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Thermo-mechanical Numerical Modelling of Structural Glass under Fire - Preliminary Considerations and Comparisons

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In this paper, careful consideration is paid for structural glass elements under fire loading. In particular, a thermo-mechanical Finite Element (FE) numerical investigation is carried out in ABAQUS on small-scale structural glass elements exposed to fire. Taking advantage of past literature efforts, major thermal effects on the material properties are taken into account in the form of key input parameters for numerical simulations. Further validation of the so calibrated FE models is then carried out towards past small-scale experimental fire tests on monolithic glass panels. A sensitivity FE study is hence proposed, giving evidence of major influencing parameters on the thermo-mechanical performance of the same structural glass elements, including variations in the fire exposure, thermal-to-mechanical loading ratio, geometrical and mechanical features of the specimens.

Keywords: Structural Glass, Thermo-Mechanical Performance, Finite Element (FE) Numerical Modelling, Fire Conditions, Sensitivity Study, Experiments

1. Introduction

This paper focuses on the numerical modeling of structural glass under fire loading. The performance of structural glass under fire loading is currently largely unknown and has to date been investigated in only a limited number of research projects. For instance, Debuyser et al. (2017) has experimentally investigated monolithic and laminated glass panels with different glass and interlayer configurations under radiant heat flux exposure. In the study, also a preliminary 1D numerical model was developed, to predict the glass surface temperature and interlayer temperature of the executed experiments. Furthermore, Louter & Nussbaumer (2016) reported on fire testing of small structural glass beams of different configurations with a sustained in-plane load. The beams showed appreciable resistance to the fire loading and could sustain the load for a significant duration of time within the given test configuration. However, several aspects should be properly accounted for the assessment of structural glass performance in fire conditions (Bedon, 2017).

The current study adds to the knowledge on the performance structural glass under fire loading. More specifically, a thermo-mechanical Finite Element (FE) numerical investigation is carried out in ABAQUS (Simulia, 2017), simulating small scale glass panels under fire loading. For initial calibration, the FE results are compared with earlier experimental results of a Master Thesis study performed at TU Delft (Nodehi, 2016) in which such monolithic glass panels were exposed to fire loading. Furthermore, several aspects that may influence the performance of the glass panels under fire loading are investigated through an FE parametric analysis. More specifically, within the parameter study, the effects of glass thickness, support conditions, fire exposure conditions and the level of mechanical load on the glass panels are investigated.

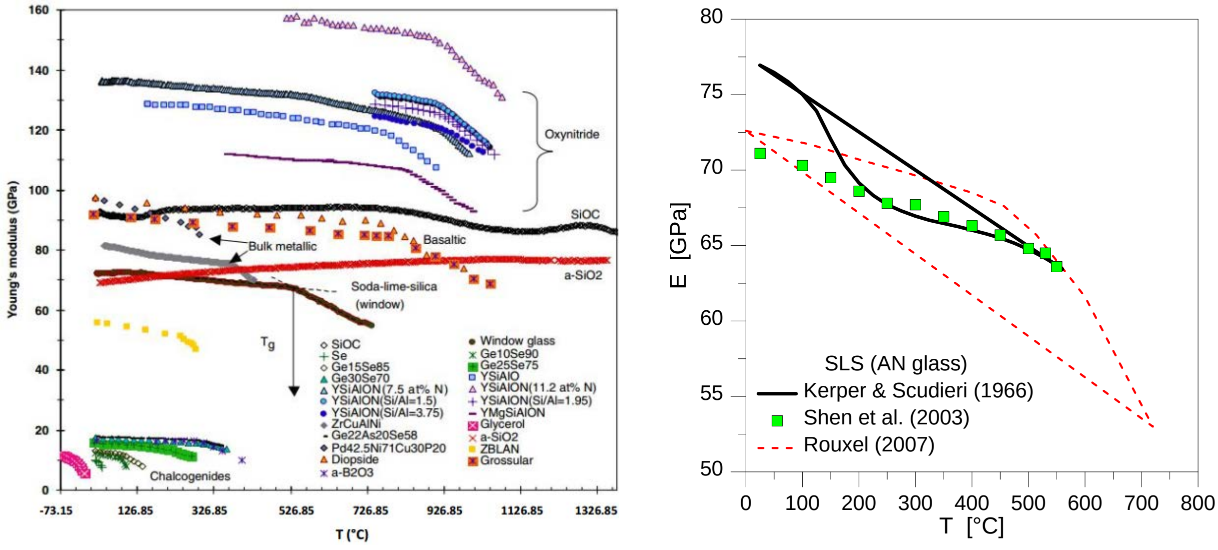
First, a short literature study on the thermo-mechnical properties of glass under high temperatures is given. Secondly, the numerical model configuration is explained and analyses are described. Finally, a discussion and conclusions are provided.

2. Summary on thermo-mechanical properties of glass under high temperatures

Since the 50s, the performance of glass under high temperatures under heating and fire loading attracted the attention of several experimental research studies, due to the consistent use of glass panels in windows and fenestrations. Most of those investigations are related to thermal shock effects in Soda Lime Silica (SLS, in the following) glass, as well as to its thermal characterization in general, including variations of modulus of elasticity (MOE) and resistance with high temperatures, while only limited experimental studies are currently available for composite glass systems and assemblies under fire or combined fire and mechanical loads. Input thermal and mechanical properties and variation with temperature, however, represent a key aspect for Finite Element numerical investigations. In this regard, the following paragraphs report a summary of major research outcomes at glass material level, giving evidence of key influencing parameters that should be properly accounted for the assessment of the fire response of structural glass systems.

2.1. Modulus of elasticity and tensile resistance

The elastic properties of standard glass at elevated temperatures have been extensively assessed by Rouxel (2007), by accounting for experimental data available in the literature after the 50s, giving evidence of SLS glass' MOE sensitivity to temperature, as compared with other glass types, see Figure 1(a) - with SLS annealed float glass (AN) labeled as 'window glass'. Rather linear dependency and limited decrease can be observed for MOE values of SLS glass, as far as *T* does not exceeds the transition temperature T_g of glass, while a subsequent abrupt loss of stiffness is shown.



a) b)

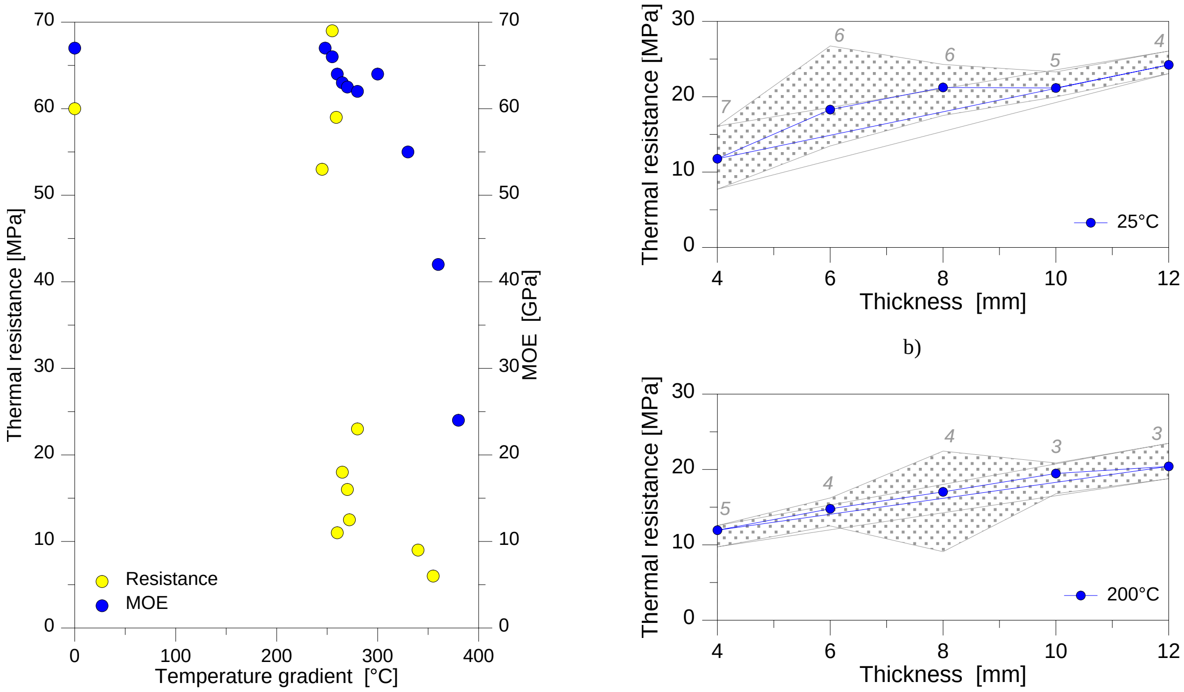
Fig. 1 MOE variation in glass, as a function of temperature, with evidence of a) several glass types (Rouxel, 2007) or b) SLS glass type.

Earlier experiments were also carried out on SLS glass components by Kerper & Scudieri (1966), with careful attention for specimens including (i) chemically strengthened (HS) SLS glass and (ii) thermally fully-tempered (FT) SLS glass. Through the experimental study, glass laths with dimensions of 254×38.1mm (6.35mm in thickness) and 152.4×25.4mm (2.54mm in thickness) were considered. Given the examined specimen types and a reference temperature (0-560°C the tested range), almost stable MOE values were experimentally derived, even after sequential heating and cooling cycles. MOE values were generally found to be completely relaxed for temperatures higher than 400°C. Close correlation can be observed with MOE variations of standard AN glass specimens, as derived from different literature sources, see Figure 1(b), where test results from Shen et al. (2003) on monolithic SLS samples (75.43×14.80mm the size, with 3.26mm the nominal thickness) are also reported.

Worth of interest for structural design purposes is that Kerper & Scudieri (1966) also assessed the resistance variations in SLS glass at high temperatures. In particular, no resistance losses were reported for temperatures up to 375°C (less than 5% losses, compared to room temperature), for thermally FT specimens. Substantial decrease of resistance was recorder only for temperatures higher than 500° (fire exposure of several hours) and 550°C (15 minutes of fire exposure). Chemically strengthened SLS glass showed indeed a pronounced resistance degradation with the temperature increase, up to 5% loss at 204°C (500 hours of fire exposure), 5.8% at 260°C (500 hours) and 100% at 600°C (6 hours).

2.2. Thermal shock resistance

A huge number of experimental studies related to SLS glass performance has been focused on thermal breakage assessment, being representative of the major cause of glass cracking for windows. The issue of glass thermal cracking and fall-out has been first raised in the 80s by Emmons (1986), while in the last decades an increasing number of experiments has been carried out on small scale specimens, single glass panes, or double glass panes variably supported, under the effect of fire or heat radiation. Malou et al. (2013) carried out thermal resistance experiments on 3mm thick, SLS, AN glass specimens (15×50mm their nominal size). A rather constant value was recorder for the tensile strength of glass, up to a temperature increase of 270°C, see Figure 2(a). Higher temperatures were indeed associated to sharp decrease in the measured resistance (more than 50% the reference value at room temperature), giving evidence of thermal shock effects and damage propagation in glass specimens, as well as of generally limited performances of AN glass. A rather smooth MOE decrease was also observed, see Figure 2(a). Later on, Xie et al. (2011) experimentally investigated the tensile resistance of SLS, AN glass specimens at high temperatures. Quasi-static tensile tests were carried out on small specimens, with thickness comprised between 4mm and 12mm (2mm the difference between each set of specimens). Test repetitions on specimens with the same geometrical properties were carried out at 25°C and 200°C, where the critical breakage resistance was derived as the first cracking occurrence. In Figures 2(b)-(c), evidence of such test results (average values, with minimum and maximum values for each series) is provided. Negligible decrease of resistance was noticed for specimens exposed to 200°C, compared to room temperature results, while higher sensitivity was observed especially to glass thickness (see Figures 2(b)-(c)). Worth of notice that as far as different literature references are examined, even counterposed experimental findings can be derived, giving evidence of a typically high scatter and sensitivity of glass thermal resistance to elevated temperatures, hence suggesting further testing and investigations at the material level.



a)

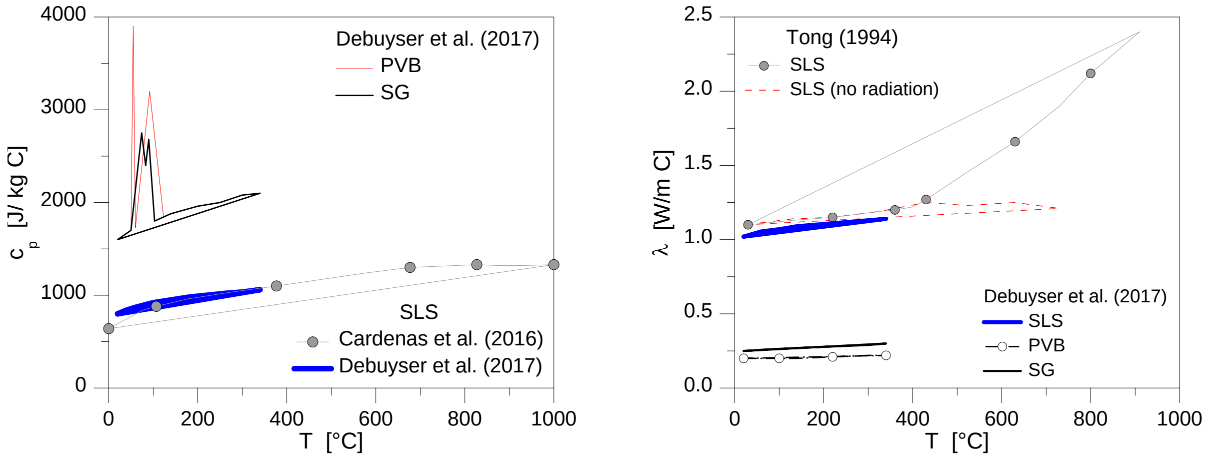
b)

c)

Fig. 2 Thermal characterization of SLS glass. a) Variation of MOE and resistance, under thermal shock (Malou et al., 2013) and b)-c) dependency of thermal shock resistance to glass thickness (in gray italic, the number of tests for each thickness), in accordance with (Xie et al., 2011).

2.3. Specific heat and thermal conductivity

Specific heat and thermal conductivity represent further key input parameters for numerical modelling of structural glass systems, especially when composite resisting sections consisting in laminated glass (LG) panels and/or glass systems in general under various boundary restraints are examined. For LG sections, the thermal performance of glass as well as of interlayers of common use for glazing applications should be in fact properly taken into account. In this regard, Debuyser et al. (2017) investigated the behaviour of monolithic and triple layer LG specimens composed of AN glass, being bonded together by PVB or SG layers. Both radiant and transmittance tests were carried out, giving evidence - in accordance with earlier research efforts - of the relatively limited resistance and low thermal performance of AN glass specimens, due to the premature occurrence of thermal cracks as well as to the poor thermal reaction of bonding interlayers. Thermal properties of AN glass, as well as PVB and SG foils, were also reported, see Figure 3. Test results for glass - even limited to maximum temperatures of 340°C - showed a close correlation with past literature references, see Figure 3.



a) b)

Fig. 3 Thermal properties of glass, as a function of temperature: a) specific heat and b) conductivity.

3. Finite Element numerical analyses

In this research paper, Finite Element numerical investigations carried out in ABAQUS (Simulia, 2017) are presented for simple monolithic glass specimens under fire and/or combined fire/mechanical loading, giving evidence of capacity and possible limits of advanced FE methods with respect to experimental testing. In doing so, part of the past fire tests and experimental observations reported in (Nodehi, 2016) are taken into account, for extended parametric studies.

3.1. Reference experimental glass specimens

The full experimental program discussed in (Nodehi, 2016) included fire experiments on monolithic panels, 10mm in thickness, with 1.5m length×0.3m width nominal dimensions, composed of AN, HS and FT glass types. The original experimental protocol was defined to assess the thermo-mechanical performance of glass panels under various loading and boundary conditions, including simply supported glass panes in lying or standing configuration, as well as subjected both to fire loading only or a combination of fire and mechanical loads, see (Nodehi, 2016). In this research study, for comparative FE purposes, two test specimens are taken into account, see Table 1 and Figure 4.

Table 1: Summary of selected past experiments (Nodehi, 2016).

Specimen	Dimensions [mm]	Thickness [mm]	Glass type	Orientation	Mechanical loads	Failure time [s]
A	1500 x 300	10	AN	Lying	Self weight + 16Kg	46
B					Self weight	126

Both the specimens A and B were subjected to a standard ISO fire curve, in accordance with (EN 1363-1). Steel supports were used to sustain the glass panes. The difference was given by the presence - for the panel A only - of additional permanent loads applied in accordance with Figure 4a).

Collapse of both the specimens resulted in premature cracking of glass, in the vicinity of steel supports, after 46s and 126 s respectively of fire loading.

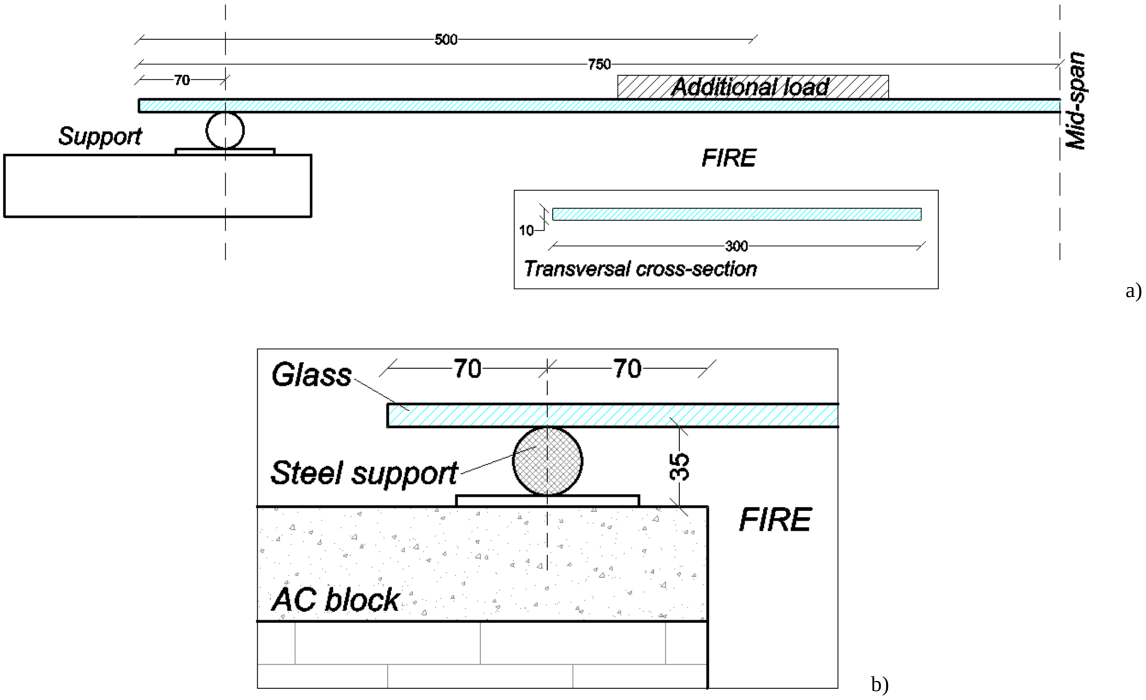


Fig. 4a) Test setup (lateral view), with b) supports detail (cross-section). Nominal dimensions in mm.

Experimental measurements included a set of thermocouples positioned on the top surface of glass panels, in accordance with Figure 5(a), as well as 4 additional temperature regulators, to monitor the temperature evolution within the oven. Basically, temperature measurements revealed a non uniform distribution of temperatures, see Figures 5(b) and (c). Major issues proved to derive from steel supports, being representative of additional local thermal effects for the glass panels, see (Nodehi, 2016).

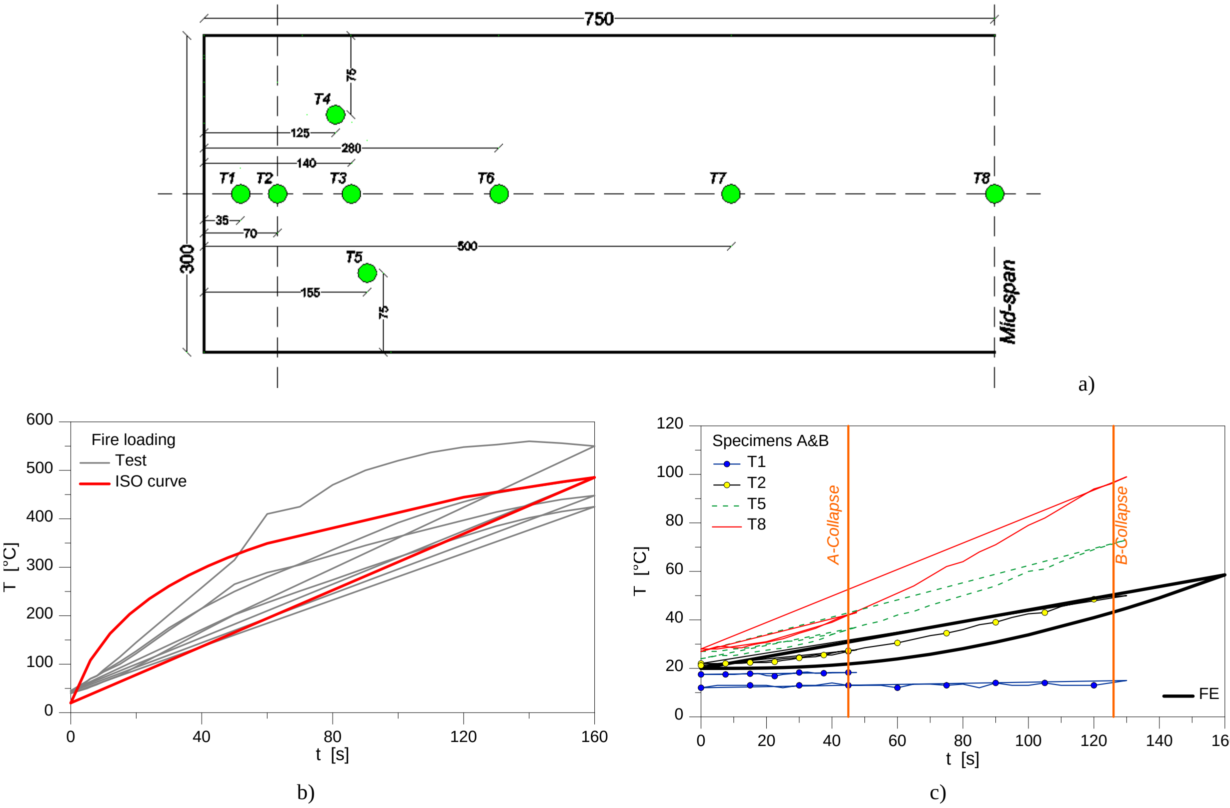


Fig. 5a) Test setup (lateral view), with b)-c) supports detail (cross-section) and d) position of temperature control points (top view). Nominal dimensions in mm.

3.2. Thermal analyses in fire conditions

Given the reference specimens described in Table 1, the typical FE simulation consisted of two uncoupled steps. In particular, a transient, heat transfer analysis was first carried out to describe the thermal state of the typical glass specimen subjected to the ISO fire curve displayed in Figure 5(a). 8-node, heat transfer solid elements were used to describe the nominal geometry of glass panels (DC3D8 type from ABAQUS library). In order to optimize the computational efficiency of FE simulations, 1/2 the actual geometry was numerically described. In doing so, symmetry thermal constraints were considered along the middle symmetry axis, while the full 3D assembly was subjected to an initial ambient temperature of 20°C. The fire exposure of glass specimens was then simulated by means of appropriate boundary conditions of radiation and convection, being defined at the interface between glass panels and the surrounding environment, as well as in the vicinity of supports (see sections 4 and 5). In terms of thermo-physical characterization of glass, conductivity and specific heat were defined in accordance with Figure 3. Emissivity and convection coefficients of glass were set to 0.95 and 8.02W/m^{2}K (EN ISO 10077-2).

3.3. Mechanical analyses in fire conditions

As a subsequent stage of each heat transfer simulation, an uncoupled nonlinear mechanical analysis was carried out on the same FE model described in section 3.2, aiming to assess the effects of the imposed fire and/or mechanical loads. To this aim, the results of the thermal simulation were separately saved, in the form of a distribution of nodal temperature histories for all the nodes composing the FE model, and then imported as reference configuration for the mechanical analysis. In this way, under the assigned mechanical loads, the variations in maximum stresses occurring in glass due to temperature increases were properly taken into account. To this aim, the same geometry and mesh pattern of FE models was hence used for both the thermal and mechanical simulations. In the latter case, compared to section 3.2, modifications of thermal FE models were introduced at different levels, including the (i) type of 8-node solid elements, (ii) boundary and loading conditions, (iii) contact interactions and (iv) material mechanical properties. C3D8R type, linear brick elements with reduced integration were in fact used. The symmetry of the FE model was ensured by nodal restraints for the nodes laying on the vertical symmetry plane of the specimen. The full FE model was hence simply supported in accordance with Figure 4, while self-weight of glass was automatically assigned in the form of a distributed gravity load. Glass density at 20°C was set to a nominal value of 2500kg/m^3. Given the glass MOE variation with temperature reported in Figure 1(b), the input data reported by Rouxel (2007) were taken into account. The tensile brittle behaviour of material was also accounted in the form of a *concrete damaged plasticity* mechanical model (Simulia, 2017; Bedon & Louter, 2018). Based on a nominal tensile resistance of 45MPa for AN glass (EN 572–2), the material strength was assumed to linearly decay with temperature, as also reported by Kerper and Scudieri (1966), hence to fully vanish at 500°C.

4. Discussion of FE thermal simulations

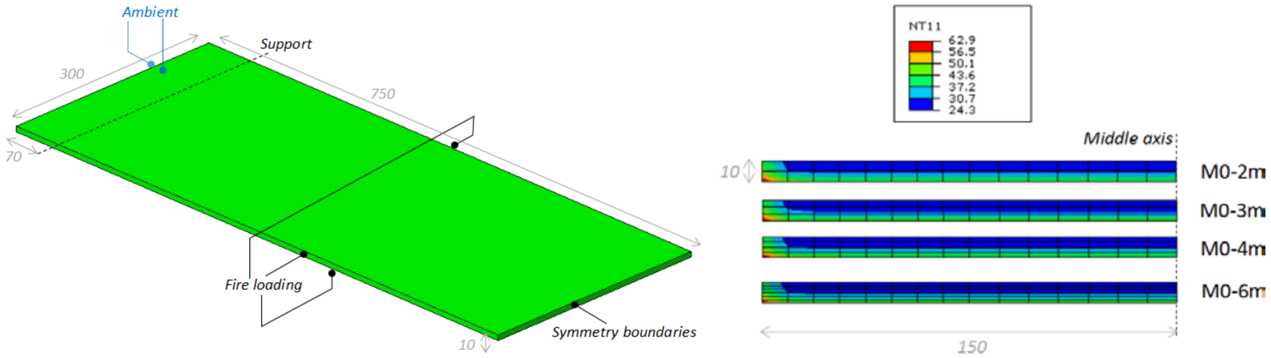
The specimens A and B were first numerically explored by spending careful attention for key influencing parameters and assumptions on their actual thermal performance, such as mesh features, as well as the FE description of boundary restraints or fire exposure. As known, the load bearing capacity of the examined glass panels in fire conditions is strictly related to temperature sensitivity of glass mechanical properties. The temperature distribution and evolution in time should be consequently properly assessed. The full set of FE models summarized in Table 2 was considered through the parametric investigations.

Table 2: Summary of parametric FE models (ABAQUS).

FE Model #	Label	Elements in glass thickness	Supports	Exposed surfaces	Fire exposure	Mechanical loads
M0	M0-2m	2	No	3	Uniform (ISO fire curve)	Self weight 16kg
	M0-3m	3				
	M0-4m	4				
	M0-6m	6				
MS	MS-0.5b	4	Yes (steel cylinders)	3	Uniform (ISO fire curve)	Self weight 16kg
	MS-1b					
	MS-1.5b					
	MS-2b					
MR	MR-0.9f	4	Yes (steel cylinders)	3	Non-uniform (ISO fire curve, with partial exposure of B2 surfaces - see also Fig.8)	Self weight 8, 16, 24, 32kg
	MR-0.7f					
	MR-0.5f					
	MR-0.1f					

4.1. Mesh sensitivity

Preliminary mesh sensitivity studies were carried out to assess the effects of mesh size and pattern for the reference glass panes. To this aim, a set of ‘M0’ thermo-mechanical FE models was implemented in ABAQUS by accounting for the nominal glass geometry only, that is by fully disregarding the effects due to steel supports detailing. In doing so, see Figure 6(a), the typical glass panel was exposed on 3 sides (bottom surface and and lateral surfaces) to the standard fire ISO curve of Figure 5(a). Given a reference mesh size of 10mm, the temperature distribution and evolution in time was hence explored, by varying the number of solid elements in the glass thickness (from a minimum of 2 elements up to 8 solid elements). In Figure 6(b), selected cross-sectional contour plots of temperatures are compared for the panel mid-span section, with evidence of the temperature scenario after 45s of exposure to the standard fire ISO curve. Comparative results suggested a good balance for the M0-4m model with 4 elements in the thickness of glass.



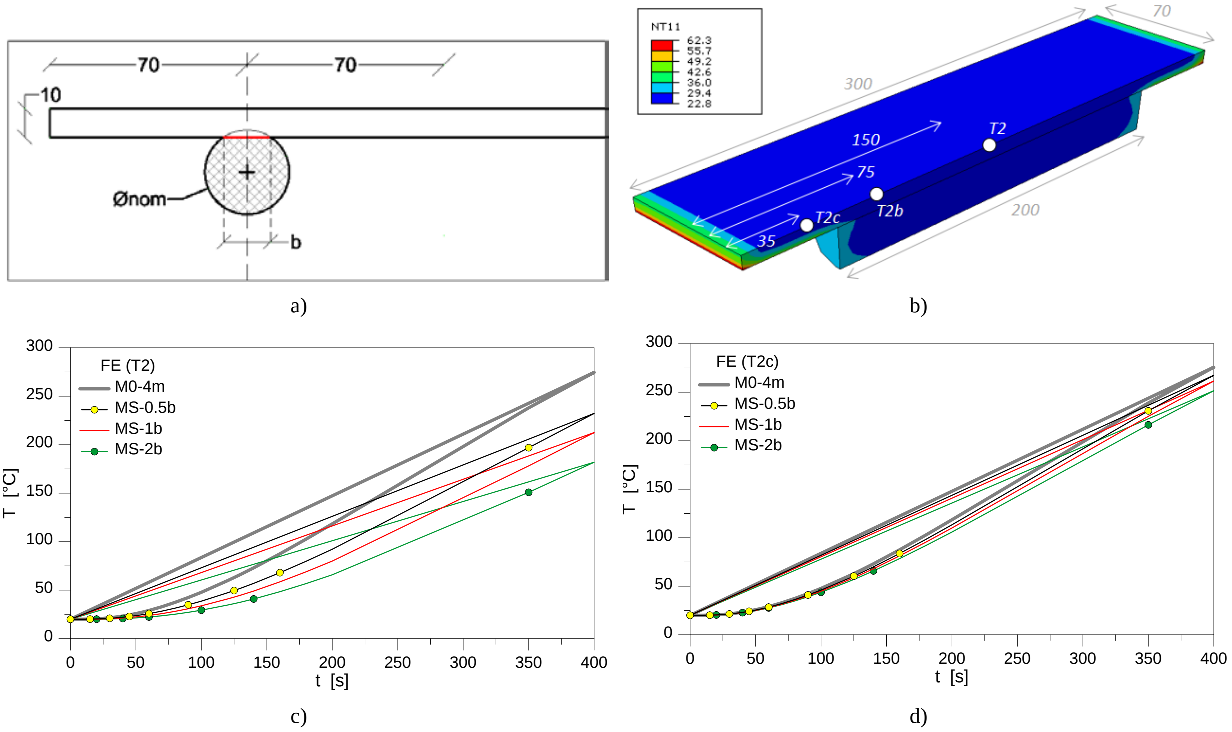
a) b)

Fig. 6 Preliminary M0 models, with a) assembly and b) temperature distribution after 45s of fire exposure. Nominal dimensions in mm.

4.2. Geometry of supports

Further thermal FE simulations were hence carried out on the M0-4m mesh pattern, in order to assess the actual effect of supports detailing. Both geometrical features and thermal exposure aspects were separately taken into account (see also section 4.3). In accordance with the test setup summarized in section 3, small steel cylinders (30mm the nominal diameter and L_s=200mm their length) were in fact included in the so called ‘MS’ models. In doing so, compared to the M0-4m model, careful consideration was spent for the definition of mechanical interactions between the glass panel and the steel supports, so to account for the physical contact region between them. The effects of local detailing, in particular, were explored by defining a $A_s= b \times L_s$ contact surface on the bottom face of glass (with b= 0.5, 1, 1.5 and 2 times the glass panel thickness, respectively), see the schematic drawing of Figure 7(a). Steel was thermally and mechanically characterized in accordance with the Eurocode provisions (EN 1993-1-2). The so assembled glass panel was hence subjected to the standard fire curve reported in Figure 5(a), as also in accordance with section 4.1 and Figure 6(a).

FE thermal results, as expected, generally manifested a totally different distribution and evolution of temperatures in the reference glass panel, especially in the region of contact with the steel supports. Even minimum variations in the geometry description, in particular, proved to have marked effects on the observed temperature scenarios. In Figures 7(c)-(d), selected comparative results are proposed as a function of time, giving evidence of temperature variations for the T2 and T2c control points in the region of restraints (see Figure 7(b)). Worth of interest, compared to the M0-4m temperature estimations, is that the presence of steel supports with different geometrical features proved to have major thermal effects especially towards the centre of glass (i.e. T2 control point), where consistent scatter in predicted temperatures was numerically observed from the examined models. As far as the As contact region increases with respect to the nominal restraints, a decrease in monitored temperatures can be noticed, being resulting from a combination of material properties (glass and steel) as well as to an increased protected surface for glass.



a) b) c) d)

Fig. 7 Thermal analyses on the MS models: a) geometrical description of steel supports (cross-section), with b) temperature scenario after 125s of fire exposure and c)-d) temperature evolution in time for the T2 and T2c control points (nominal dimensions in mm).

4.3. Fire exposure of supports

At a subsequent stage, following the qualitative thermal observations reported in section 4.2, the MS-0.5b model was further investigated by taking into account the actual fire exposure of the examined glass panels, including the support detailing.

Given the standard ISO curve of Figure 5(b), in particular, an idealized fire loading condition was considered for the B1 surfaces of Figure 8 (bottom face and lateral surfaces of glass panels). The top and end surfaces of glass and steel supports (B3, in Figure 8) were assumed exposed to ambient convection and radiation only. A further B2 surface, being inclusive of steel supports and glass, was hence detected in the region of panels restraints. In this later case, the standard fire ISO curve was progressively reduced (from 0.9 times to 0.1 times its nominal amplitude), so to account for a possible limitation of fire loading due to the presence of AC blocks and test setup components. Such a numerical assumption was assumed to be well representative of possible (even partial) fire protection of the region of supports, hence to result in major sensitivity of thermal effects on the examined glass panels.

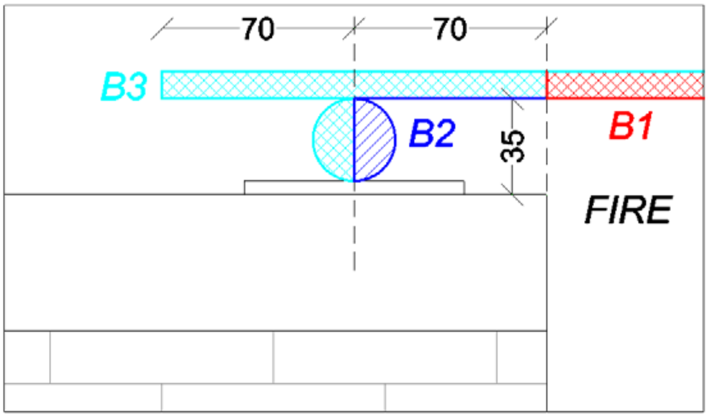
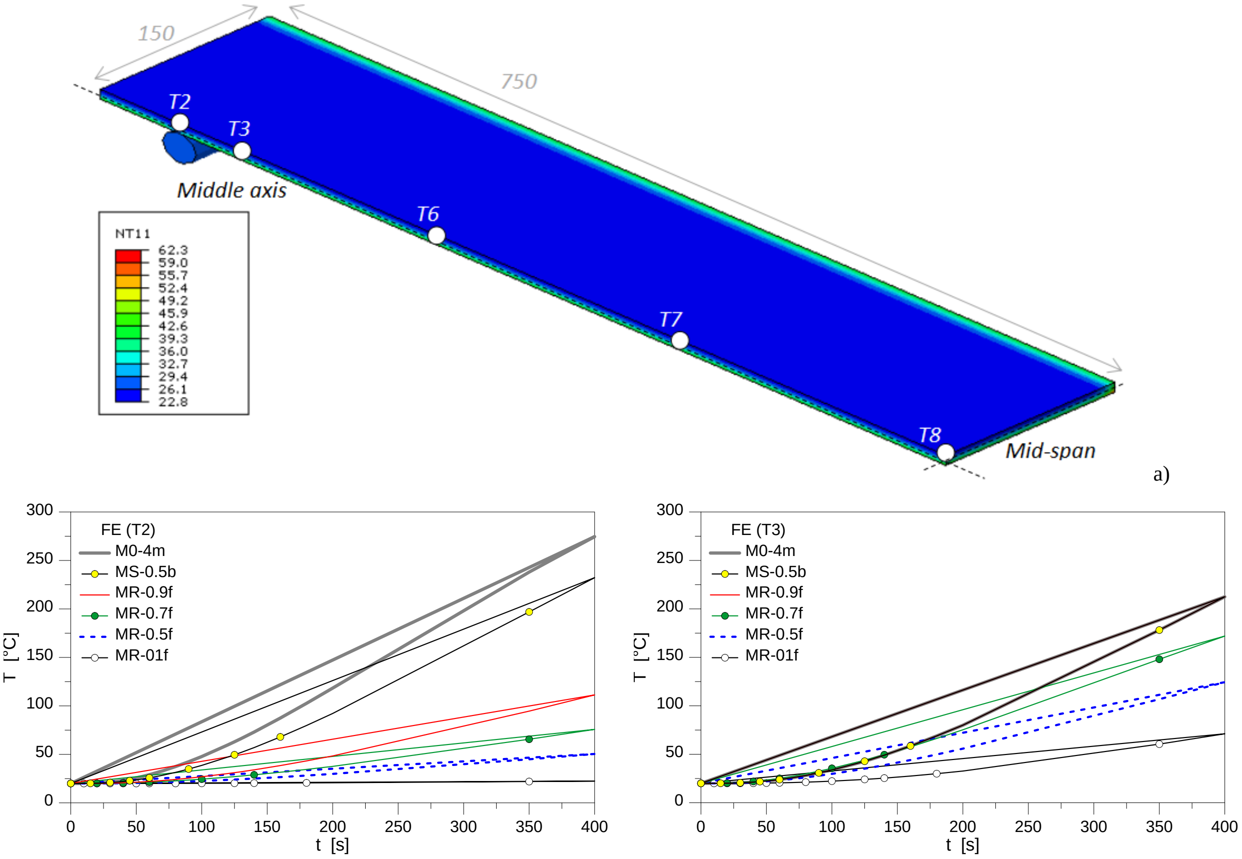


Fig. 8 Thermal exposure of MR models (schematic cross-section view in the region of supports). Nominal dimensions in mm.

Major thermal FE results are proposed in Figure 9, where the temperature evolution in time is emphasized for the T2 and T3 control points. While strong variations in temperature scenarios were obtained over time for the T2 control point of the selected FE models, less sensitivity was generally observed for the T3 measurements, see Figure 9(c).



b) c)

Fig. 9 Thermal analyses on the MR models: a) temperature scenario after 125s of fire exposure (nominal dimensions in mm) and b)-c) temperature evolution in time for the T2 and T3 control points.

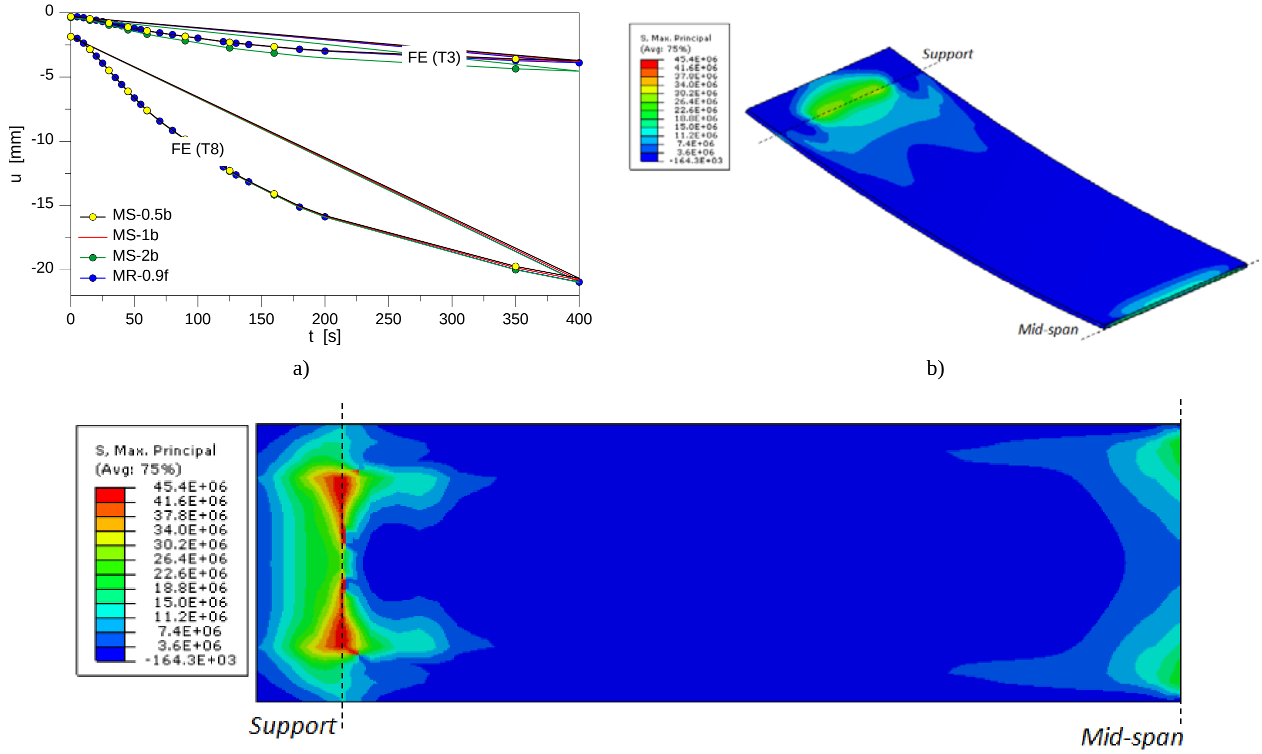
5. Thermo-mechanical simulations in fire conditions

Following the thermal assessments partially discussed in section 4, uncoupled mechanical simulations were hence carried out on the same selection of FE models summarized in Table 2, so to investigate the actual load bearing performance of the A and B glass panel. In doing so, given the loading and boundary conditions, careful consideration was spent for the evolution of maximum deflections in time, as well as for the distribution and propagation of maximum stresses in glass.

5.1. Self weight effects

While mostly negligible effects were observed in terms of deflection in time of the examined FE models, with typical deformed shape of simply supported beam in bending, see Figure 10, important effects were noticed in terms of local stress peaks.

The FE models able to capture the actual mechanical interaction between glass and steel components, as well as a realistic fire exposure of the FE assembly regions, proved in fact to offer reasonable stress distribution and close correlation with experimental observations. In Figure 10(c), in particular, the stress scenario (bottom view) after 125s of fire exposure is proposed for the MR-09f model. As shown, critical issues in the region of steel supports can be perceived, as also in line with test predictions for panel B (section 3).



a) b)

c)

Fig. 10 Thermo-mechanical analyses: a) variation of maximum deflections in time and b)-c) stress distribution in glass (axonometry&bottom view, MR-09f model) after 125s of fire exposure (legend in Pa).

5.2. Additional mechanical loads

Finally, the MR-09f model was further analyzed by assessing the effects of additional permanent loads on the actual performance of the examined glass panels, as also experimentally explored for the panel A of Table 1. In doing so, appropriate mechanical modifications were implemented, so to account for the effects due to additional 16kg according to the test setup of Figure 3. Parametric FE studies were also carried out by changing the amplitude of the so imposed permanent loads, see Figure 11.

Actually, marked variations were observed in the overall performance of the examined FE models, as also expected to do the presence of additional - even limited in amplitude - permanent weights. Worth of interest, see Figure 11(b), is the close correlation with past experimental findings. As far as 16kg are imposed in accordance with the experimental setup, the region of supports can in fact be noticed to represent a critical issue for the whole glass system. In addition, maximum stresses in the region of contact with the steel supports were found to lie in the range of 45MPa, after 45s of fire exposure. In this regard, taking into account the high scatter in the actual mechanical properties and resistance of glass, compared to nominal assumptions discussed in this research paper, the discussed FE simulations proved to offer reliable estimation of experimental observations.

At the same time, it was shown that several aspects and assumptions can markedly affect the obtained predictions, hence requiring further extended studies and investigations.

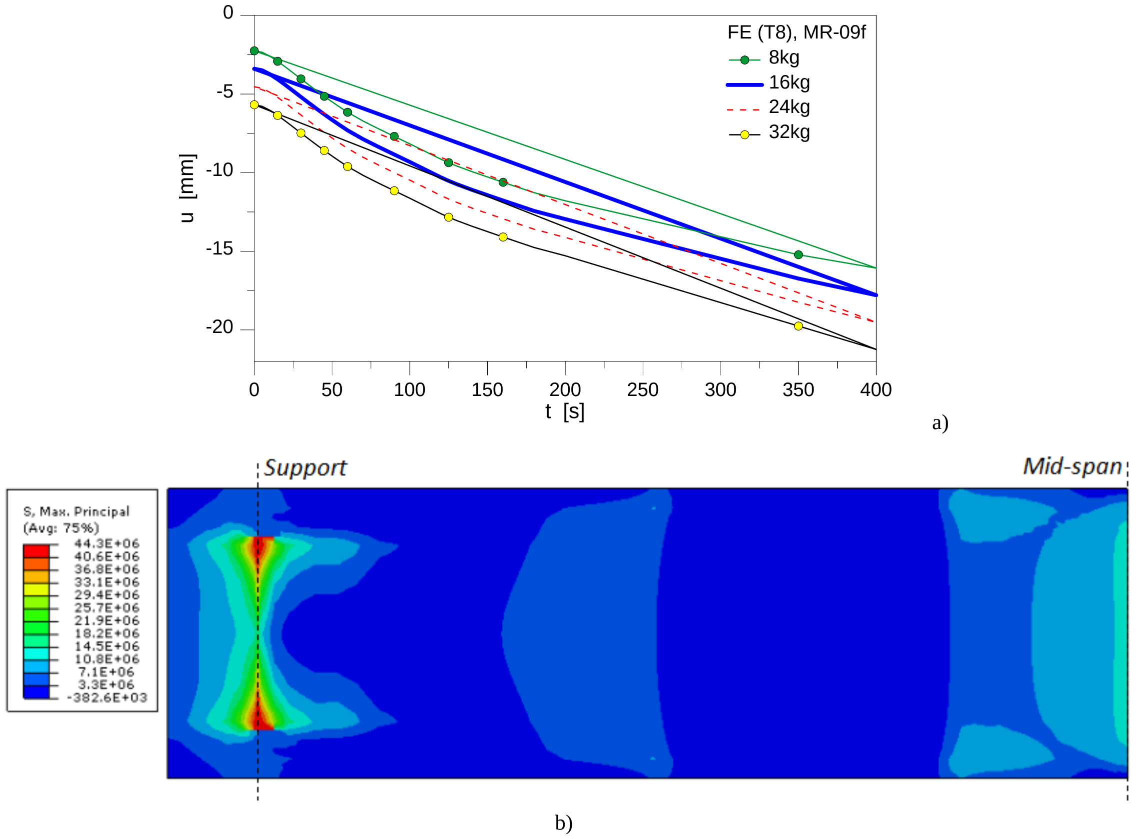


Fig. 11 Thermo-mechanical analyses (MR-09f model): a) variation of imposed permanent loads and b) stress distribution in glass (bottom view) after 45s of fire exposure (16kg the additional load, legend in Pa).

6. Conclusions

In this paper, the thermo-mechanical performance of structural glass elements in fire conditions has been numerically assessed, based on past literature contributions and small-scale experimental tests. As known, glass thermo-mechanical properties are highly sensitive to several aspects, hence representing an influencing parameter for reliable Finite Element numerical simulations. At the same time, additional key aspects are represented by the actual loading and boundary conditions of a given structural glass system, hence requiring careful attention in calibration of single structural components as well as of their reciprocal thermo-mechanical interaction. While rather interesting correlation was observed with experimental test results, the same FE investigations partly discussed in this paper gave evidence of the generally high susceptibility of numerical estimation to even small variations in the loading and boundary input properties, hence requiring additional extended investigations to properly assess the actual load bearing capacity of glass systems in fire conditions.

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