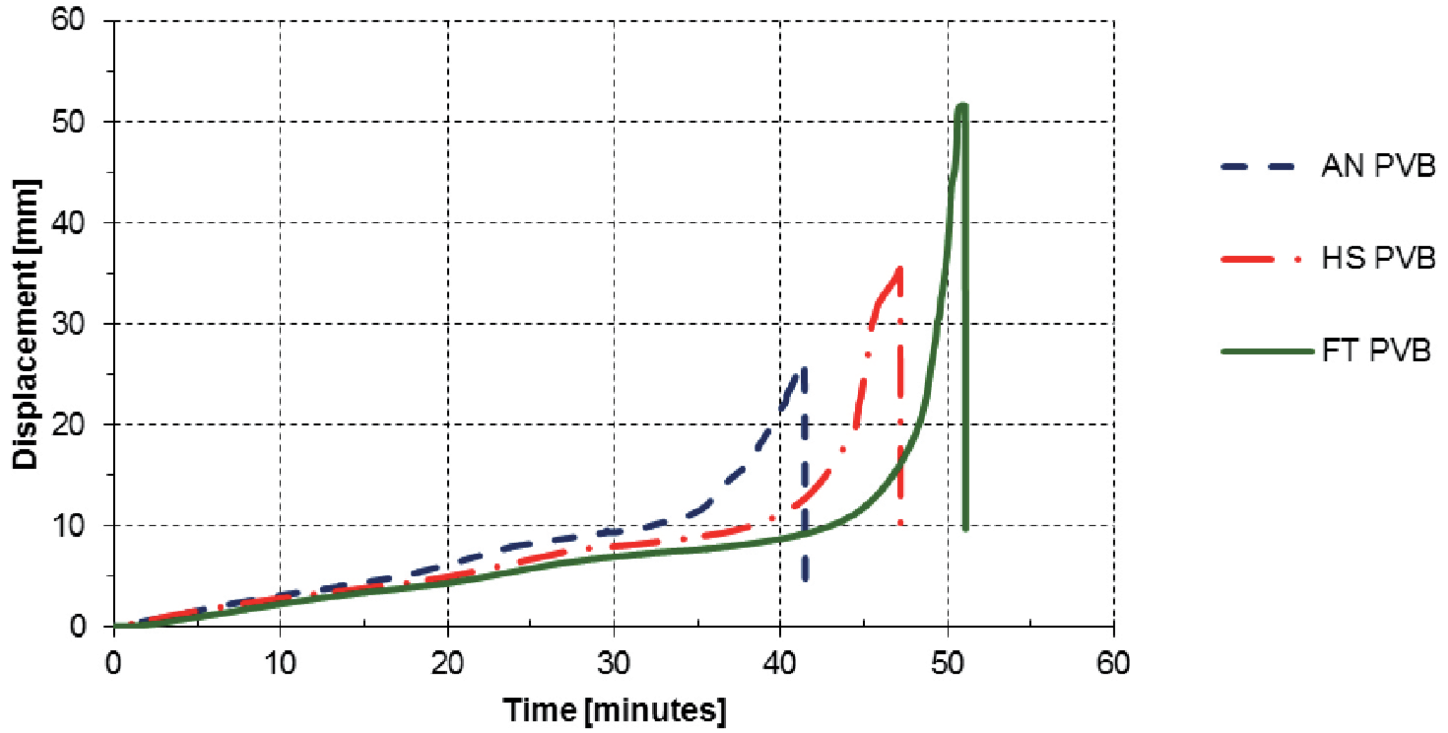
FIRE TESTING OF STRUCTURAL GLASS BEAMS

~DR. CHRISTIAN LOUTER & ALAIN NUSSBAUMER









Source: Fire testing of Structural Glass Beams - Dr. Louter & Nussbaumer

FOLLOW UP OF THE EMPA TEST

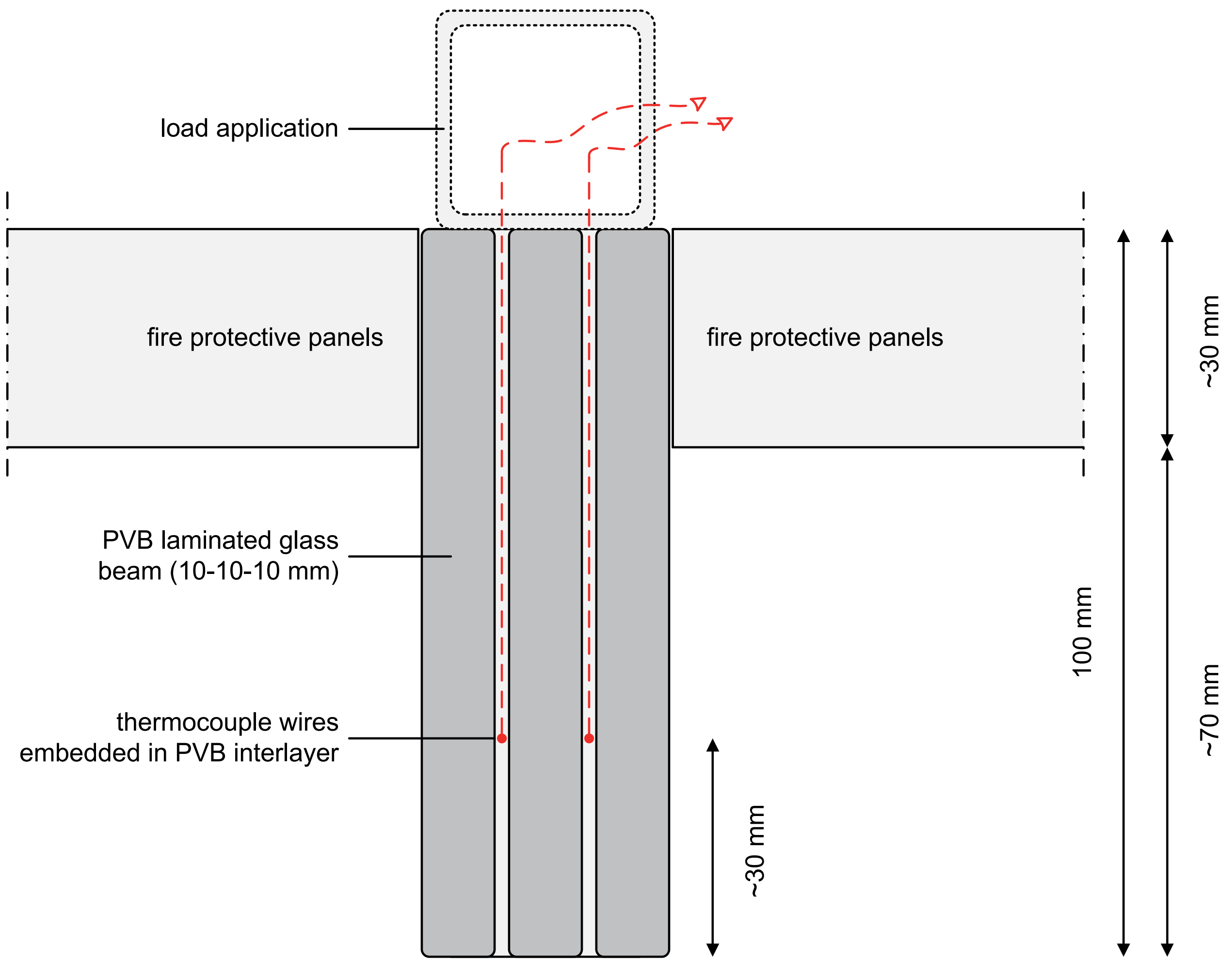


Figure: Beam configuration during EMPA test with protected top of flange
Source: Fire testing of structural glass beams - Dr. Louter and Nussbaumer

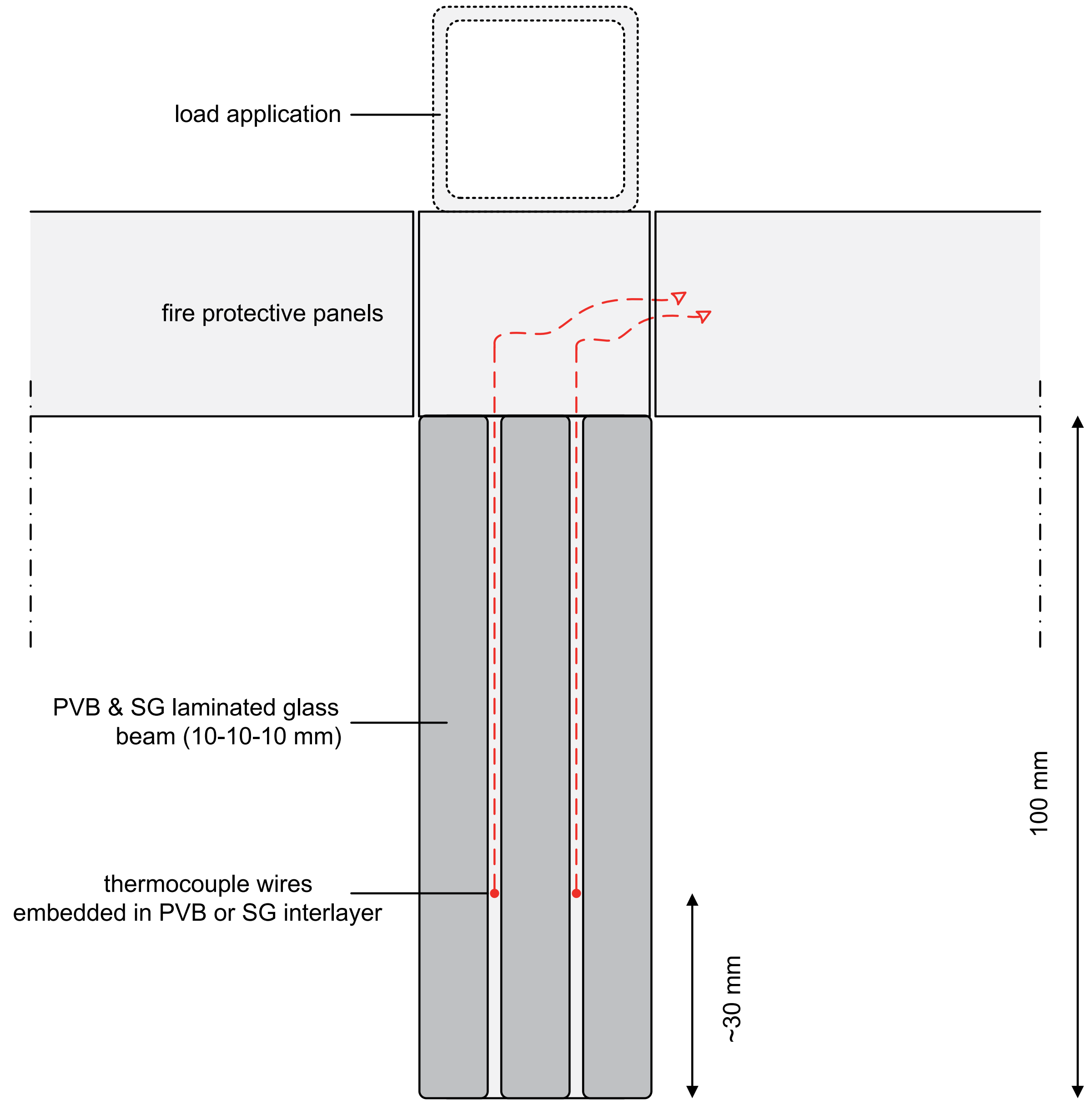
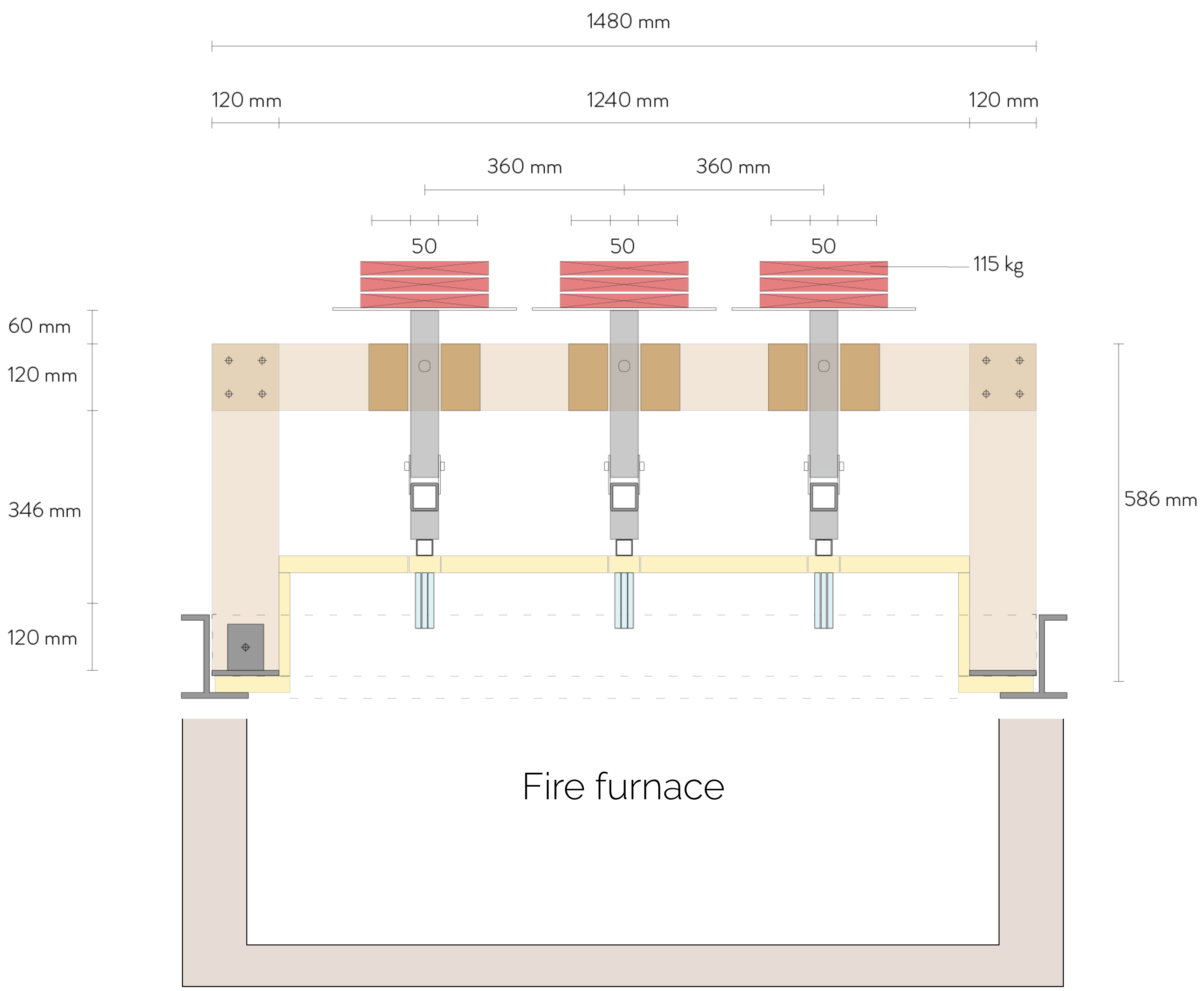
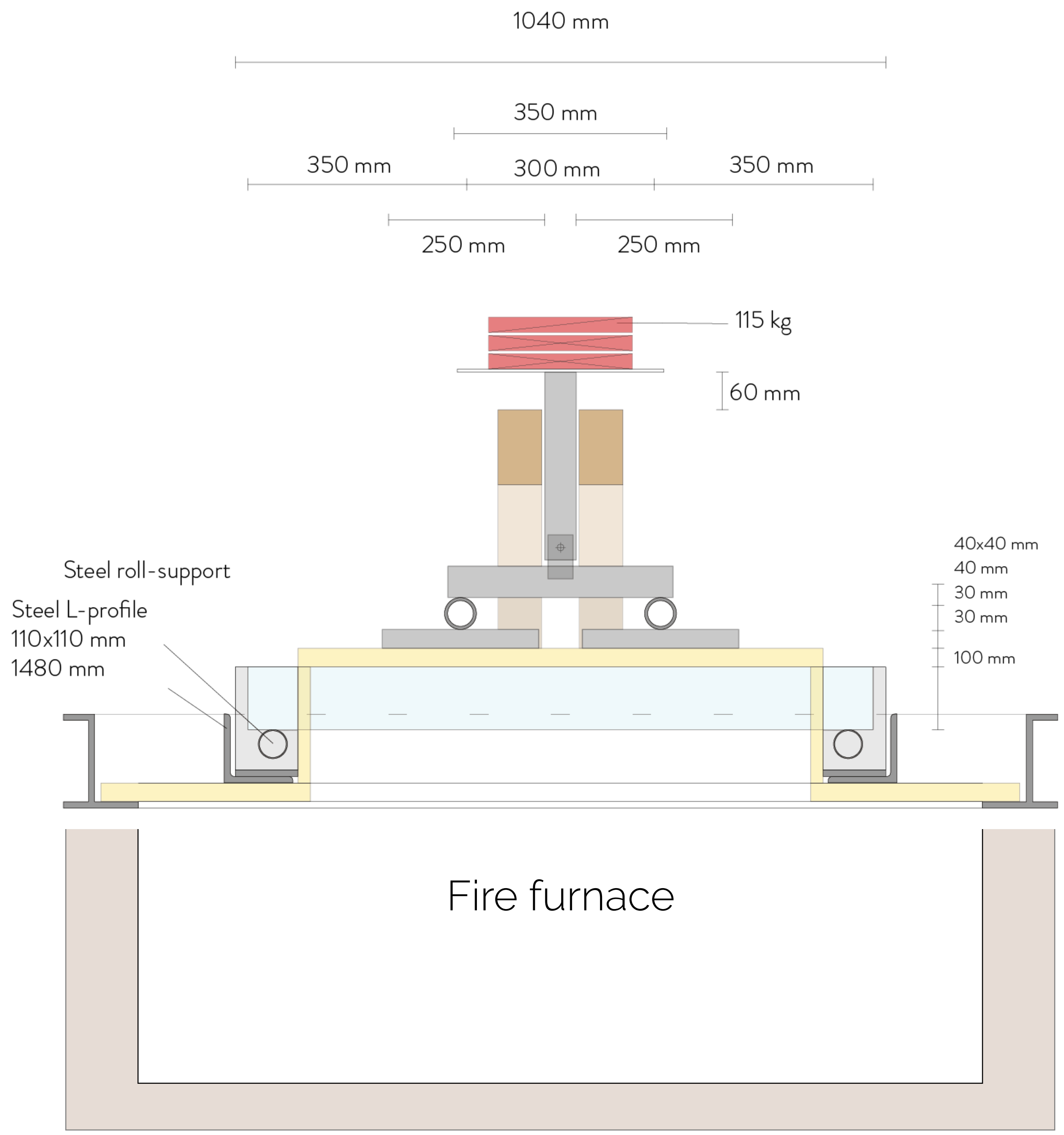


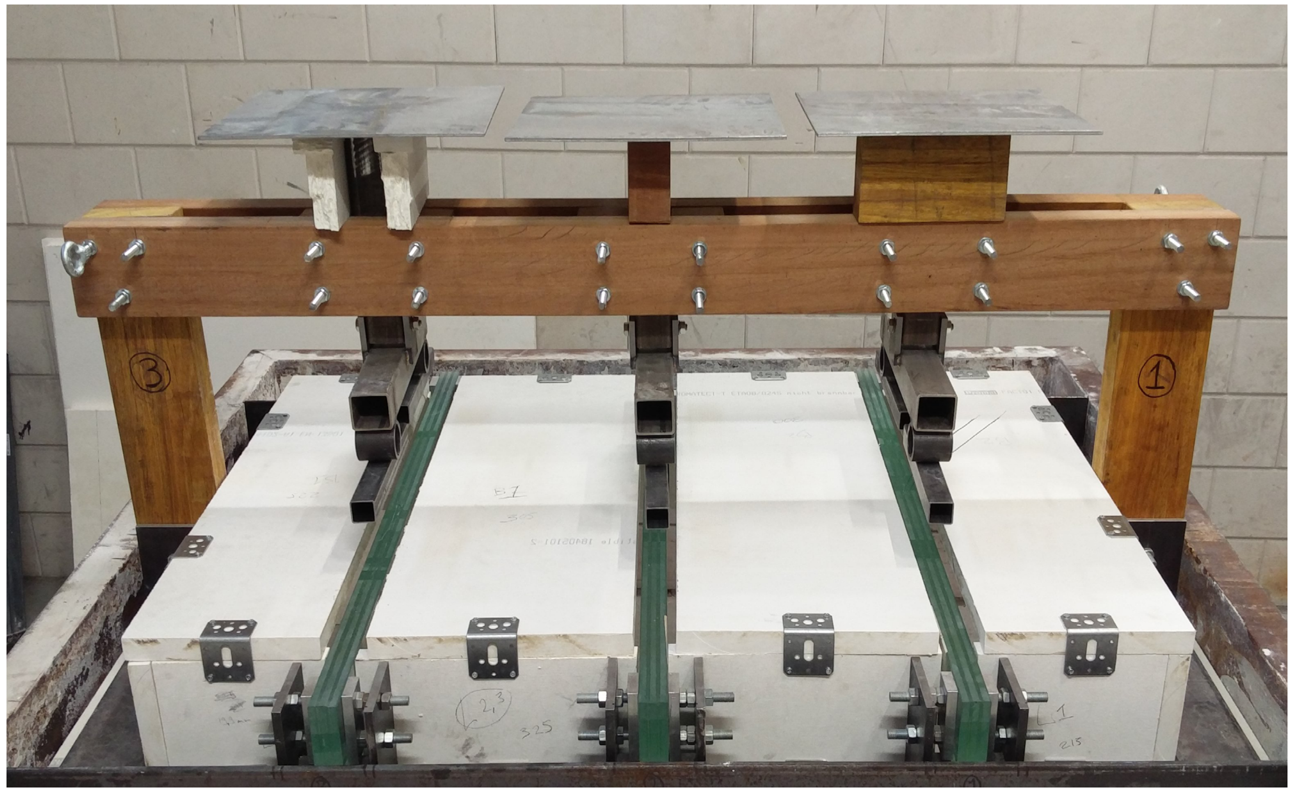
Figure: Proposed test configuration of second set of glass beams at Efectis
Source: Based on schematic made by Dr. Louter

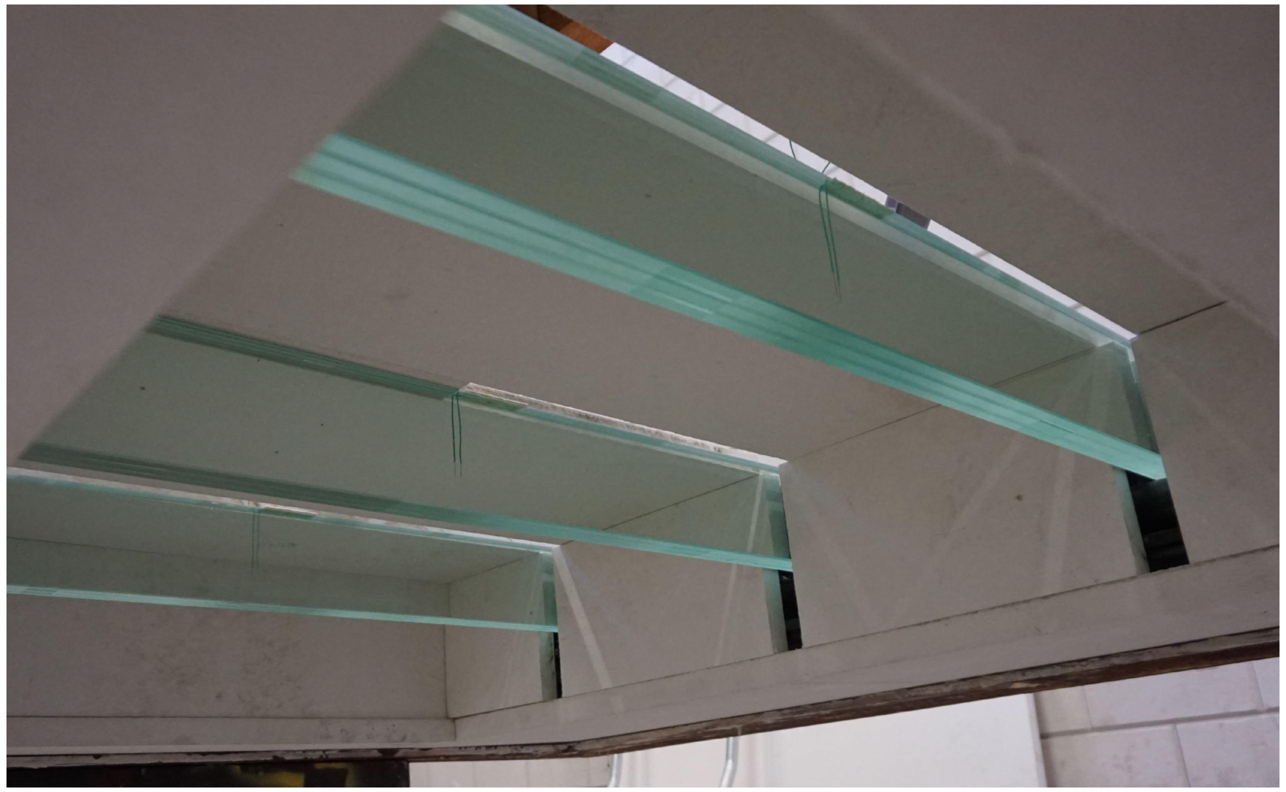
EXPERIMENTAL TEST SET-UP



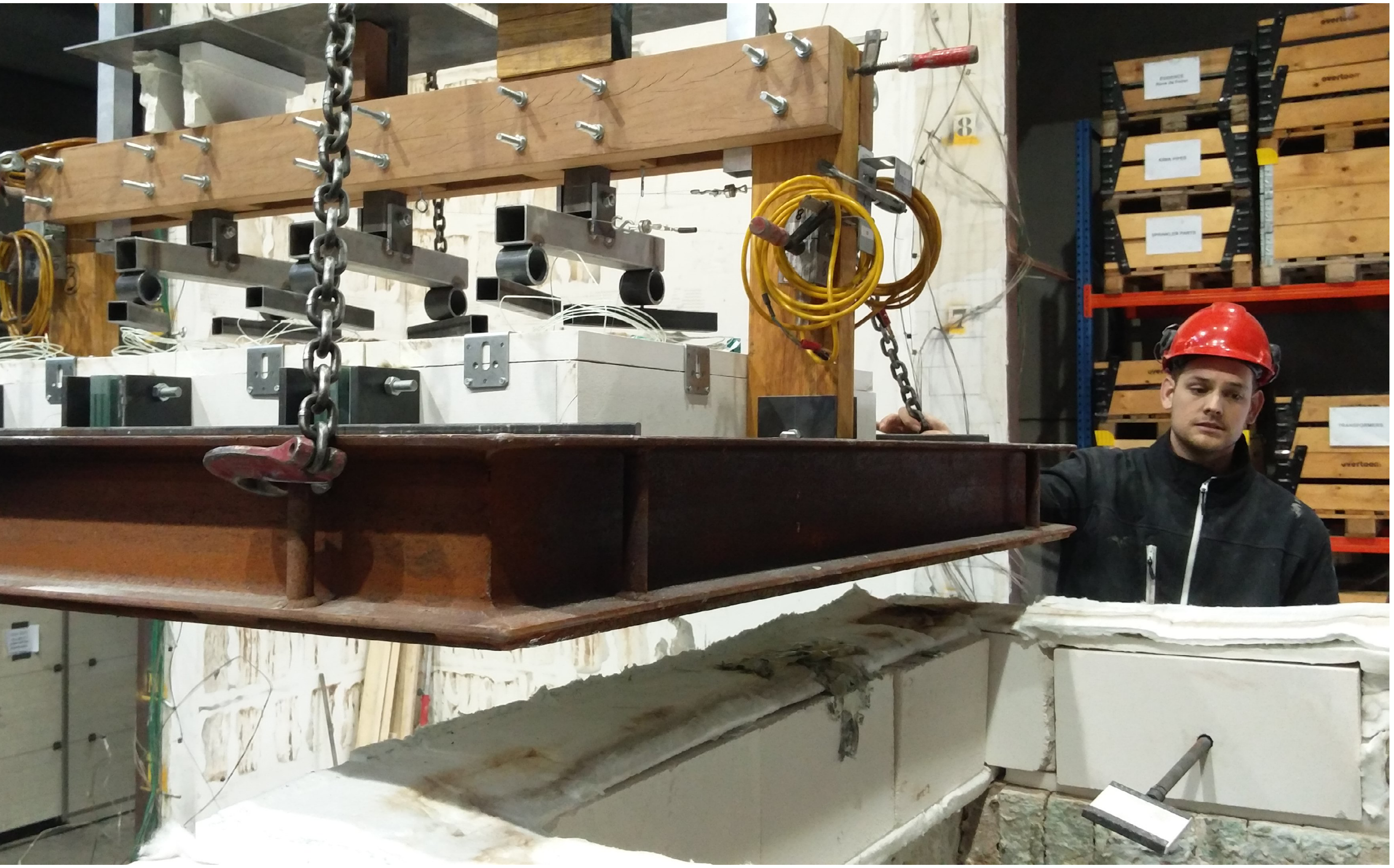


BUILDING THE TEST SET-UP

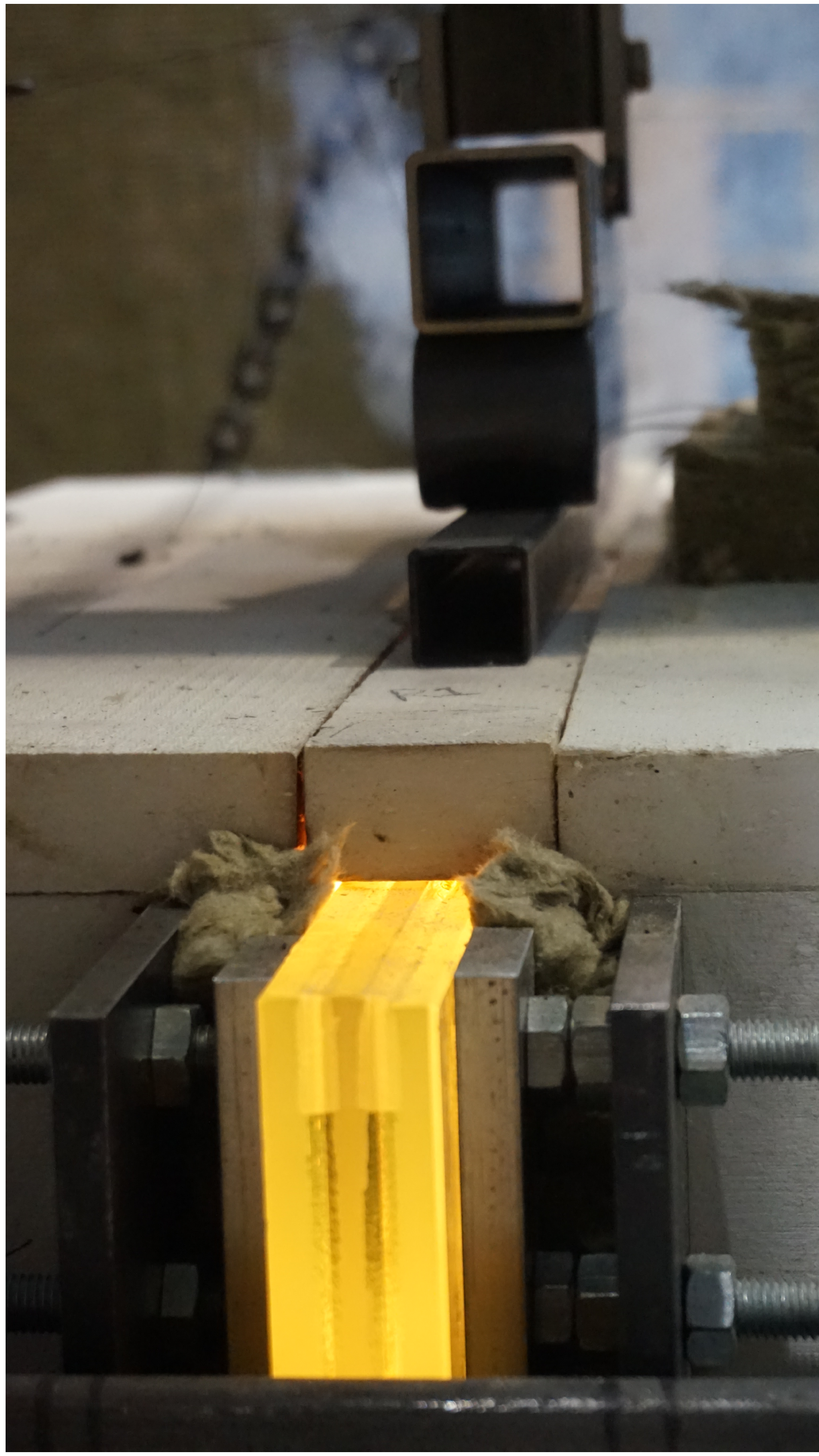




TEST SET-UP ON THE FIRE FURNACE



FIRE FURNACE TESTING AT EFECTIS



PHYSICAL TESTING AT EFECTIS

~ VIDEO OF TEST ~

PHYSICAL TESTING AT EFECTIS

PHYSICAL TESTING AT EFECTIS

PHYSICAL TESTING AT EFECTIS

TEST 1 - THERMAL FRACTURE

Beam 1 - **PVB (AN)**

Time: ***14.89 min*** *(513 ˚C)*

- thermal shock

Beam 2 - **PVB (HS)**

Time: ***17.23 min*** *(599 ˚C)*

Beam 3 - **SG (AN)**

Time: ***7.81 min*** *(219 ˚C)*

- thermal shock

TEST 2 - RADIANT HEATING OF BEAM 2

Beam 1 - **SG (HS)**

Time: ***17.04 min*** *(508 ˚C)*

Beam 2 - **SG (FT)**

Time: ***15.39 min*** *(578 ˚C)*

- influenced by PVB flames

Beam 3 - **PVB (FT)**

Time: ***16.23 min*** *(585 ˚C)*

TEST 2 - DISPLACEMENT

Beam 1 - **SG (HS)**

Time: ***17.04 min*** *(508 ˚C)*

Beam 2 - **SG (FT)**

Time: ***15.39 min*** *(578 ˚C)*

- influenced by PVB flames

Beam 3 - **PVB (FT)**

Time: ***16.23 min*** *(585 ˚C)*

TEST 3 - THERMAL FRACTURE

Beam 1 - **SG (FT)**

Time: ***17.46 min*** *(515 ˚C)*

Beam 2 - **SG (AN)**

Time: ***4.71 min*** *(139 ˚C)*

- thermal shock

Beam 3 - **SG (HS)**

Time: ***15.71 min*** *(571 ˚C)*

TEST 3 - DISPLACEMENT

Beam 1 - **SG (FT)**

Time: ***17.46 min*** *(515 °C)*

Beam 2 - **SG (AN)**

Time: ***4.71 min*** *(139 °C)*

- thermal shock

Beam 3 - **SG (HS)**

Time: ***15.71 min*** *(571 °C)*

PHYSICAL TESTING AT EFECTIS - OVERVIEW

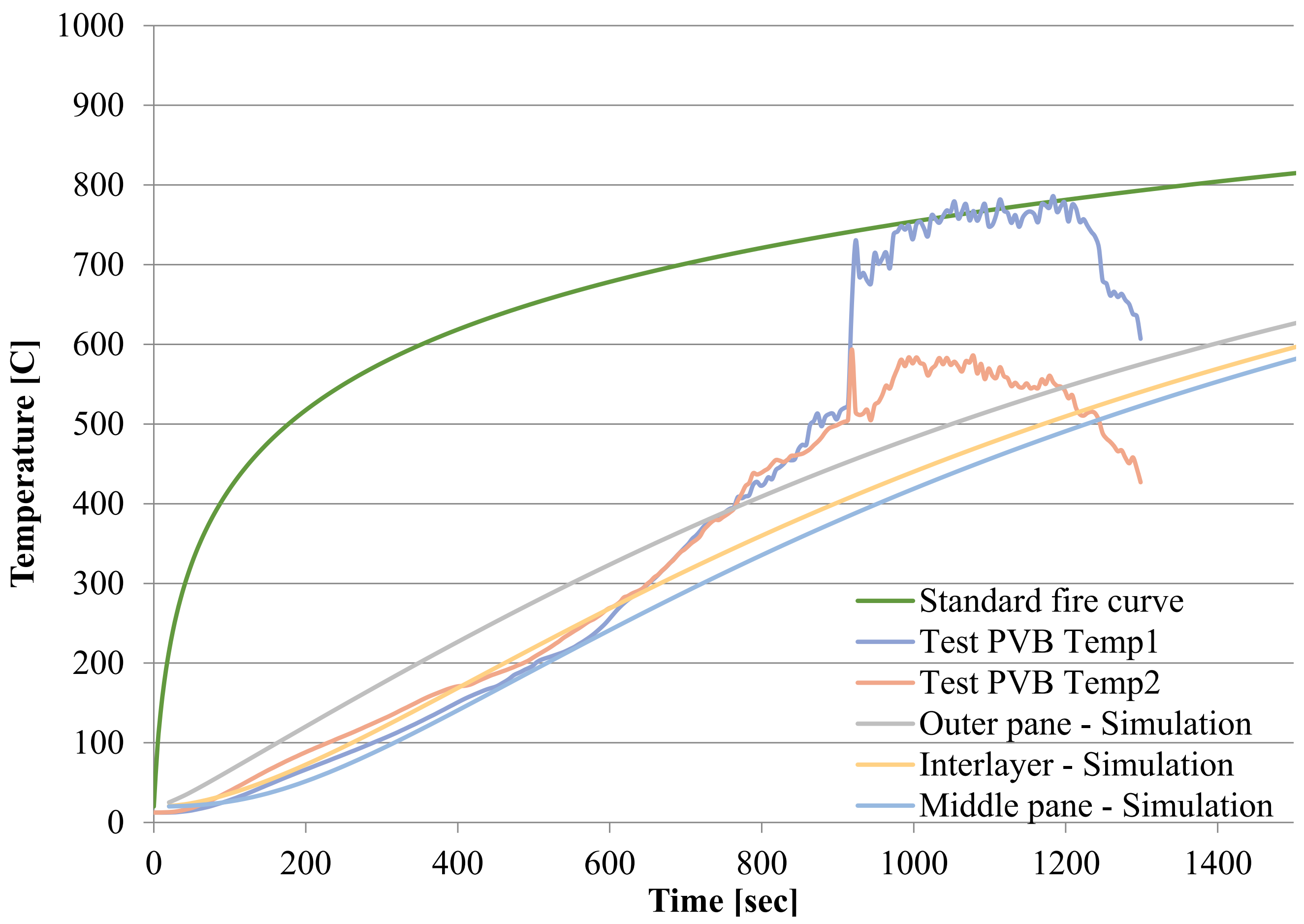
Comparison of failure times with the EMPA test by Louter

PVB Interlayer	Failure time Louter – EMPA	Failure time Sturkenboom - Efectis	Time difference
Annealed glass	34.6 min	14.9 min	19.8 min
Heat Strengthened	39.6 min	17.2 min	22.4 min
Fully Tempered	42.8 min	16.2 min	26.6 min

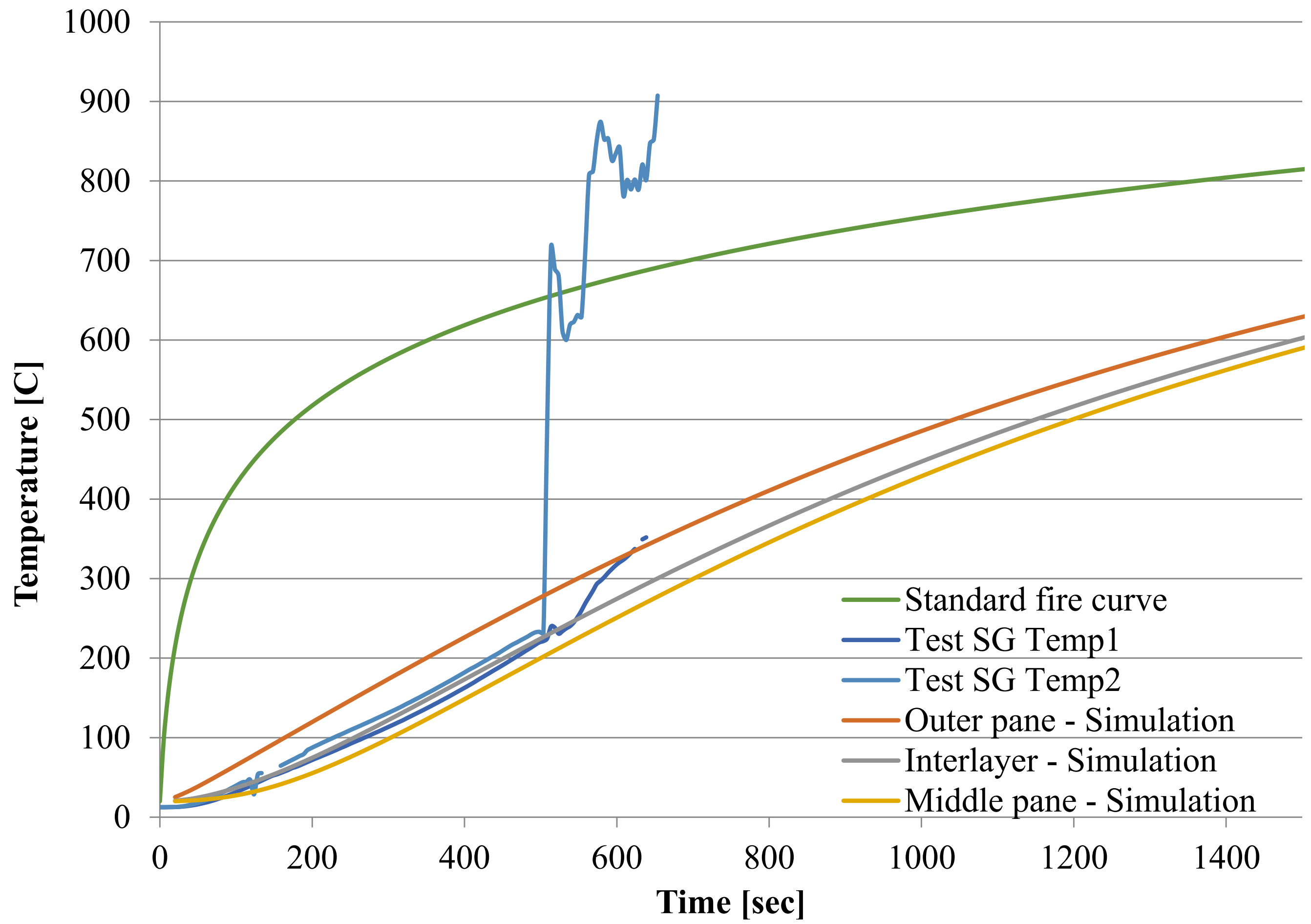
SentryGlas Interlayer	Failure time Louter – EMPA	Failure time Sturkenboom - Efectis	Time difference
Annealed glass	32.9 min	7.8 min (fracture)	25.1 min
Heat Strengthened	41.8 min	17.0 min	24.8 min
Fully Tempered	48.0 min	17.5 min	30.5 min

DIANA SIMULATION - TEMPERATURE VALIDATION

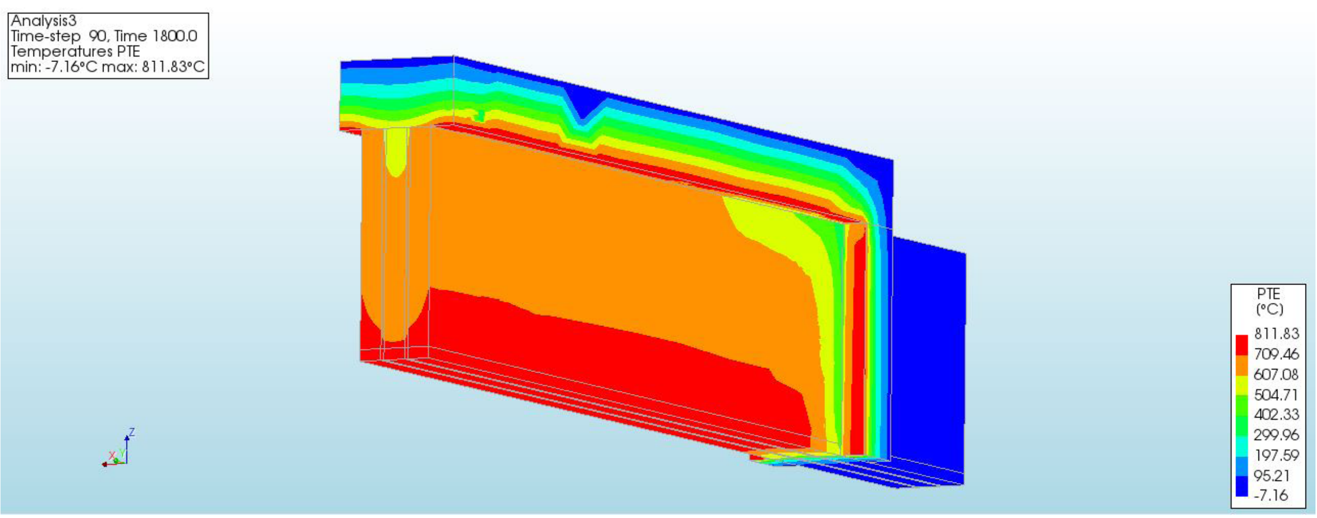
Comparison SentryGlas - Simulation vs. Test

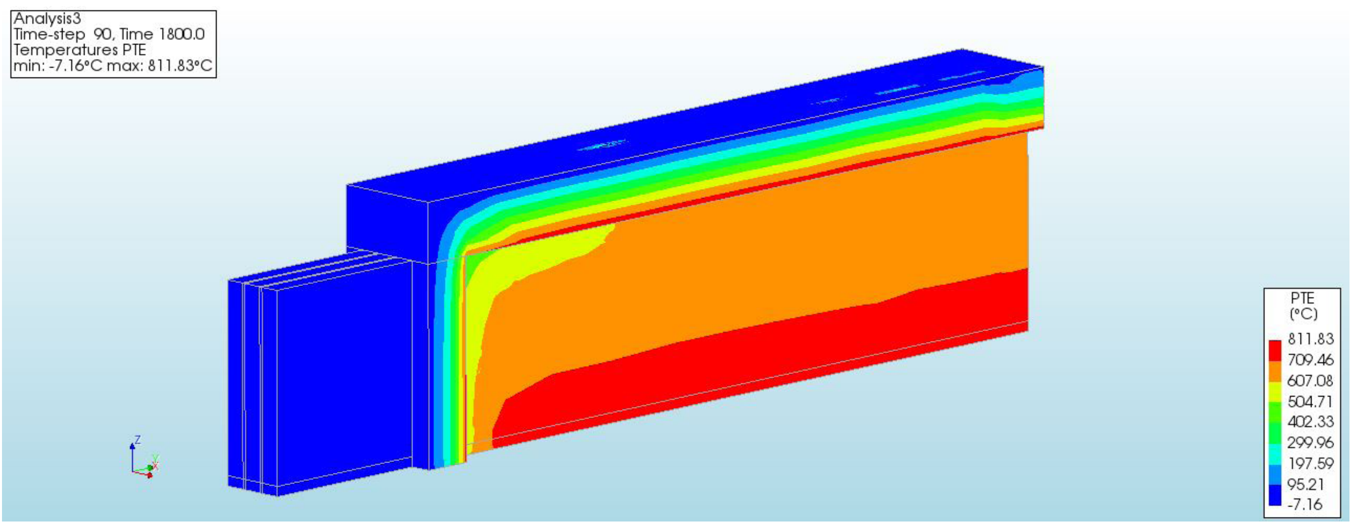


Comparison PVB - Simulation vs. Test



Heat flow simulation





CONCLUSIONS AFTER TEST 1,2 & 3

1. The ***tougher*** the glass, the ***slower*** the ***temperature increase*** the later the failure. ~ Louter

2. ***PVB laminate*** starts to evaporate and burn at an ***earlier*** stage than ***SentryGlas laminate*** ~ Debuyser

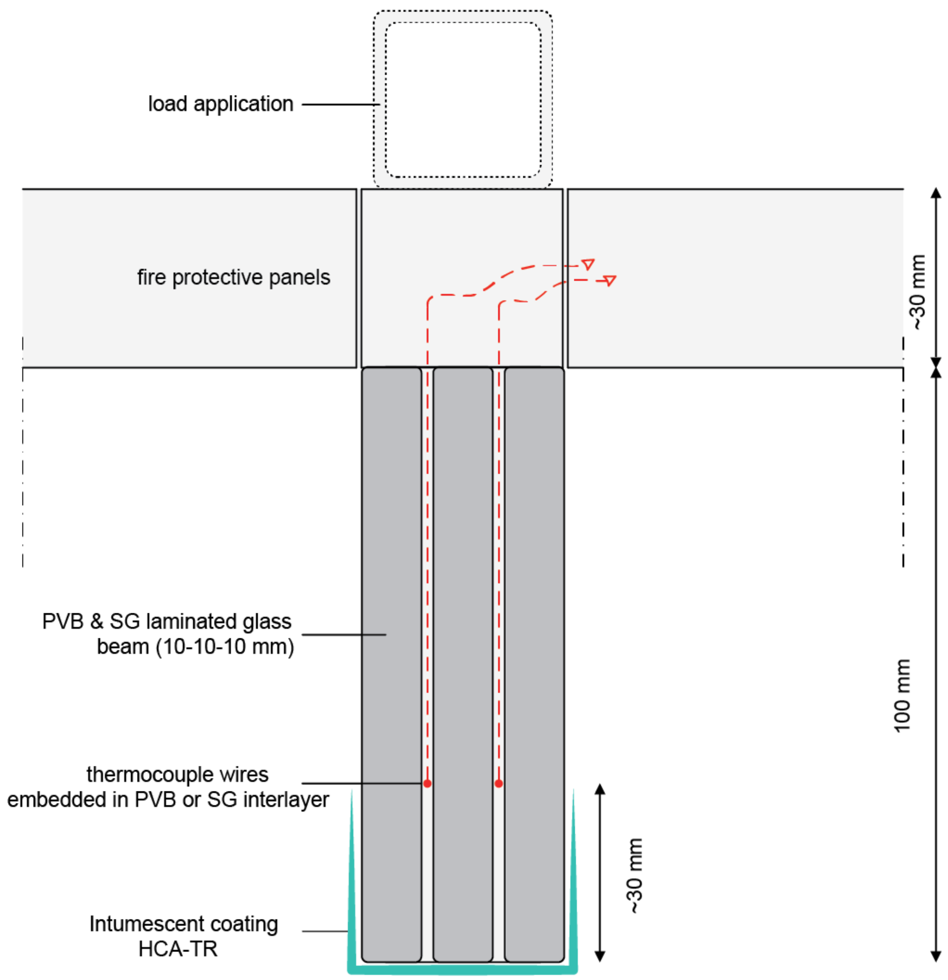
3. The ***increased load*** does ***not*** seem to ***influence*** failure time

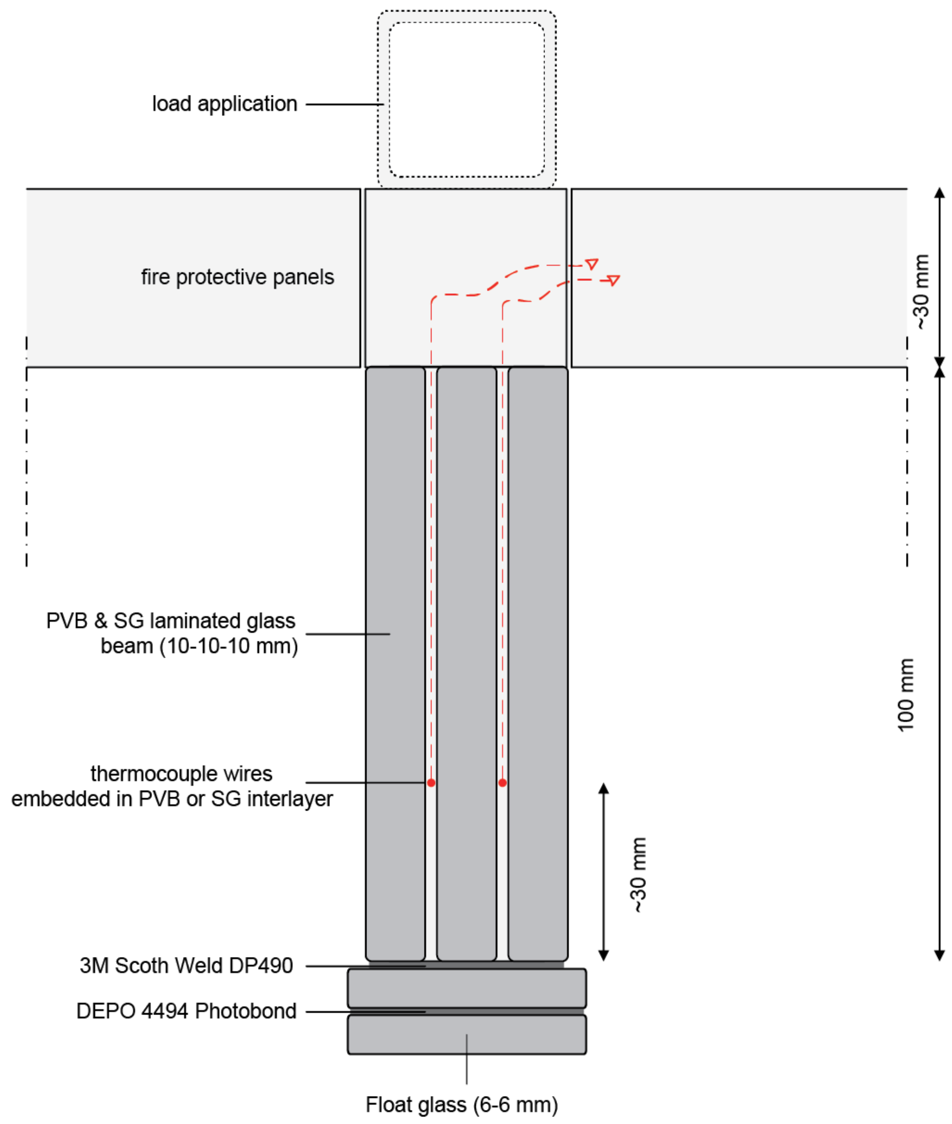
4. Protecting the ***top 3 cm*** of the beam by ***Louter*** seems optimal ~ ***33 - 48*** minutes

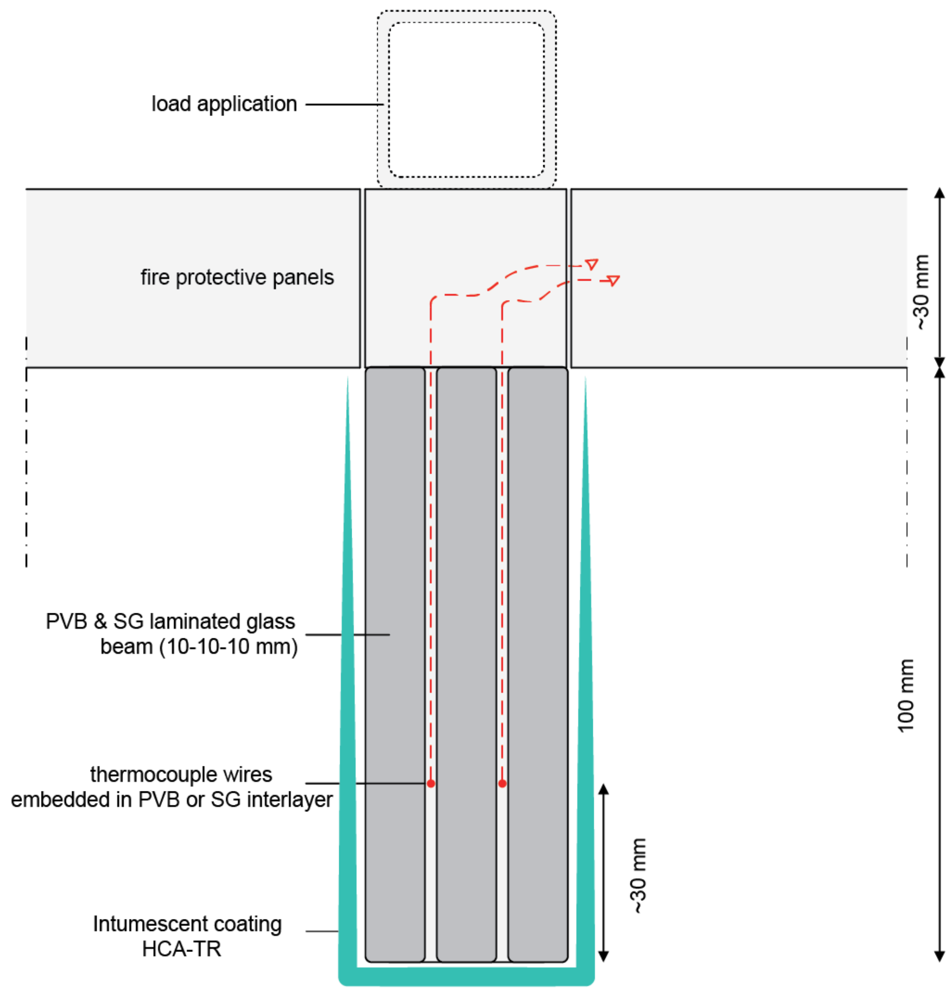
5. The ***radiant heat*** from the burning PVB interlayer ***influences*** the heating of the ***glass*** and ***interlayer*** facing the flames

MODIFIED BEAM - FINAL TEST

IMPLEMENTATION TEST AT EFECTIS - TEST 4







Heat-strengthened PVB

Bottom 3 cm - HCA-TR
Intumescent paint ~ Veer

Heat-strengthened PVB

6-6 mm Glass buffer

Heat-strengthened PVB

3 sided (10 cm) - HCA-TR
Intumescent paint ~ Veer

IMPLEMENTATION TEST AT EFECTIS - TEST 4

Heat-strengthened PVB

Bottom 3 cm - HCA-TR
Intumescent paint ~ Veer

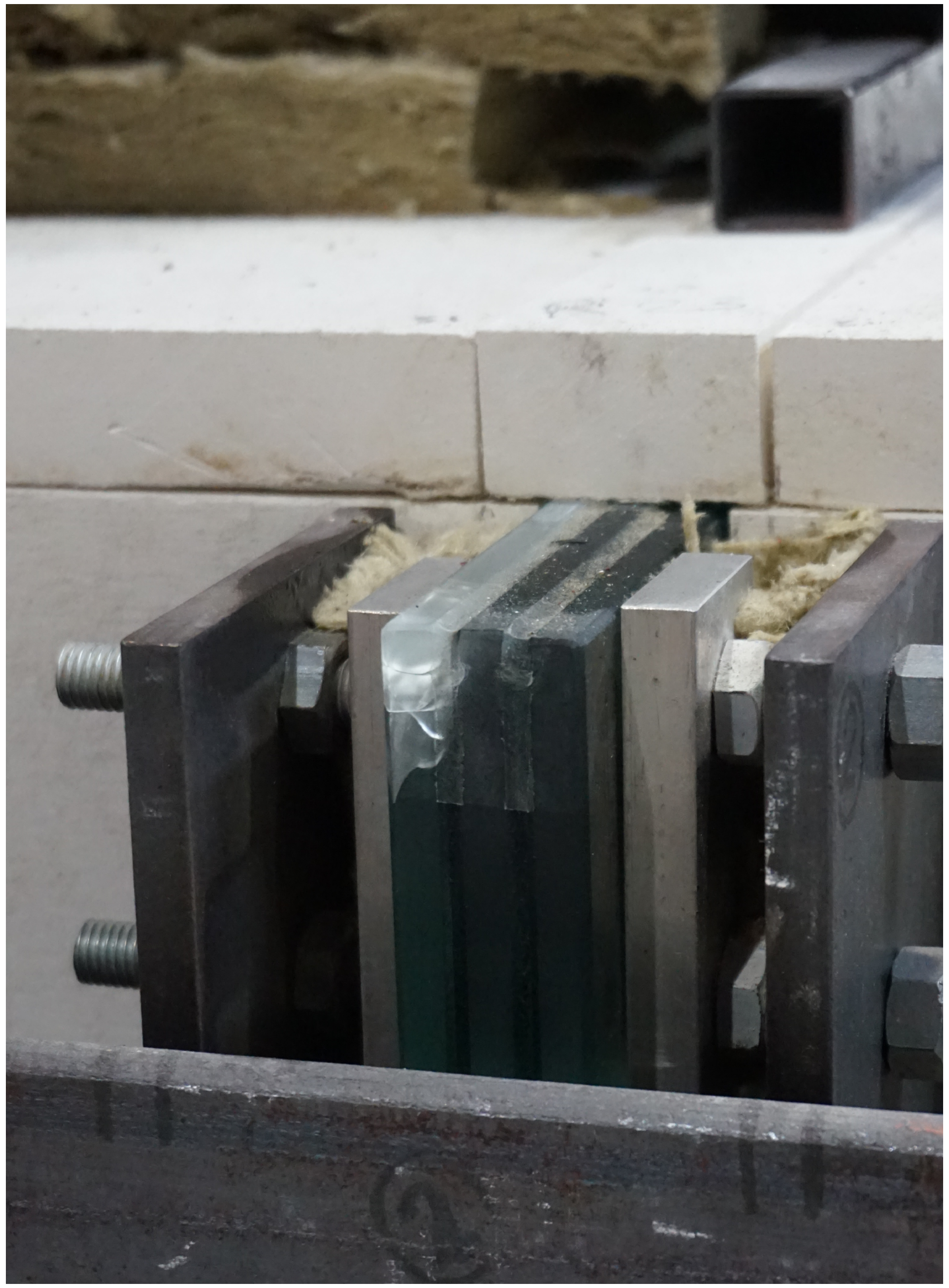
Heat-strengthened PVB

6-6 mm Glass buffer

Heat-strengthened PVB

3 sided (10 cm) - HCA-TR
Intumescent paint ~ Veer

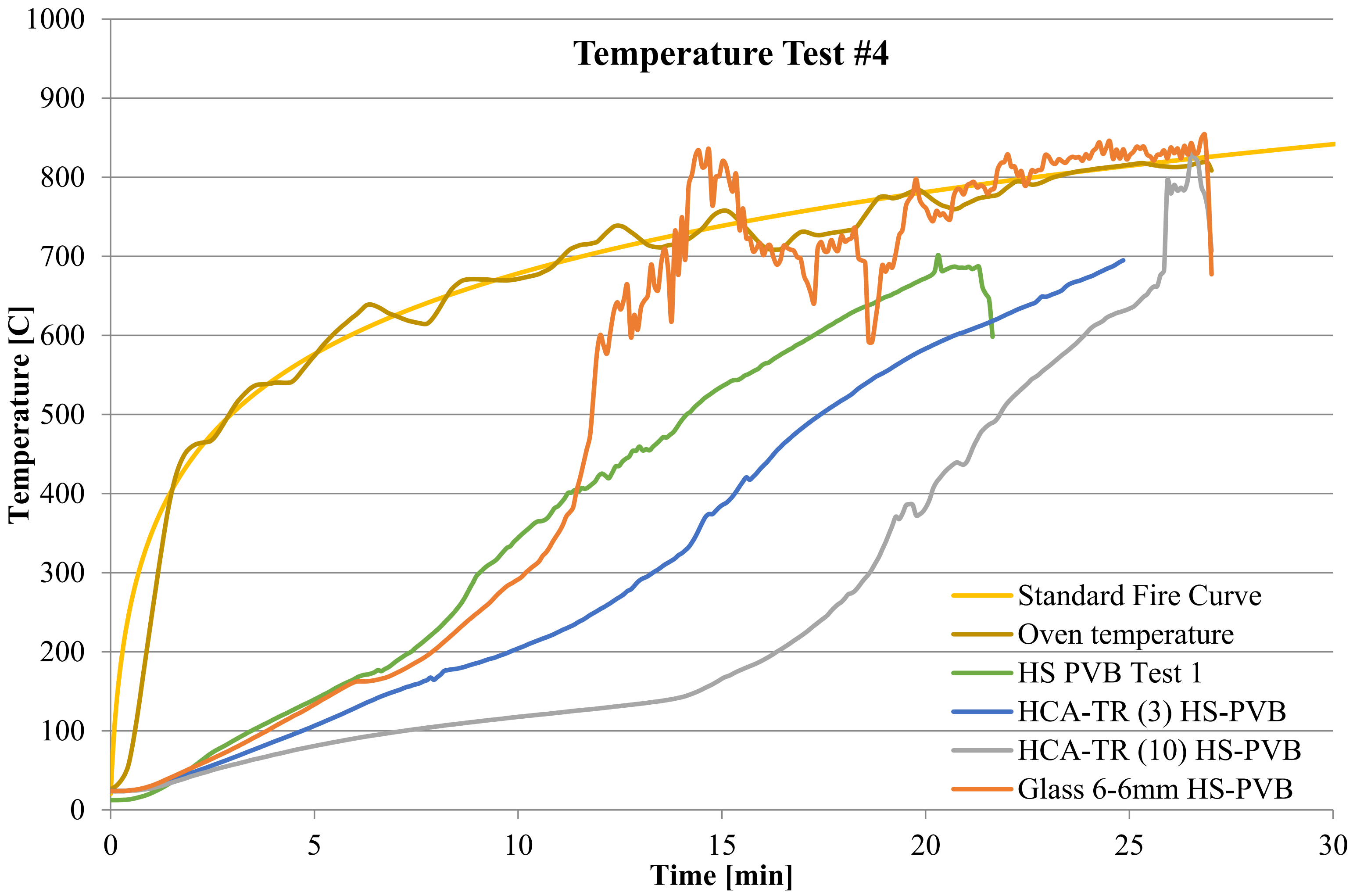
IMPLEMENTATION TEST AT EFECTIS - TEST 4

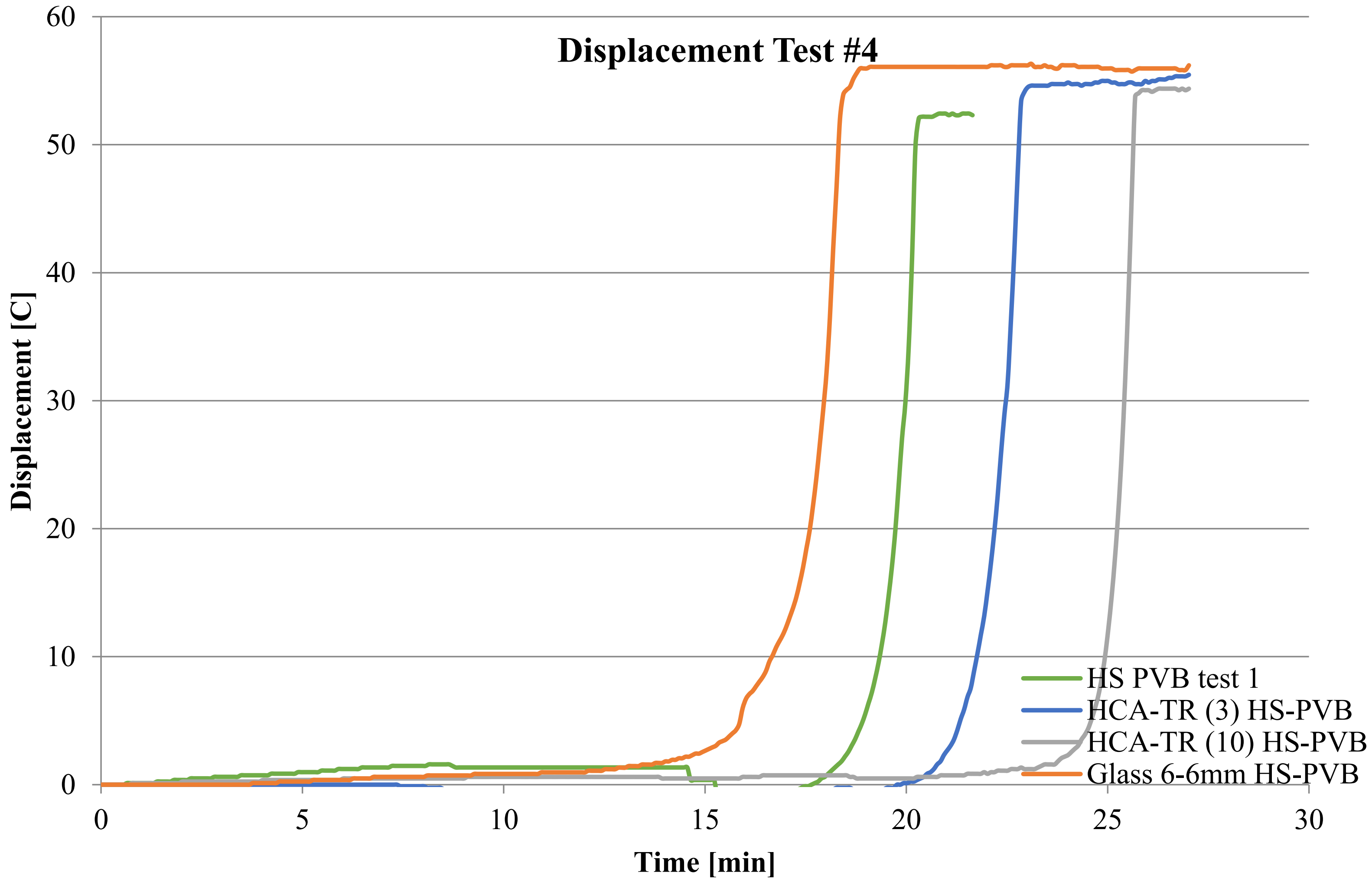


Thermal fracture - Beam 2
6-6 mm Glass buffer

Spontaneous ignition at the top of beam 3
3 sided (10 cm) - HCA-TR

RESULTS TEST AT EFECTIS - TEST 4





- Beam 1 - PVB (HS) - **3 cm HCA-TR** Time: ***19.68 min*** *(574 ˚C)*
- Beam 2 - PVB (HS) - **6-6mm Glass buffer** Time: ***14.60 min*** *(549 ˚C)* ***- thermal shock***
- Beam 3 - PVB (HS) - **10 cm HCA-TR** Time: ***23.43 min*** *(524 ˚C)*

- Reference - PVB (HS) Time: ***17.23 min*** *(599 ˚C)*

CONCLUSIONS OF TEST 4

1. ***The goal*** of a fire resistance of 30 minutes has ***not*** been achieved

2. ***HCA-TR intumescent paint*** has an improved effect on the failure time and heating rate

   +2.45 min & ***+6.2*** min

3. ***Protecting*** 3 sides of the beam from ***direct heating*** has great effect on the performance

4. Protecting the ***top edge*** of the beam is necessary

5. The ***6-6 glass buffer*** underperforms the former standard PVB-HS
   However, it provides ***resisdual strength*** after fracture.

CONCLUSIONS EXPERIMENTAL TESTING

1. ***The goal*** of a fire resistance of 30 minutes has ***not*** been achieved

2. Protecting the ***top 3 cm*** of the beam by ***Louter*** seems optimal
   ~ ***33 - 48*** minutes

3. The ***order of failure*** seems to be in the ***order of thermal treatment***

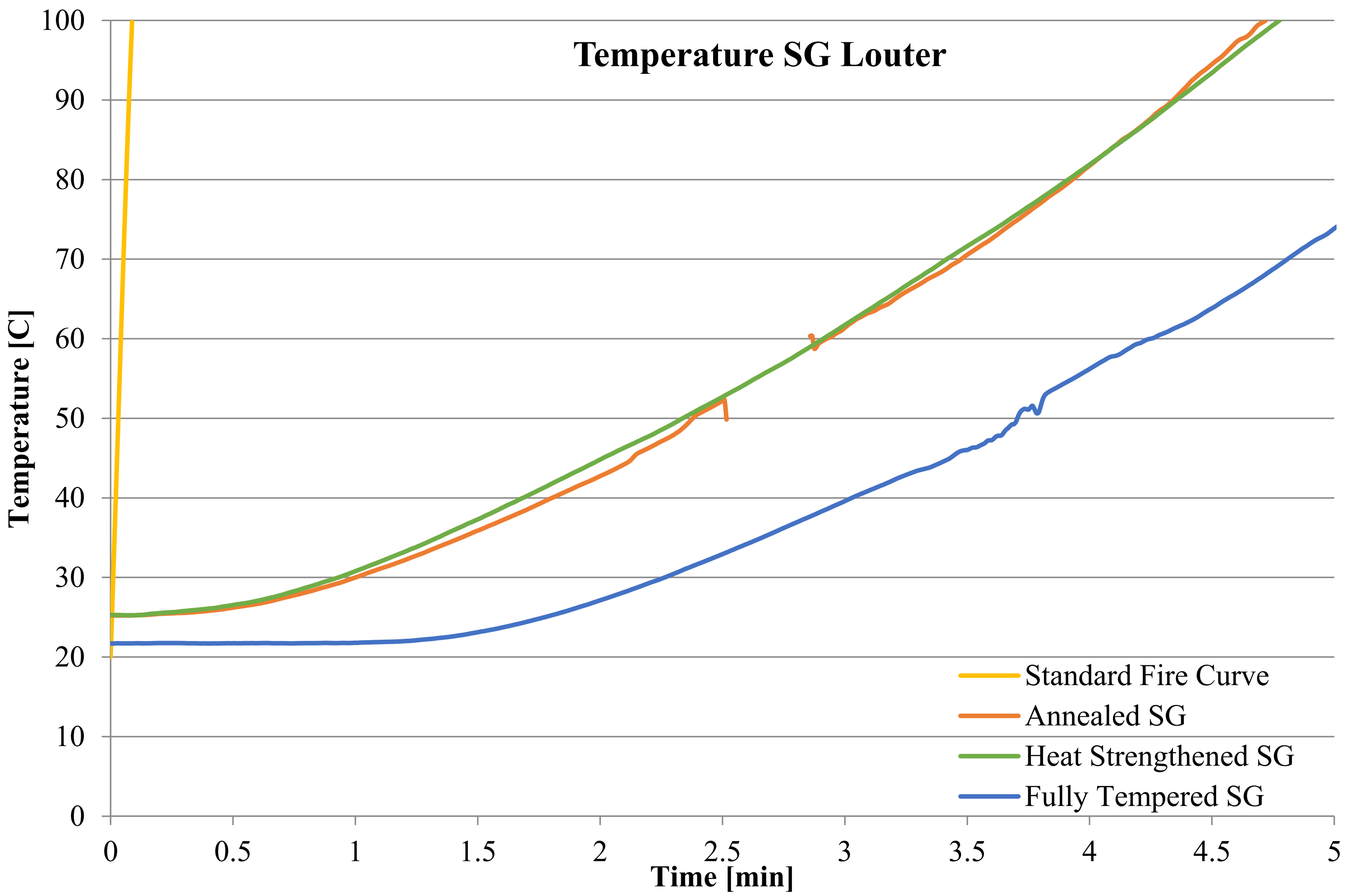
4. ***Protecting*** 3 sides of the beam from ***direct heating*** has great effect on the performance

5. ***Additional glass*** on the underside protects the interlayer from direct heating and offers ***residual strength*** after fracture

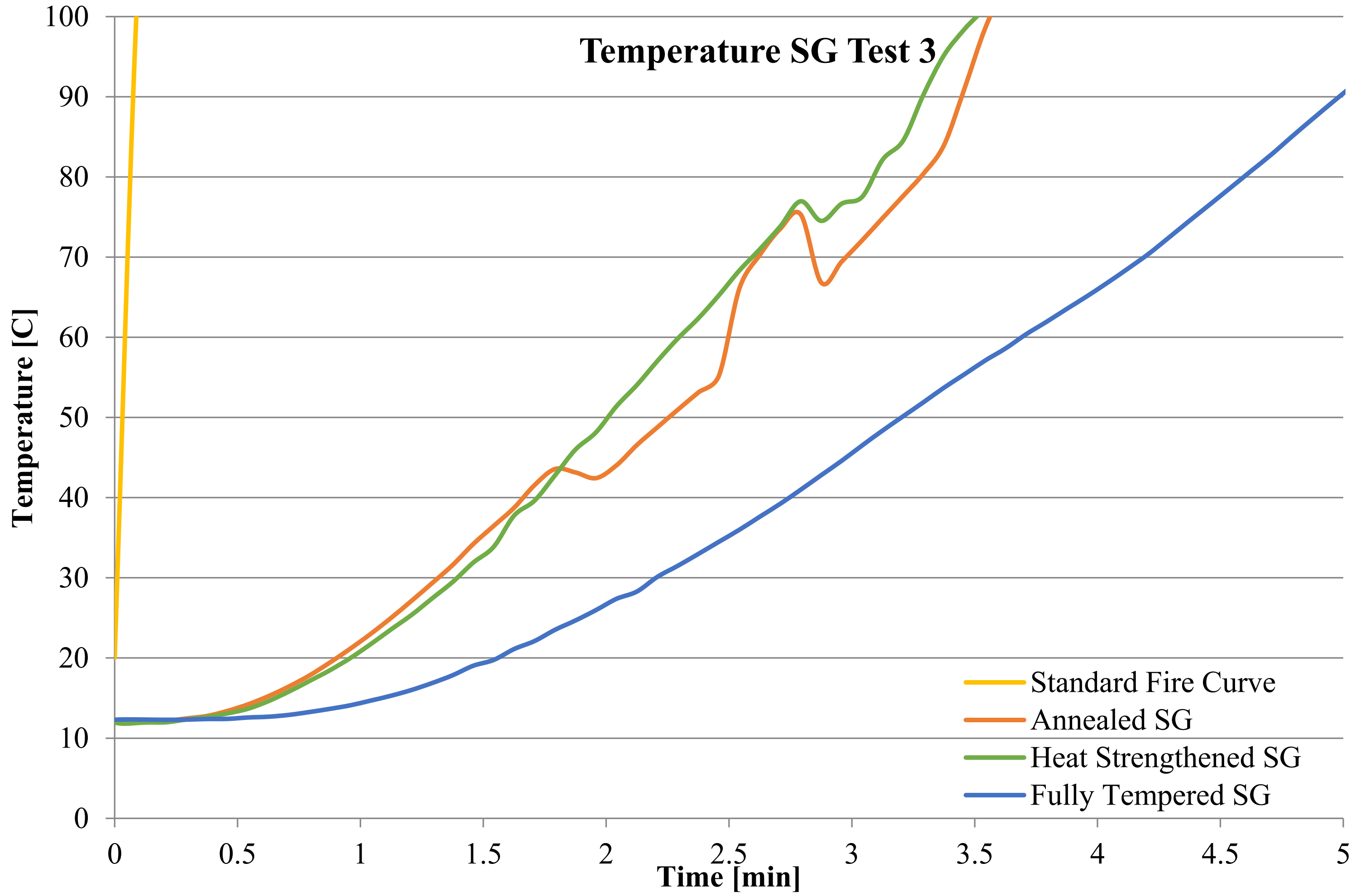
INTERPRETATION

THE EFFECT OF THERMAL TREATEMENT

EMPA test by Louter

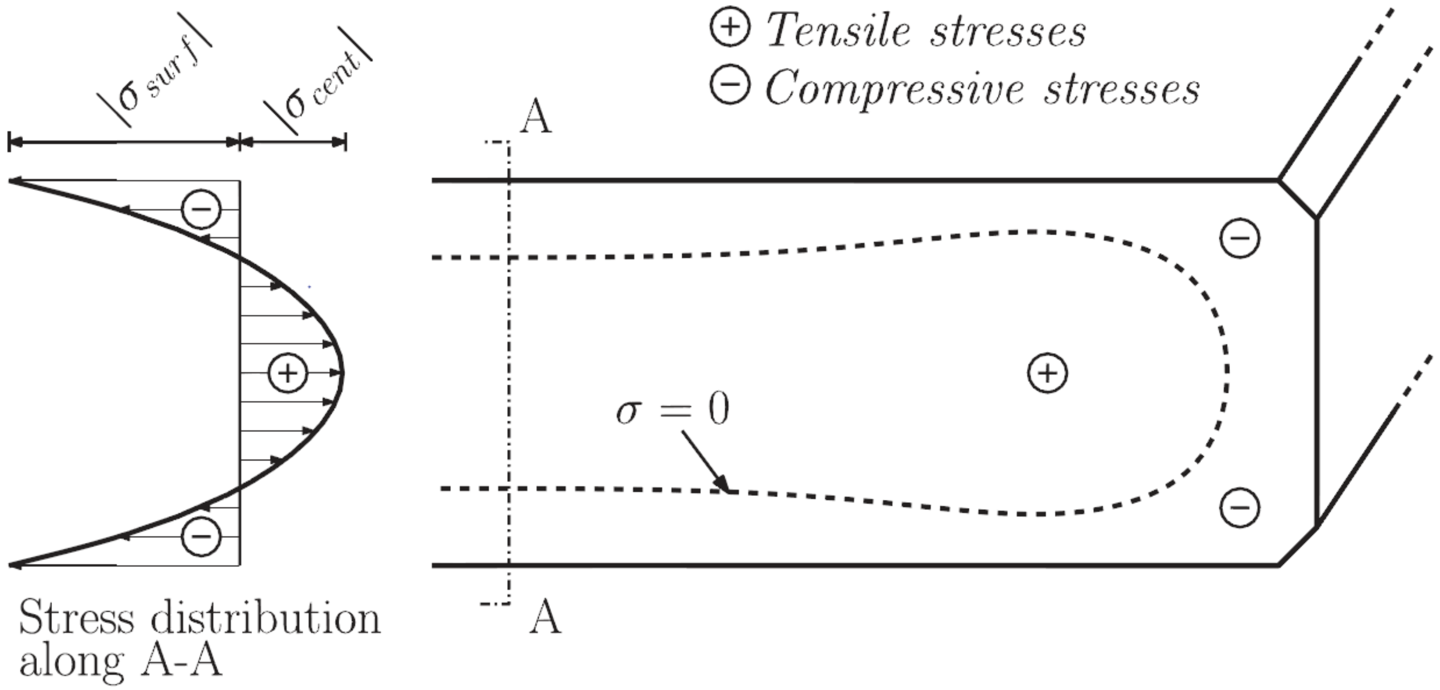


Efectis test by Sturkenboom



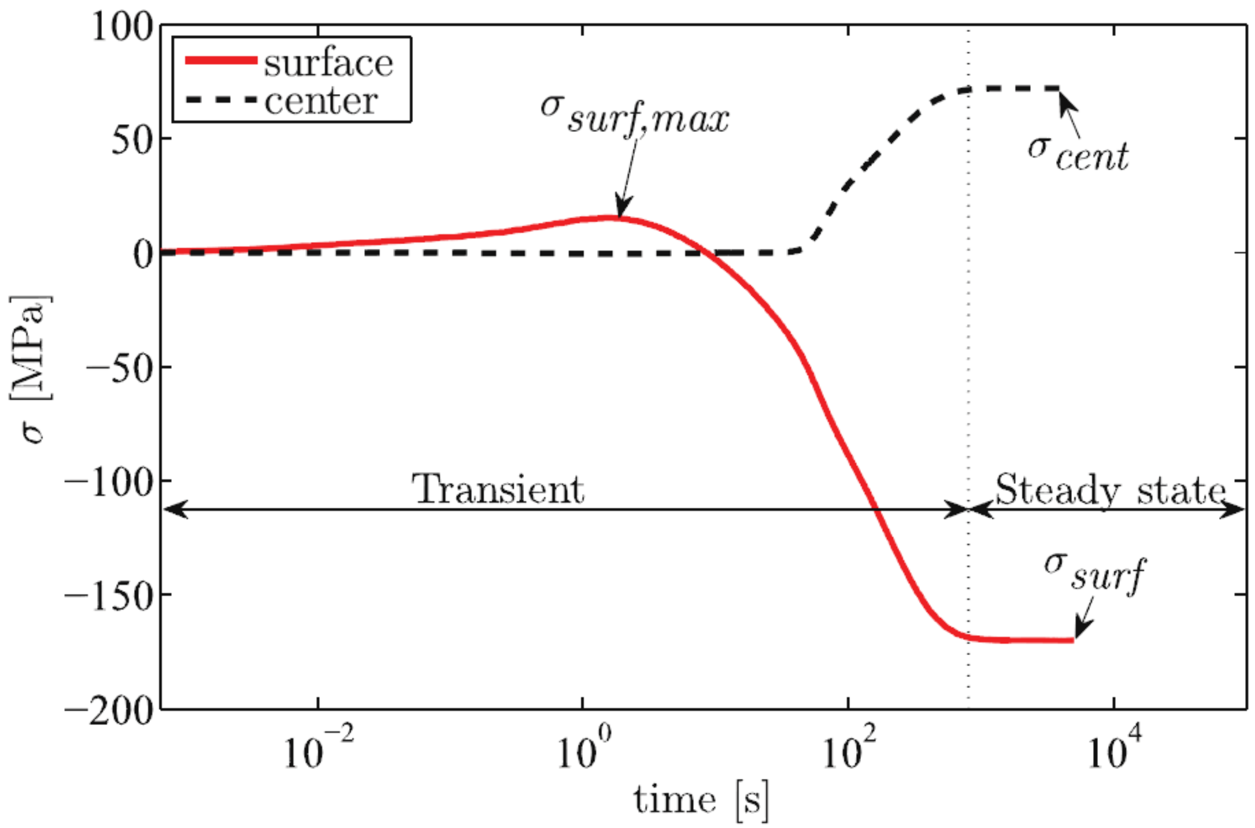
THE EFFECT OF THERMAL TREATEMENT

Development of surface & centre stress during tempering



Source: Finite element implementation of a glass tempering model in three dimensions - Nielsen

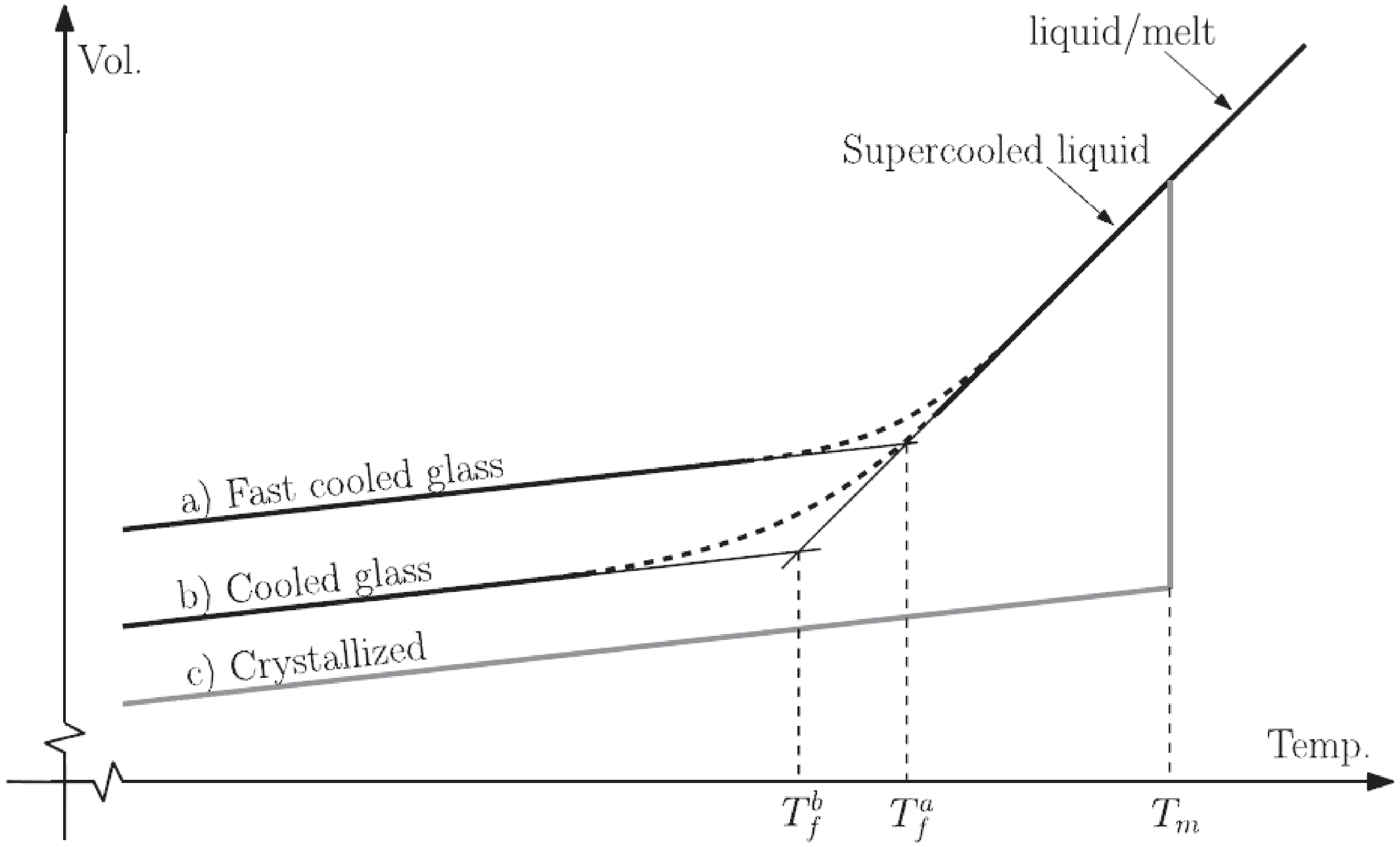
Development of surface & centre stress during tempering



Source: Stress and structural relaxation in tempering glass - Narawanaswamy

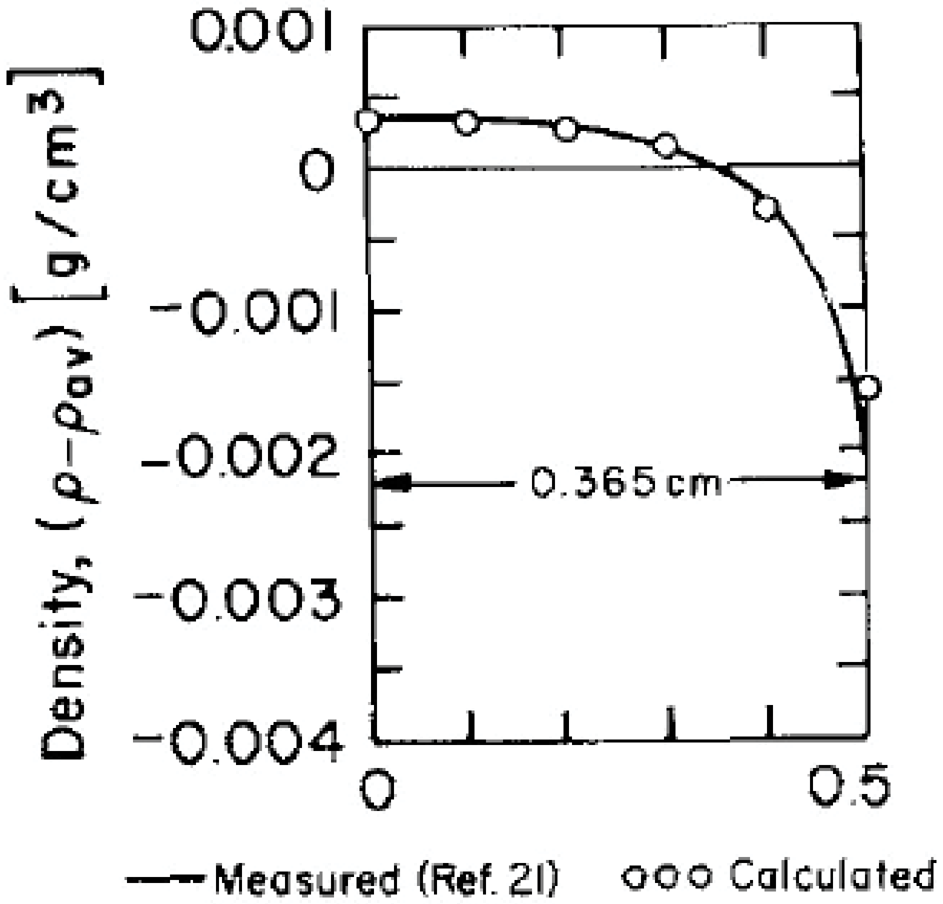
THE EFFECT OF THERMAL TREATEMENT

Volume comparisson of cooled & fast cooled glass



Source: Finite element implementation of a glass tempering model in three dimensions - Nielsen

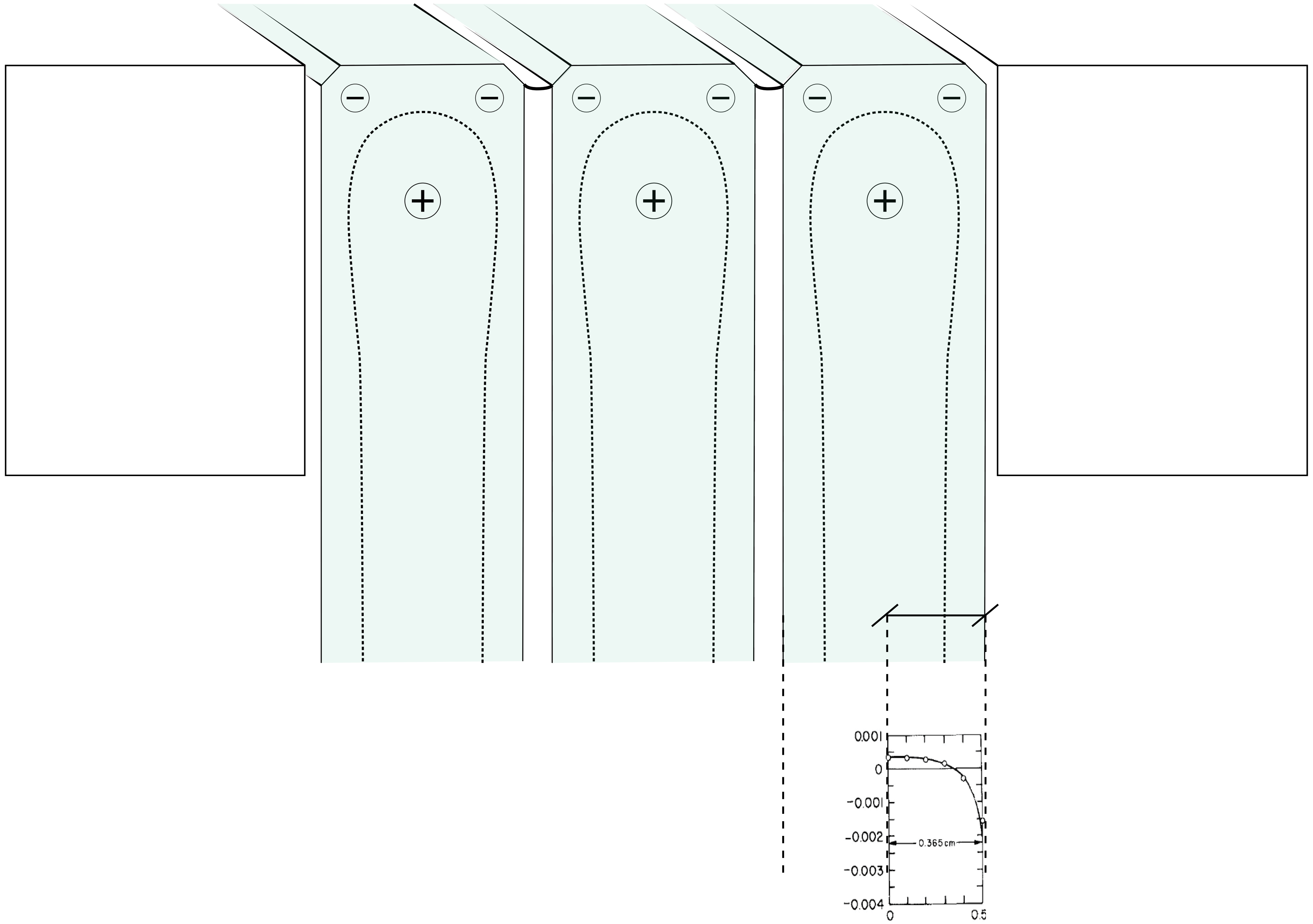
Density distribution in tempered glass



Source: Stress and structural relaxation in tempering glass - Narawanaswamy

THE EFFECT OF THERMAL TREATEMENT

Distribution of internal stresses & density in Louter set-up



THE EFFECT OF THERMAL TREATEMENT

1. ***The pre-stress in a beam "absorbs" energy in the heating process***

Because:

2. ***Thermal treatement of structural glass, induces varying thermal properties***

OR

3. ***The tests have been influenced by other variables***
   chemical composition, oven placement, oven temp, measurement errors, "n" is too small, beam thickness, etc.

CASE APPLICATION

DESIGN RECOMMENDATIONS FOR A FIRE RESISTANT STRUCTURAL GLASS BEAM

Fire Resistant Structural Glass Beams:

1. Use ***fully tempered glass***, due to delayed temperature increase

2. Use ***SentryGlas interlayers*** due to higher transition temperature

3. Apply an ***Intumescent interlayer*** on 3 sides ,laminated underneath a thin sacrificial glass plane.
   - e.g. Pilkington Pyrostop, Vetrotech Vetroflam

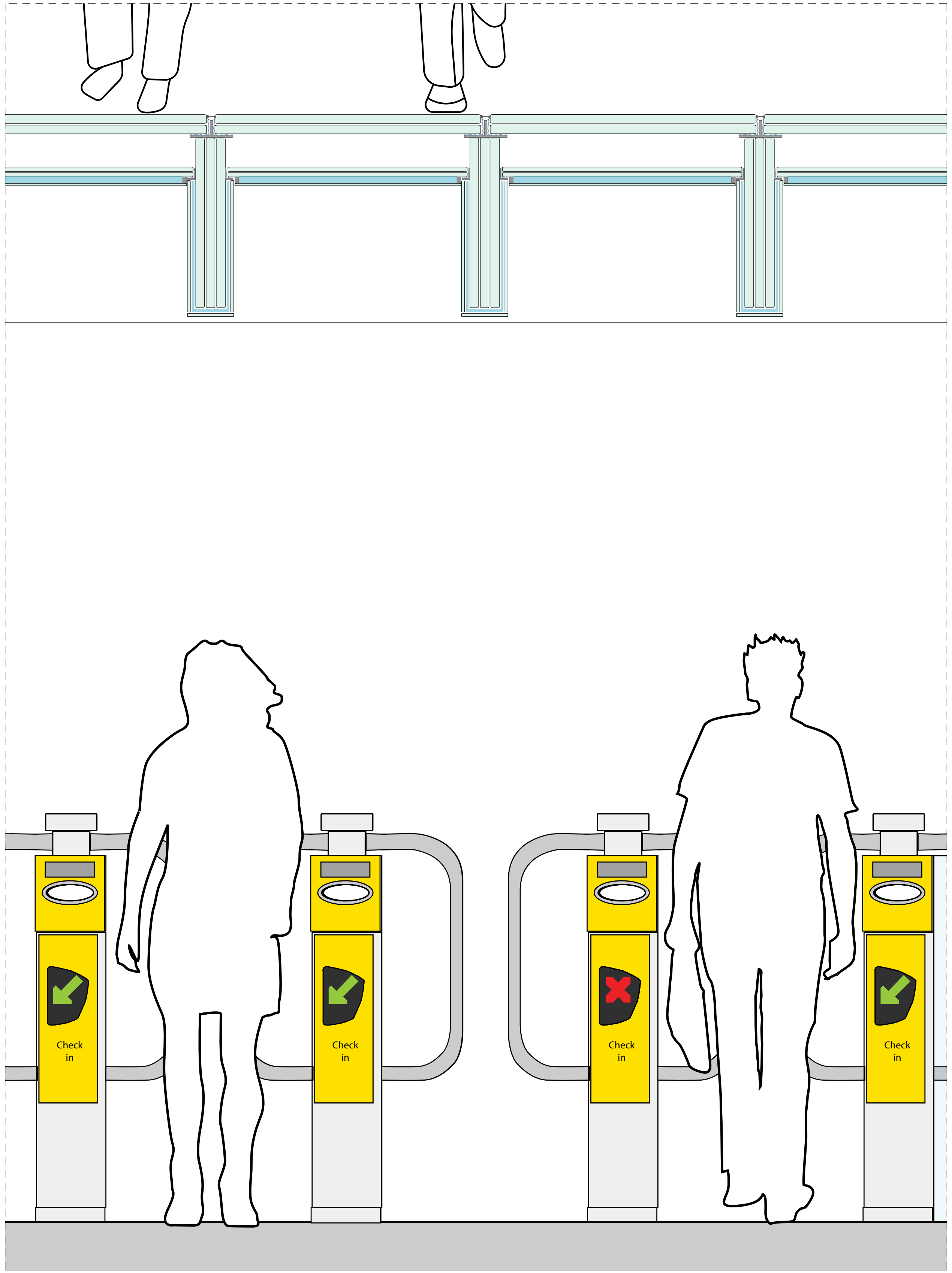
4. Protect the ***top (tempered) area*** of the glass beam

   ~ Louter

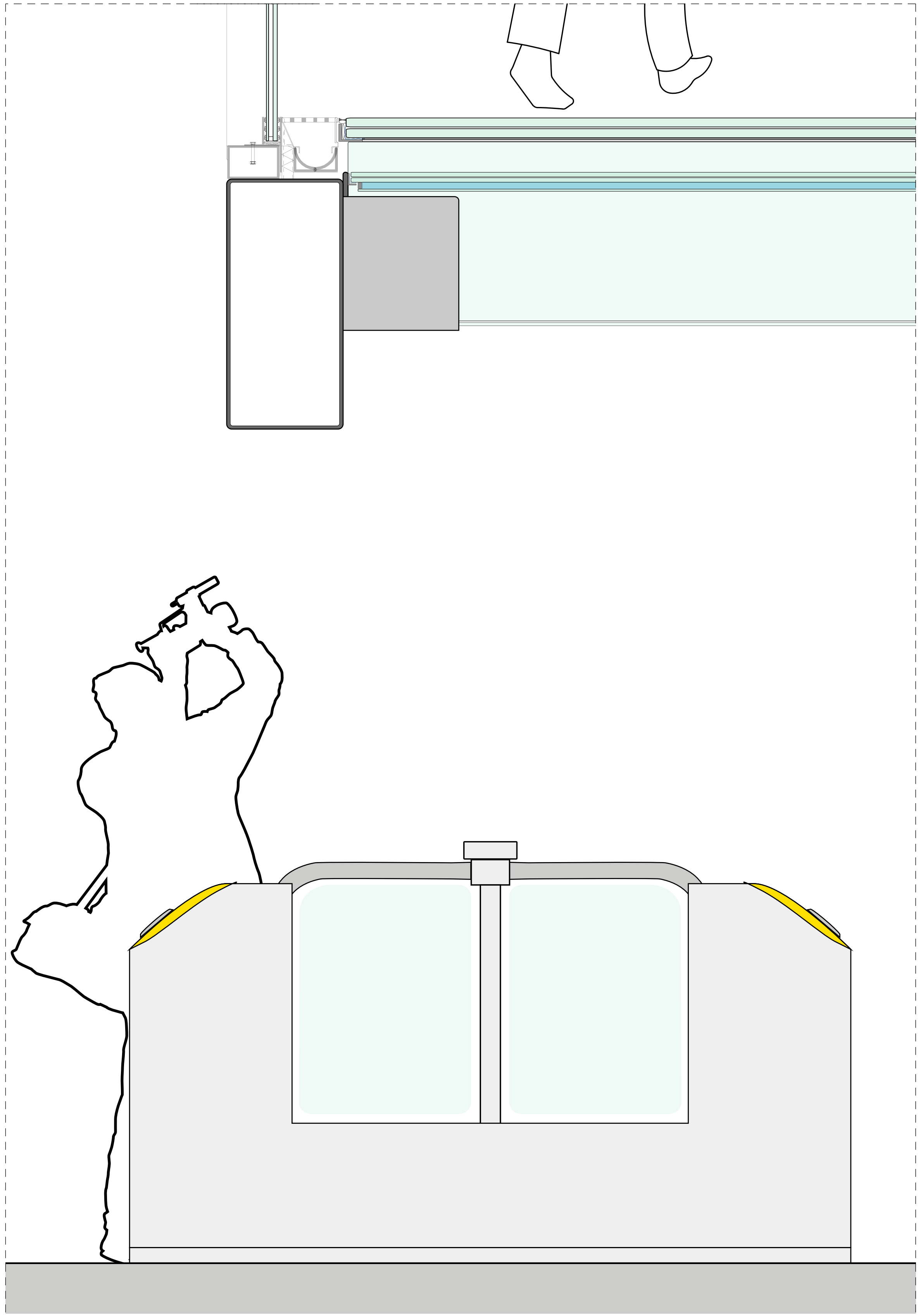
APPLICATION OF FIRE RESISTANT GLASS BEAMS

APPLICATION OF FIRE RESISTANT GLASS BEAMS

Longitudinal section - Glass ceiling & check-in gates

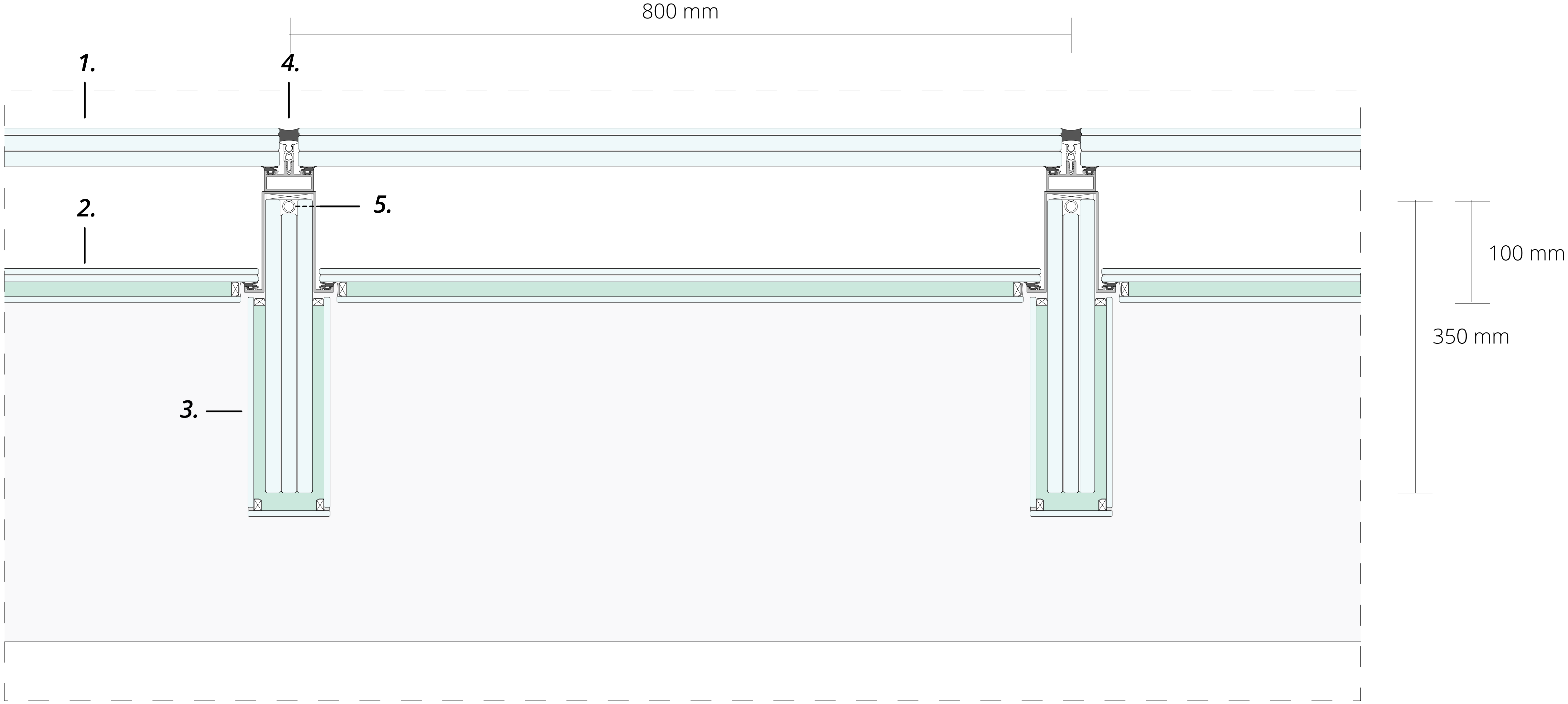


Cross section



1 : 5 Details

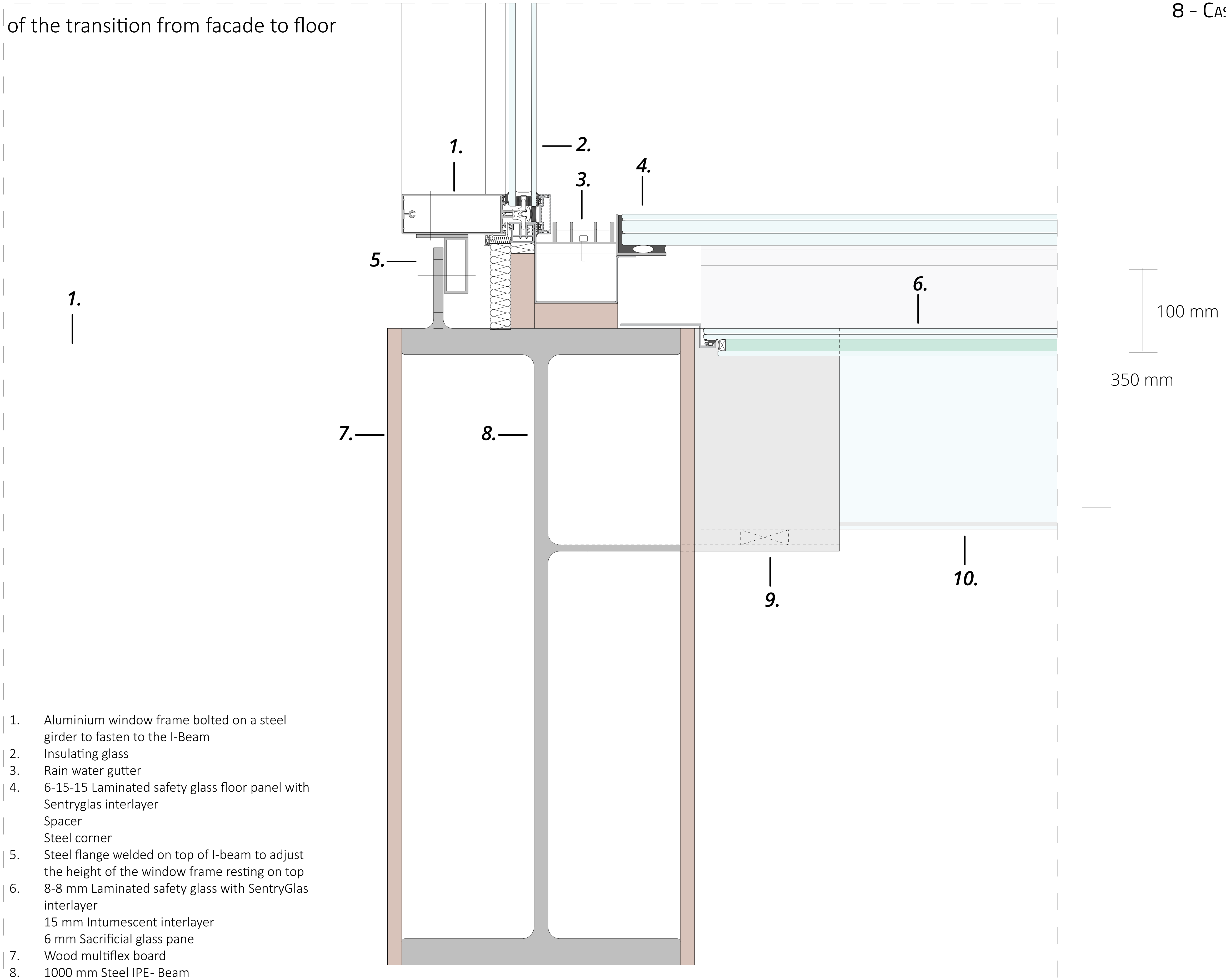
Cross section of two glass beams with spanning glass panels



1. 6-15-15 mm Laminated safety glass floor panel with Sentryglas interlayer
2. 8-8 mm Laminated safety glass with Sentryglas interlayer
   15 mm Intumescent interlayer
   6 mm Sacrificial glass pane
3. 6 mm Sacrificial glass pane
   15 mm Intumescent interlayer
   12-12-12 Laminated fully tempered glass beam
   15 mm Intumescent interlayer
   6 mm Sacrificial glass pane
4. Silicon sealant
   Aluminium window frame
   Aluminium cap to support the intumescent panels
5. LED - lighting strip

1 : 5 Details

Corner longitudinal section of the transition from facade to floor



1. Aluminium window frame bolted on a steel girder to fasten to the I-Beam
2. Insulating glass
3. Rain water gutter
4. 6-15-15 Laminated safety glass floor panel with Sentryglas interlayer
   Spacer
   Steel corner
5. Steel flange welded on top of I-beam to adjust the height of the window frame resting on top
6. 8-8 mm Laminated safety glass with SentryGlas interlayer
   15 mm Intumescent interlayer
   6 mm Sacrificial glass pane
7. Wood multiflex board
8. 1000 mm Steel IPE- Beam
9. Steel shoe as glass beam support
   Spacer
10. Structural glass beam resting in steel shoe

RESEARCH RECOMMENDATIONS

1. Increase the ***number of tests*** (n) to eleminate the factor of chance

2. Repeat - Fire furnace test with tempered glass beams from a ***different manufacturer***

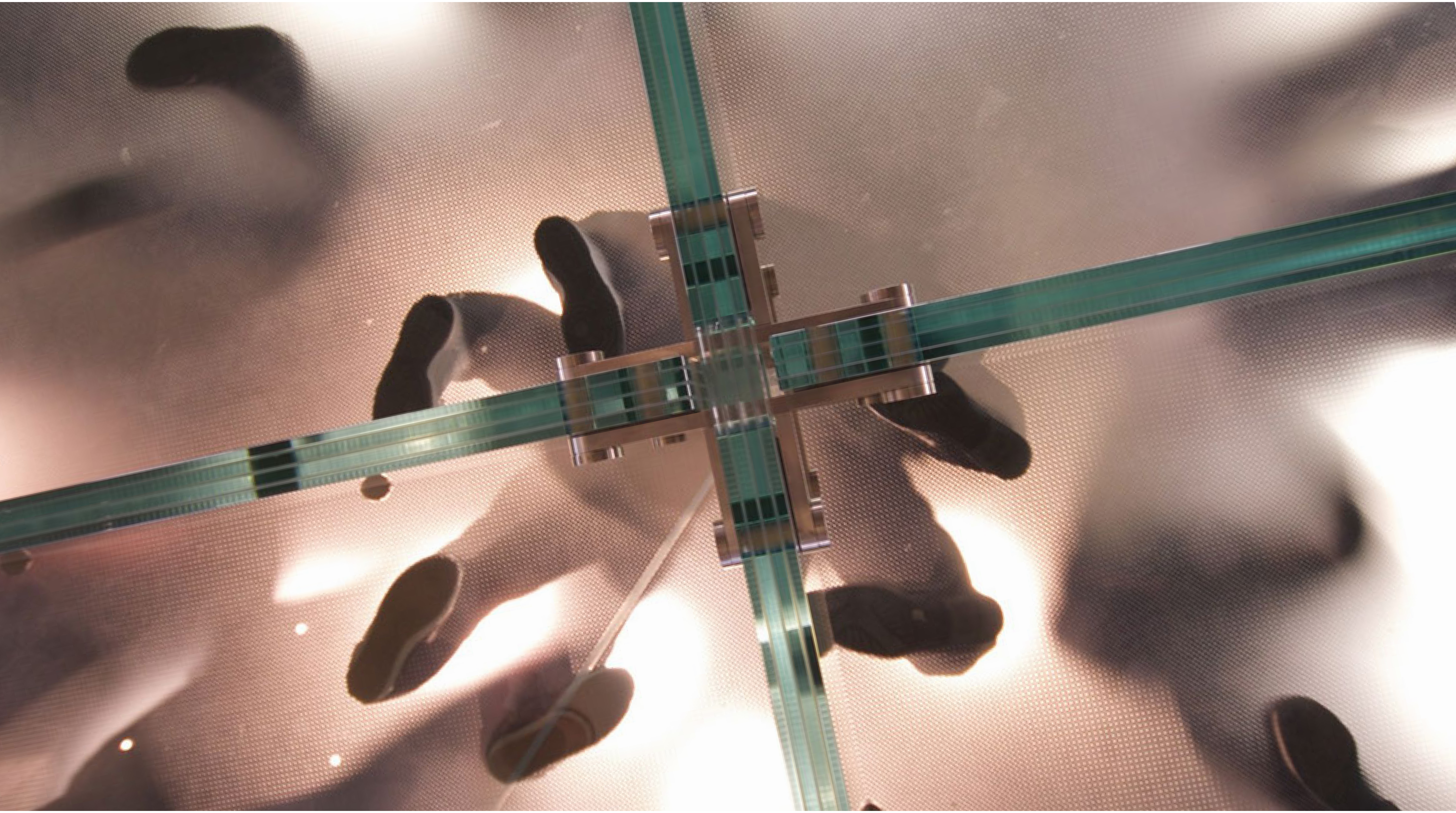
3. Determine the ***thermal coefficient*** of of ***toughened glass***.

4. Repeat - Glass exposed to ***radiant heat***, using thermally toughened and chemically ***toughened glass***

~Debuyser, Ahmad, Jørgensen

5. Investigate the effect of a ***low-e coating***, which stops radiation/light with a low wavelength.

MY VISION



THANK YOU

PHYSICAL TESTING AT EFECTIS

Table 17 – Failure comparison of the PVB beams between the EMPA test and the Efectis test

PVB Interlayer	Failure time Louter – EMPA	Failure time Sturkenboom - Efectis	Time difference
Annealed glass	34.6 min	14.9 min	19.8 min
Heat Strengthened	39.6 min	17.2 min	22.4 min
Fully Tempered	42.8 min	16.2 min	26.6 min

Table 18 – Failure comparison of the SentryGlas beams between the EMPA test and the Efectis test

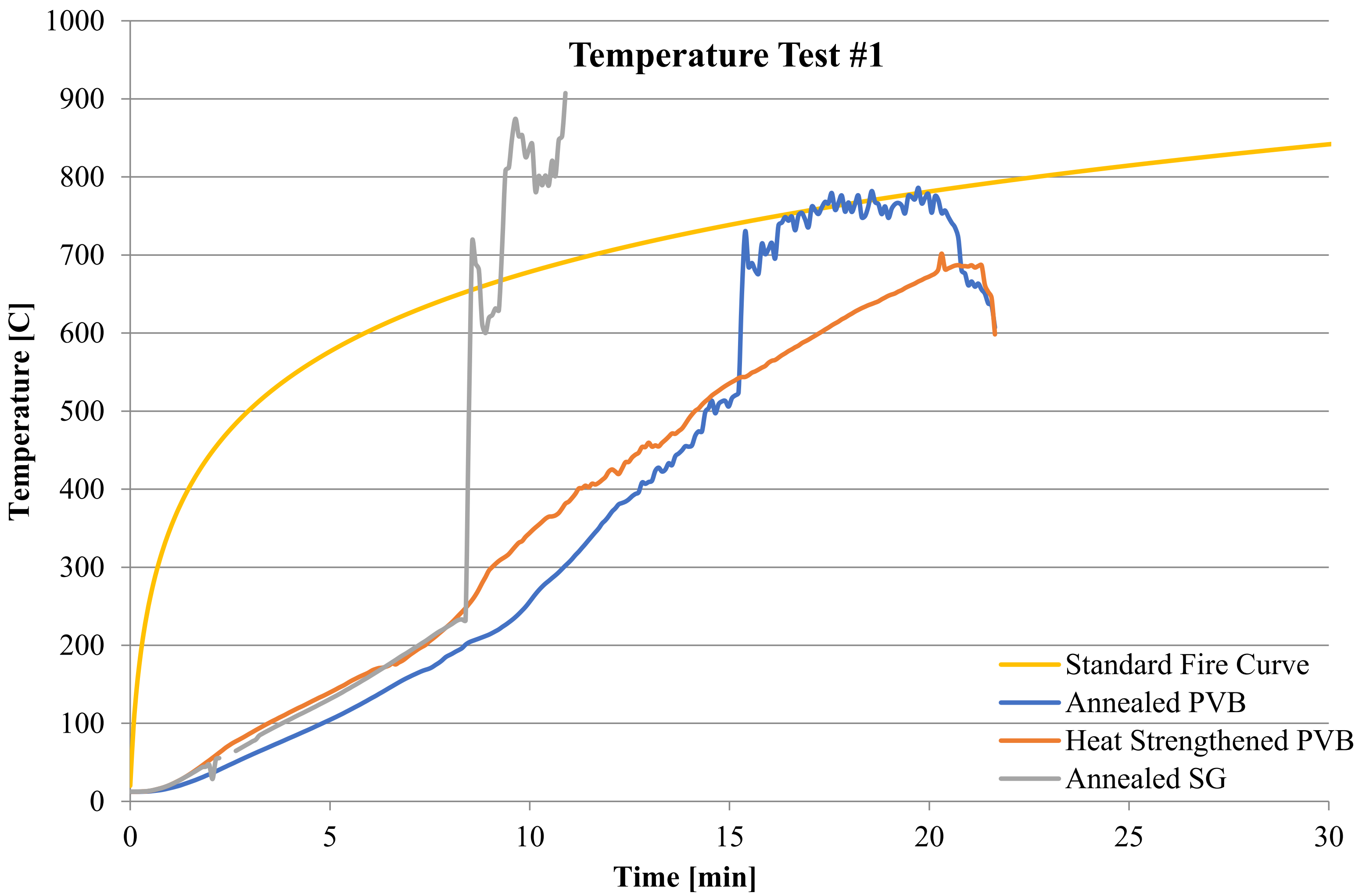
SentryGlas Interlayer	Failure time Louter – EMPA	Failure time Sturkenboom - Efectis	Time difference
Annealed glass	32.9 min	7.8 min (fracture)	25.1 min
Heat Strengthened	41.8 min	17.0 min	24.8 min
Fully Tempered	48.0 min	17.5 min	30.5 min

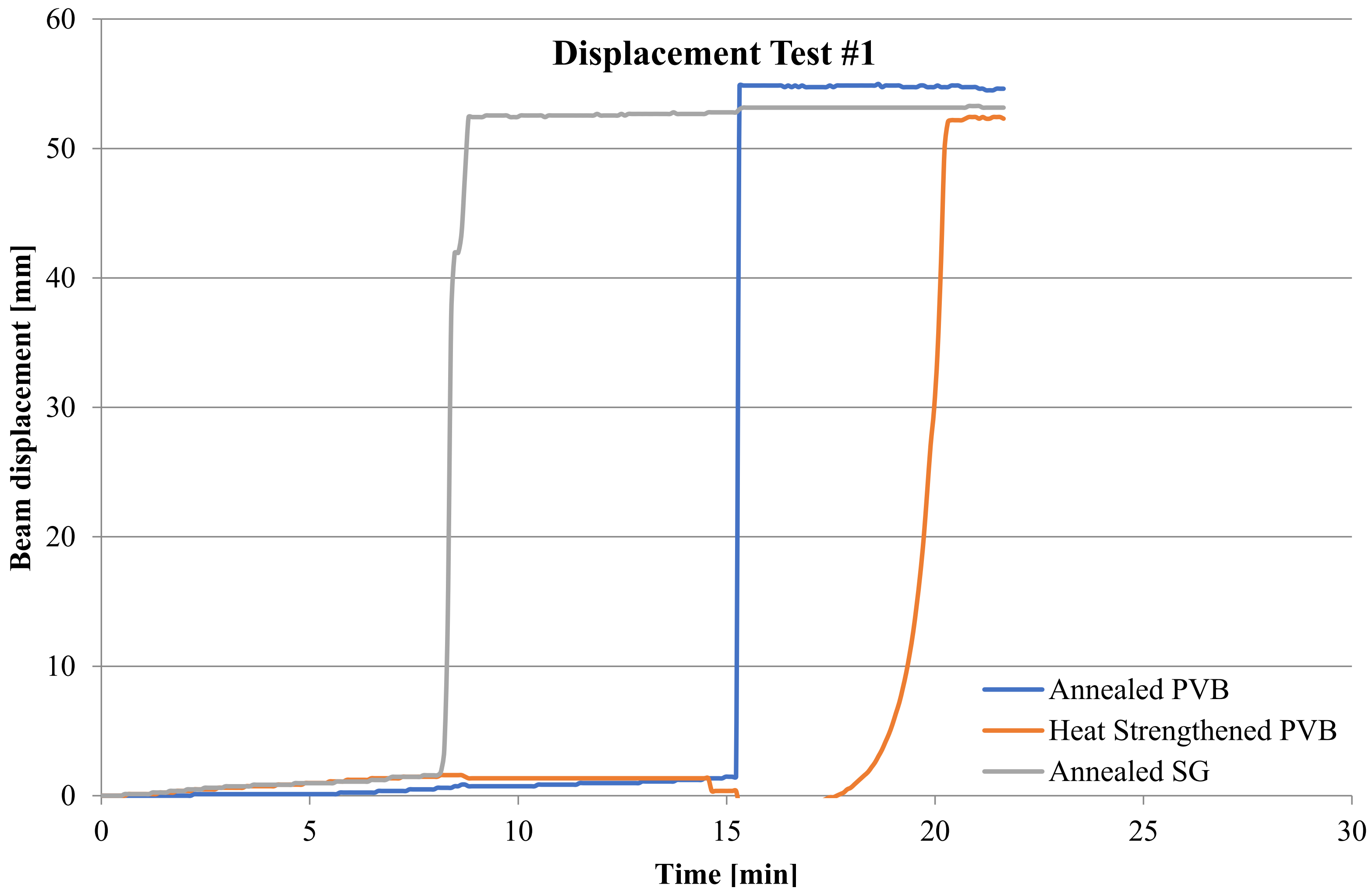
PHYSICAL TESTING AT EFECTIS

	Beam 1 - PVB (AN)	*Time:* ***14.89 min (513 C)***	
Test 1	Beam 2 - SG (AN)	*Time:* ***7.81 min (219 C)***	*- thermal shock*
	Beam 3 - PVB (HS)	*Time:* ***17.23 min (599 C)***	
	Beam 1 - SG (HS)	*Time:* ***17.04 min (508 C)***	
Test 2	Beam 2 - SG (FT)	*Time:* ***15.39 min (578 C)***	*- influenced by PVB flames*
	Beam 3 - PVB (FT)	*Time:* ***16.23 min (585 C)***	
	Beam 1 - SG (FT)	*Time:* ***17.46 min (515 C)***	
Test 3	Beam 2 - SG (AN)	*Time:* ***4.71 min (139 C)***	*- thermal shock*
	Beam 3 - SG (HS)	*Time:* ***15.71 min (571 C)***	

SG-Beams	*Time:* ***16.4 min***	*Temp:* ***543 C***	*- excl. thermal shock AN*
PVB-Beams	*Time:* ***16.1 min***	*Temp:* ***566 C***	

PHYSICAL TESTING AT EFECTIS - TEST 1





Beam 1 - **PVB (AN)**

Time: ***14.89 min*** *(513 ˚C)*

- thermal shock

Beam 2 - **PVB (HS)**

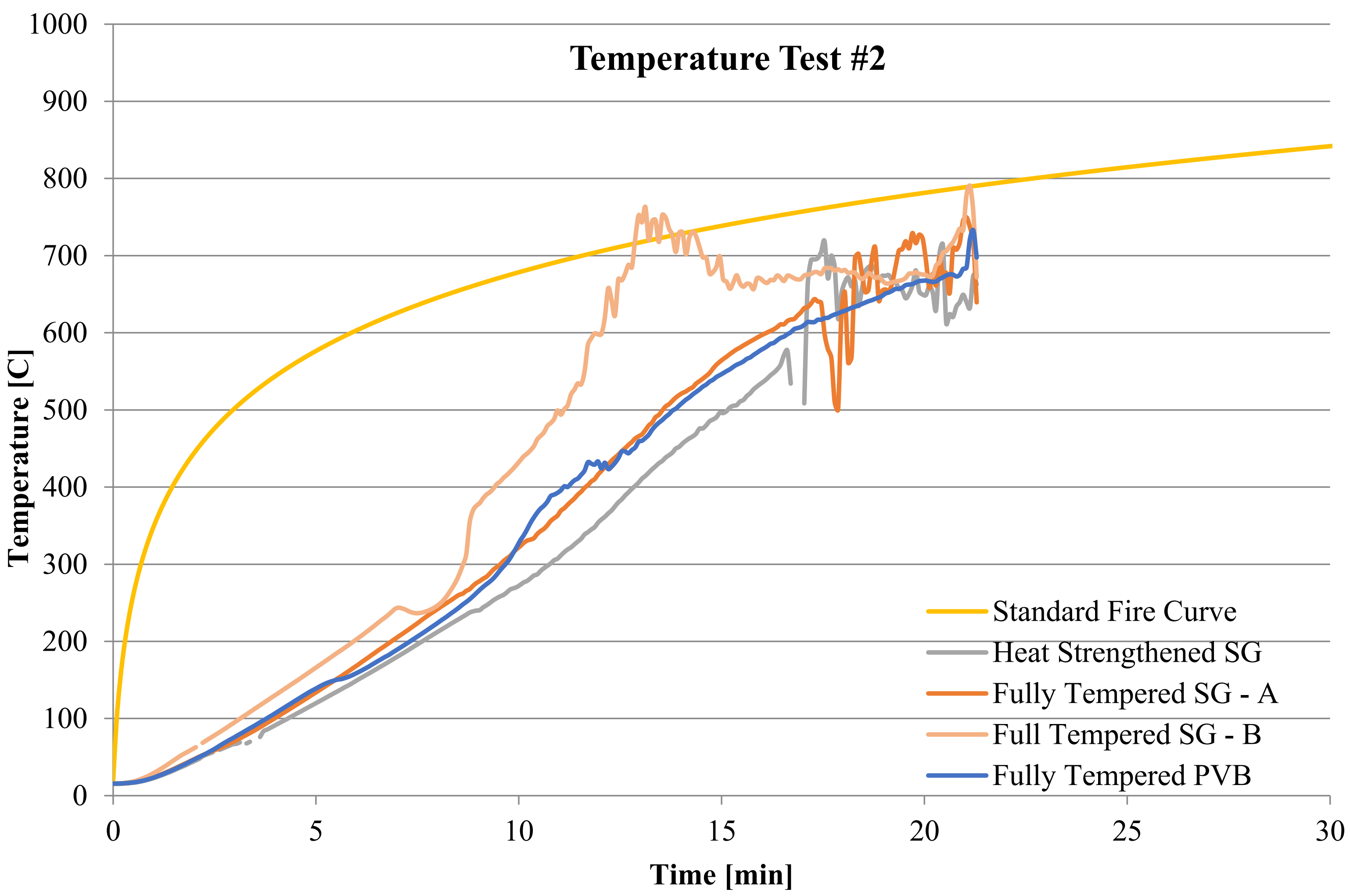
Time: ***17.23 min*** *(599 ˚C)*

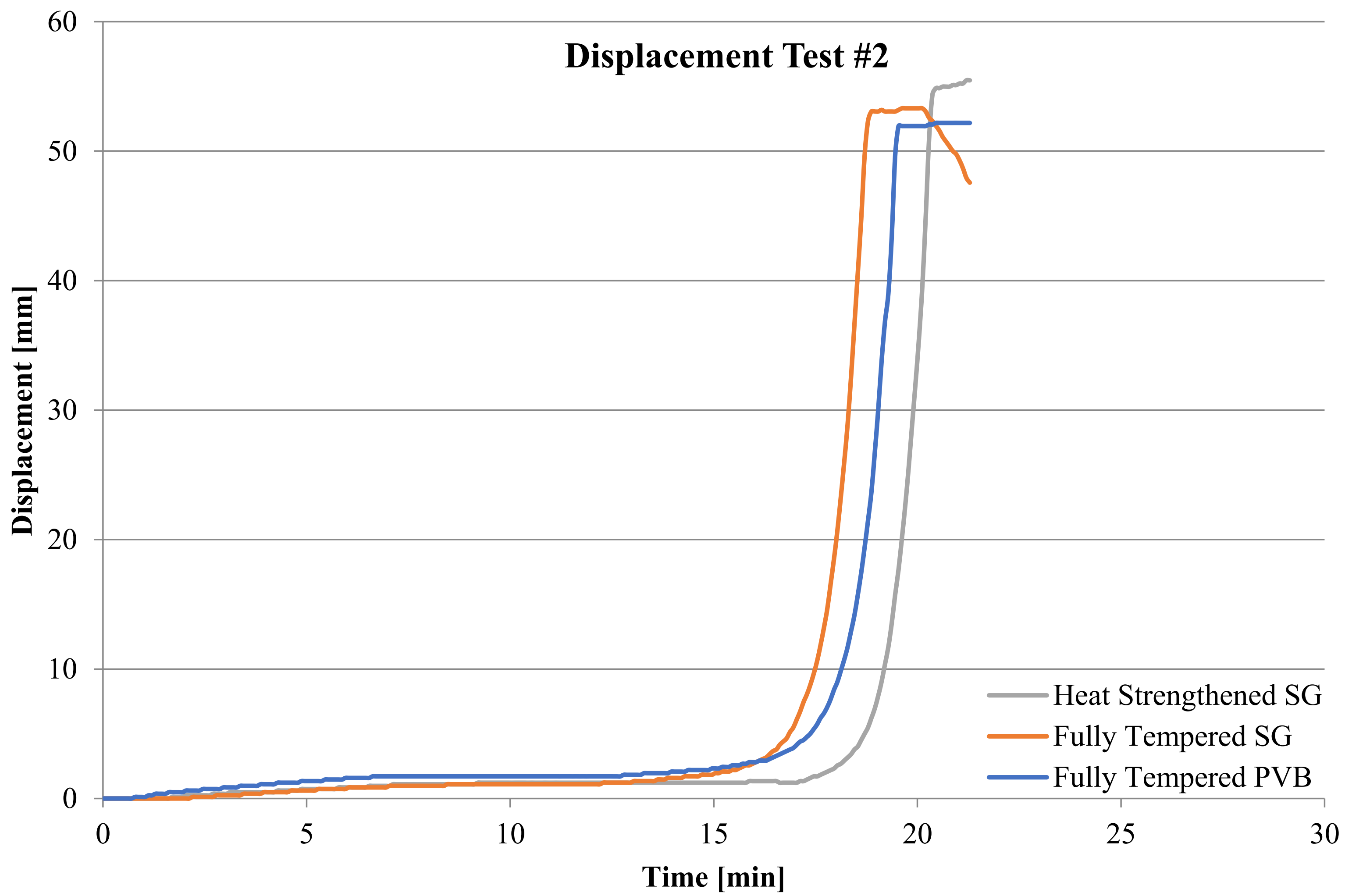
Beam 3 - **SG (AN)**

Time: ***7.81 min*** *(219 ˚C)*

- thermal shock

PHYSICAL TESTING AT EFECTIS - TEST 2



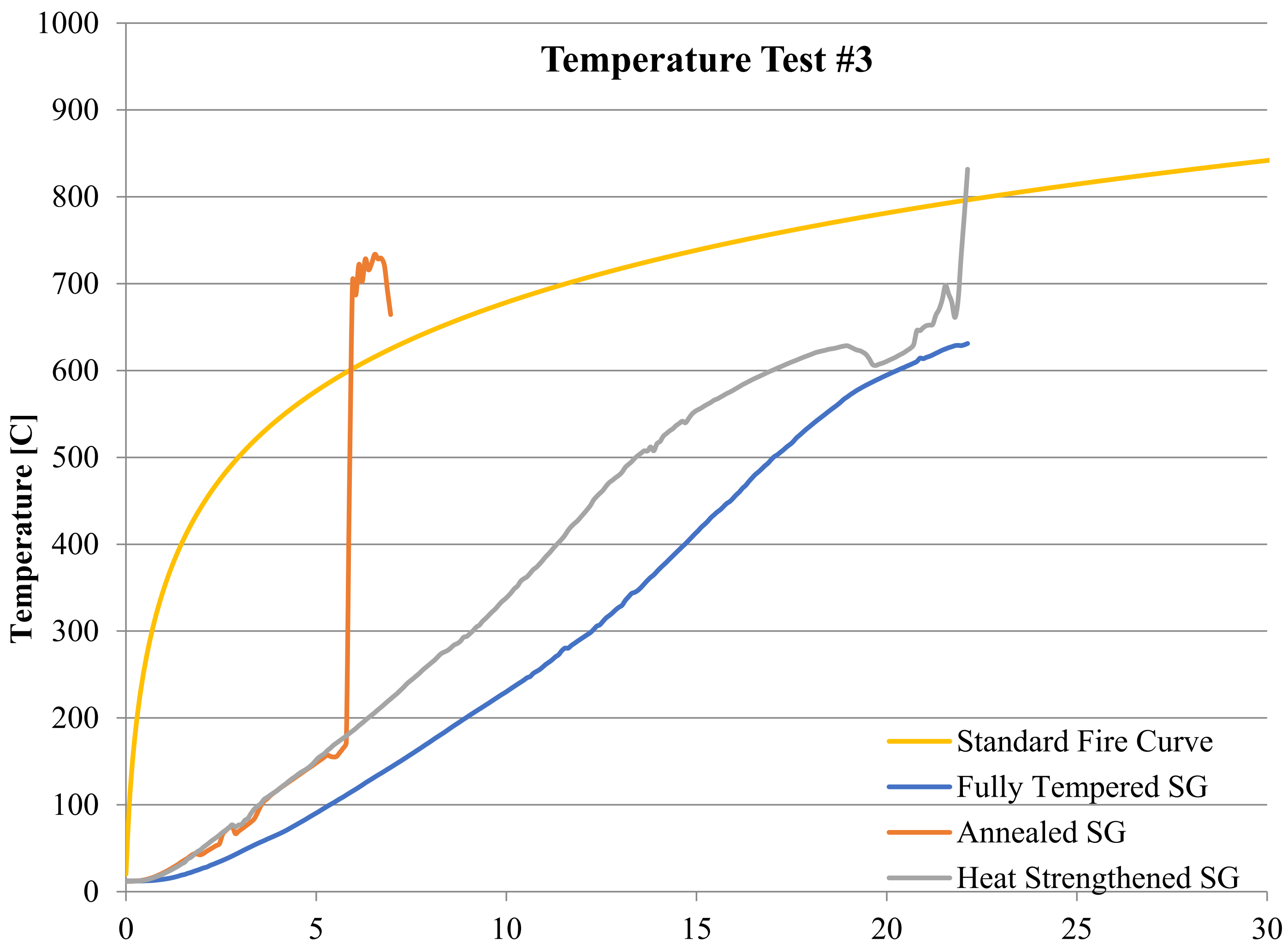


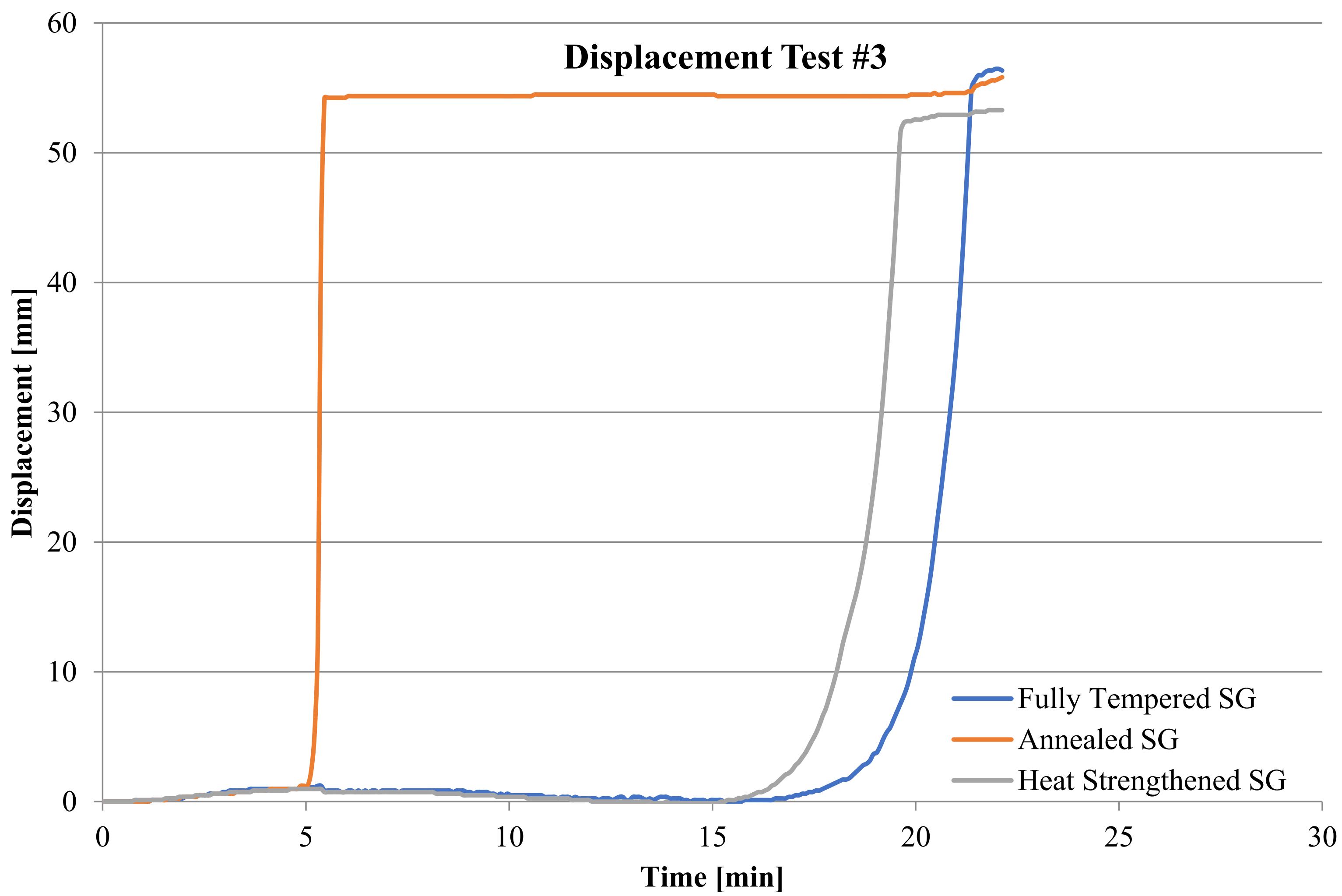
Beam 1 - **SG (HS)**
Time: ***17.04 min*** *(508 ˚C)*

Beam 2 - **SG (FT)**
Time: ***15.39 min*** *(578 ˚C)*
- influenced by PVB flames

Beam 3 - **PVB (FT)**
Time: ***16.23 min*** *(585 ˚C)*

PHYSICAL TESTING AT EFECTIS - TEST 3





Beam 1 - **SG (FT)**

Time: ***17.46 min*** *(515 ˚C)*

Beam 2 - **SG (AN)**

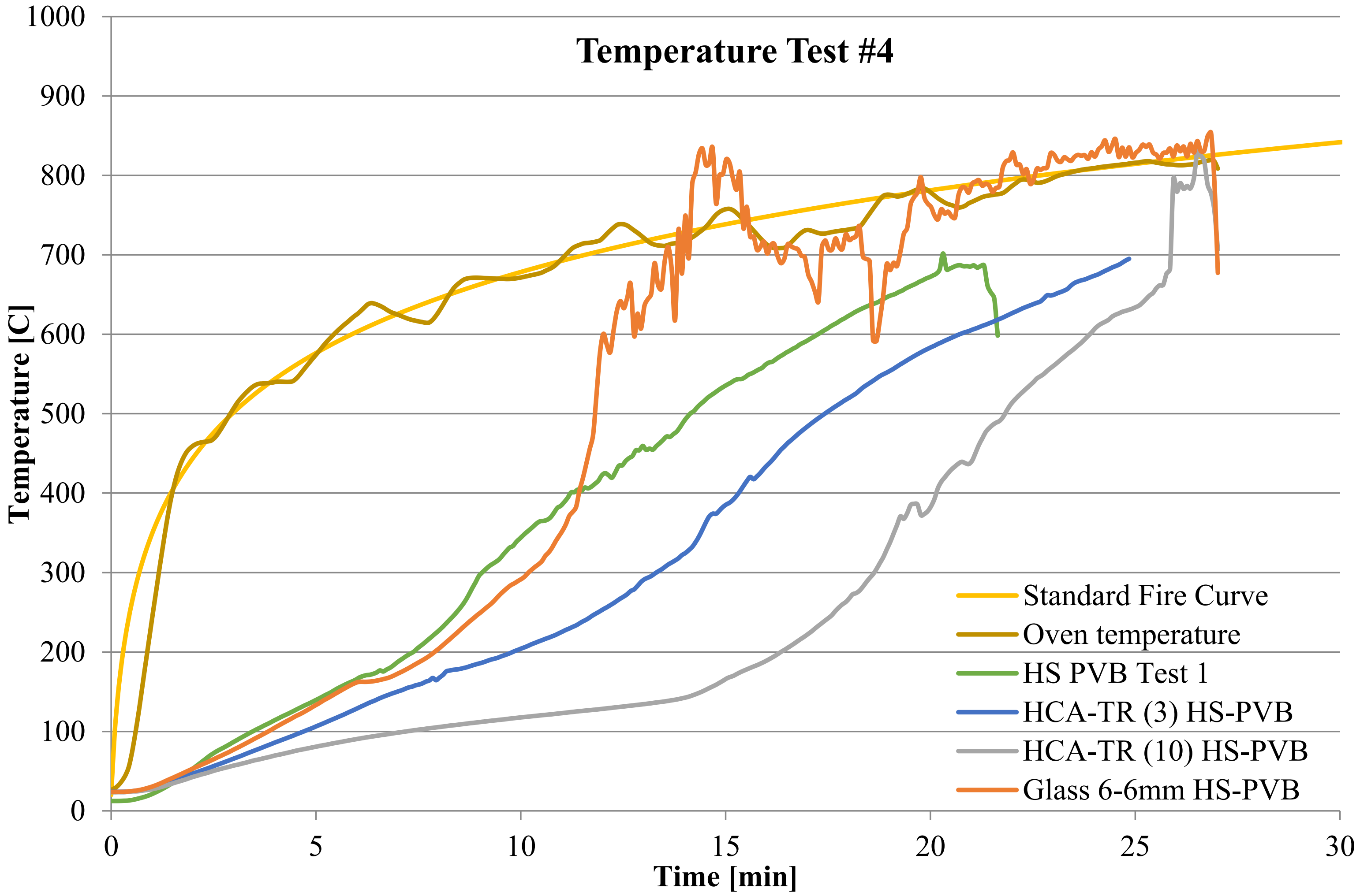
Time: ***4.71 min*** *(139 ˚C)*

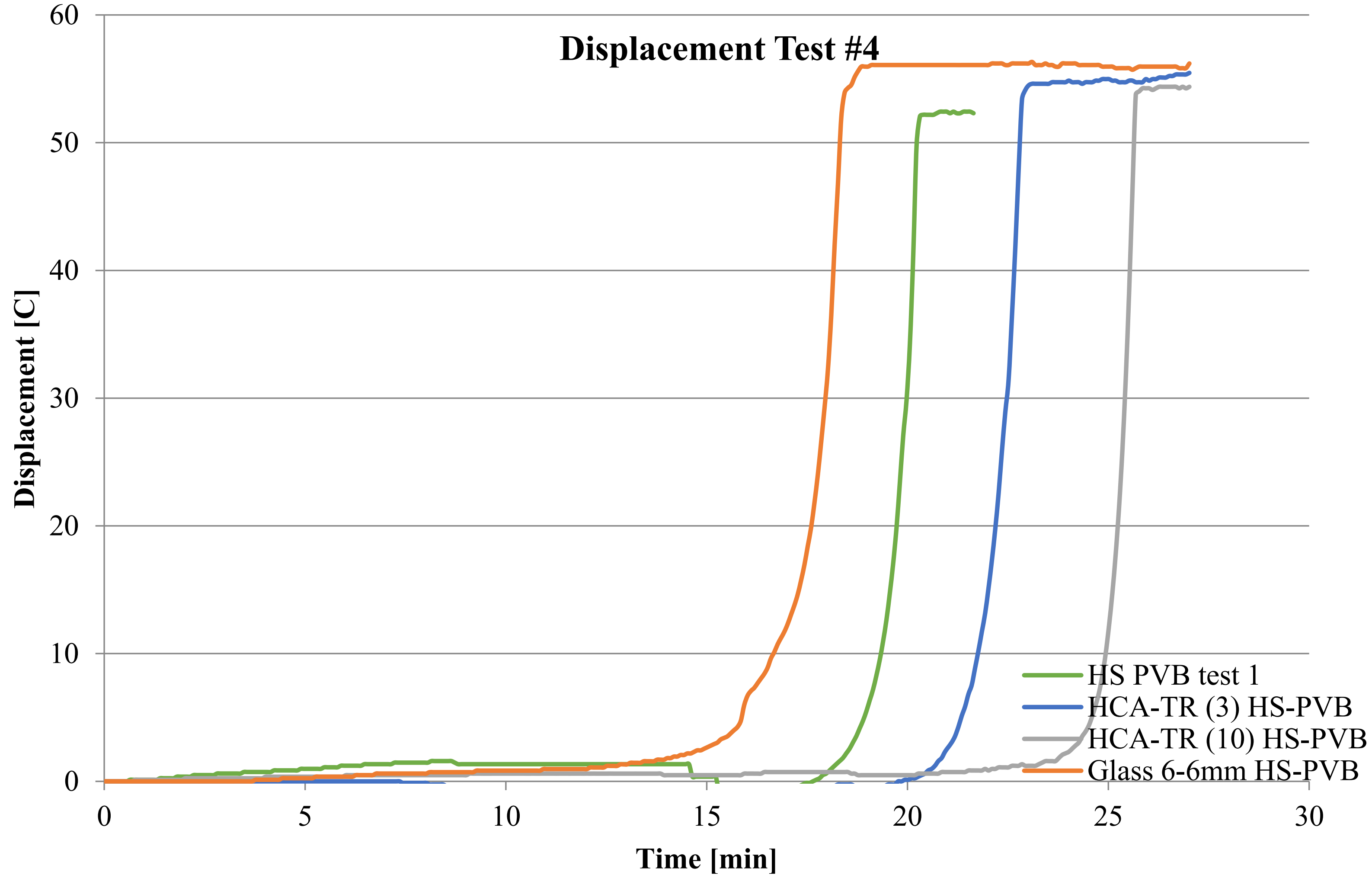
- thermal shock

Beam 3 - **SG (HS)**

Time: ***15.71 min*** *(571 ˚C)*

PHYSICAL TESTING AT EFECTIS - TEST 4





Beam 1 - **3 cm HCA-TR**

Time: ***19.68 min*** *(574 °C)*

Beam 2 - **6-6mm Glass buffer**

Time: ***14.60 min*** *(549 °C)*

- thermal shock

Beam 3 - **10 cm HCA-TR**

Time: ***23.43 min*** *(524 °C)*

PHYSICAL TESTING AT EFECTIS - OVERVIEW

SG-Beams *Time: 16.4 min (543 C)* *- excl. thermal shock AN*

PVB-Beams *Time: 16.1 min (566 C)*

PVB Beams	Beam #	Researcher	Test #	Addition	Position	Loadcase	Fracture	Observation	Start Temp.
Annealed	1	Christian	Test PVB	x	AN PVB - pos 2	115 kg	NO		27.22
	2	Jelle	Test 1	x	AN PVB - pos 1	115 kg	NO		12.27
Heat Strengthened	3	Christian	Test PVB	x	HS PVB - pos 3	115 kg	NO		25.26
	4	Jelle	Test 1	x	HS PVB - pos 2	115 kg	NO		12.43
	5	Jelle	Test 4	3 cm HCA-TR	HS PVB - pos 1	115 kg	NO		23.91
	6	Jelle	Test 4	2x 6 mm glas	HS PVB - pos 2	115 kg	(Yes)		23.81
	7	Jelle	Test 4	10 cm HCA-TR	HS PVB - pos 3	115 kg	NO		23.52
Fully Tempered	8	Christian	Test PVB	x	FT PVB - pos 3	115 kg	NO		21.74
	9	Jelle	Test 2	x	FT PVB - pos 3	115 kg	NO		15.65

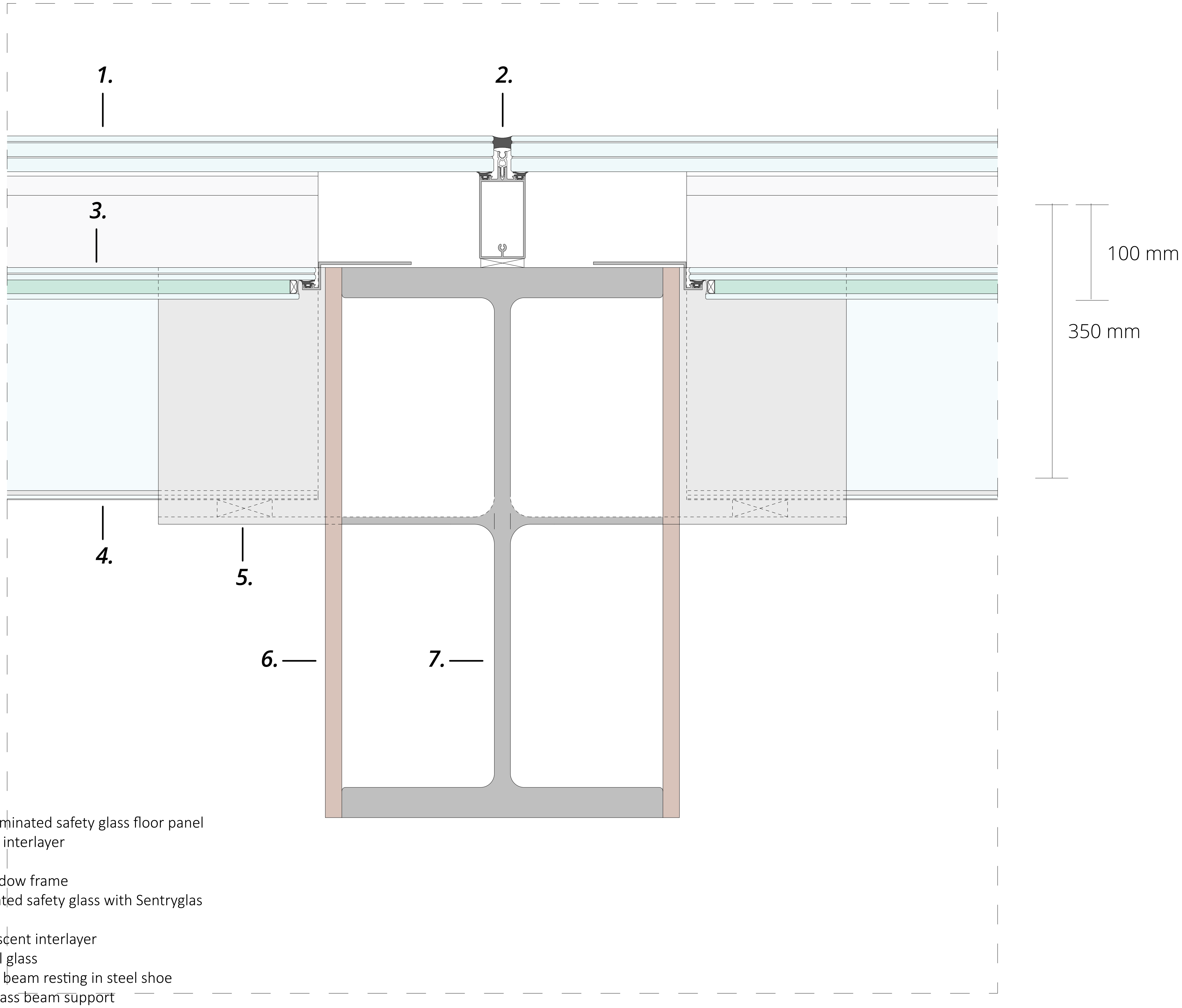
SG Beams	Beam #	Researcher	Test #	Addition	Position	Loadcase	Fracture	Observation	Start Temp.
Annealed	10	Christian	Test SG	x	AN SG - pos 1	115 kg	NO		25.23
	11	Jelle	Test 1	x	AN SG - pos 3	115 kg	Yes		12.47
	12	Jelle	Test 3	x	AN SG - pos 2	250 kg	Yes		12.03
Heat Strengthened	13	Christian	Test SG	x	HS SG - pos 2	115 kg	NO		25.25
	14	Jelle	Test 2	x	HS SG - pos 1	115 kg	NO		15.19
	15	Jelle	Test 3	x	HS SG - pos 3	250 kg	NO		11.92
Fully Tempered	16	Christian	Test SG	x	FT SG - pos 2	115 kg	NO		21.64
	17	Jelle	Test 2	x	FT SG - pos 2	115 kg	NO		15.61
	18	Jelle	Test 3	x	FT SG - pos 1	250 kg	NO		12.30

PVB Beams	Beam #	Max increase >0.94mm/min	Corresponding temperature	Max deflection >21.16 mm	Corresponding Temp.
Annealed	1	34.68	742.43	39.83	N/A
	2	14.89	513.05		
Heat Strengthened	3	39.55	755.79	44.59	779.46
	4	17.23	599.20	19.56	661.67
	5	22.27	633.06	22.27	633.06
	6	14.60	549.30	17.68	720.74
	7	23.43	582.02	25.27	644.52
Fully Tempered	8	42.83	749.46	48.48	774.56
	9	16.23	585.56	18.54	639.05

SG Beams	Beam #	Max increase >0.94mm/min	Corresponding temperature	Max deflection >21.16 mm	Corresponding Temp.
Annealed	10	32.93	723.76	42.44	765.66
	11	7.81	219.71	8.14	230.46
	12	4.71	139.27	5.13	151.96
Heat Strengthened	13	41.75	760.00	47.81	769.90
	14	17.04	508.50	19.45	654.58
	15	15.71	571.36	18.63	625.56
Fully Tempered	16	48.04	751.42	54.13	762.26
	17	15.39	578.46	17.87	500.56
	18	17.46	514.92	20.29	600.48

1 : 5 Details

Cross section of the support detail between glass beams with aluminium window frame



1. 6-15-15 mm Laminated safety glass floor panel with Sentryglas interlayer
2. Silicone sealant
   Aluminium window frame
3. 8-8 mm Laminated safety glass with Sentryglas interlayer
   15 mm Intumescent interlayer
   6 mm Sacrificial glass
4. Structural glass beam resting in steel shoe
5. Steel shoe as glass beam support
   Spacer
6. Wood multiplex board
7. 800 mm steel IPE beam