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Abstract

Purpose – Glass material is largely used for load-bearing components in buildings. For this reason, standardized calculation methods can be used in support of safe structural design in common loading and boundary conditions. Differing from earlier literature efforts, the present study elaborates on the load-bearing capacity, failure time and fire endurance of ordinary glass elements under fire exposure and sustained mechanical loads, with evidence of major trends in terms of loading condition and cross-sectional layout. Traditional verification approaches for glass in cold conditions (i.e. stress peak check) and fire endurance of load-bearing members (i.e. deflection and deflection rate limits) are assessed based on parametric numerical simulations.

Design/methodology/approach – The mechanical performance of structural glass elements in fire still represents an open challenge for design and vulnerability assessment. Often, special fire-resisting glass solutions are used for limited practical applications only, and ordinary soda-lime silica glass prevails in design applications for load-bearing members. Moreover, conventional recommendations and testing protocols in use for load-bearing members composed of traditional constructional materials are not already addressed for glass members. This paper elaborates on the fire endurance and failure detection methods for structural glass beams that are subjected to standard ISO time–temperature for fire exposure and in-plane bending mechanical loads. Fire endurance assessment methods are discussed with the support of Finite Element (FE) numerical analyses.

Findings – Based on extended parametric FE analyses, multiple loading, geometrical and thermo-mechanical configurations are taken into account for the analysis of simple glass elements under in-plane bending setup and fire exposure. The comparative results show that – in most of cases – thermal effects due to fire exposure have major effects on the actual load-bearing capacity of these members. Moreover, the conventional stress peak verification approach needs specific elaborations, compared to traditional calculations carried out in cold conditions.

Originality/value – The presented numerical results confirm that the fire endurance analysis of ordinary structural glass elements is a rather complex issue, due to combination of multiple aspects and influencing parameters. Besides, FE simulations can provide useful support for a local and global analysis of major degradation and damage phenomena, and thus support the definition of simple and realistic verification procedures for fire exposed glass members.

Keywords Structural glass, Monolithic glass, Laminated glass (LG), Fire exposure, Fire endurance, Temperature-dependent material properties, Finite element (FE) numerical modelling, Failure time

Paper type Research paper

1. Introduction

Ordinary (or commercial) soda-lime silica glass is frequently used in buildings as load-bearing material for floors, roofs, walls and columns. For this reason, national and

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international design recommendations, guidelines and codes for structural glass applications are under continuous development (CEN TC/250, 2019a, b; ASTM WK8056, 2022, etc.).

Several practical applications of glass in buildings are in fact characterized by a multitude of loading combinations, restraints, etc., which should be properly analysed and verified, especially in terms of maximum tensile stresses and deflections, against ordinary and extreme design loads, with specific calculation methods and limit performance indicators (Bedon *et al.*, 2018). In this context, research and technological developments supported, especially in last years, the definition of dedicated verification approaches, calculation steps and performance limit parameters to support safe structural design of glass under conventional mechanical loads.

Besides, relatively little is still recognized about the mechanical performance or ordinary glass under accidental loads, and possible critical scenarios in buildings may be still related to glass components and systems under impact or blast (Pyttel *et al.*, 2011; Larcher *et al.*, 2016; Bedon *et al.*, 2017; van der Woerd *et al.*, 2022), earthquakes (Sucuoğlu and Vallabhan, 1997; Mattei *et al.*, 2021), or even fire conditions (Bedon, 2017), as well as efficient retrofit and durability assessment for existing systems (Louter *et al.*, 2012; Mariggiò *et al.*, 2020). Disregarding the specific loading and boundary condition of interest, a primary issue is represented by limited tensile strength of glass in cold conditions, which governs most of structural verification steps. Among others, fire loading is recognized as a rather critical condition for ordinary structural glass design and vulnerability assessment, due to basic material properties, high sensitivity to high temperatures and lack of deep engineering knowledge (Bedon, 2017). Maximum risks are thus expected from superimposed mechanical loads and fire-related thermal loads.

Most of literature fire-related studies for glass are in fact focused on the investigation of the thermal performance and thermal fracture (failure time and "fallout" collapse mechanism) for glass infill panels of typical use in doors and windows, or even facades, see for example (Xie *et al.*, 2011; Wang *et al.*, 2014, 2017). On the other side, limited attention is presently given to the mechanical and thermo-mechanical performance of ordinary glass elements under fire exposure, and this is a major challenge for structural design of new glass components (Figure 1). Few experimental and Finite Element (FE) numerical studies have been elaborated

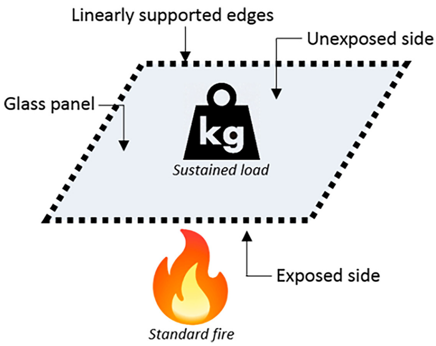

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Figure 1. Thermo-mechanical analysis of glass members under fire exposure and sustained loads: (a) out-of-plane or (b) in-plane bending

to understand and investigate the structural performance of glass elements for buildings under a combination of mechanical loads (i.e. self-weight and additional sustained mechanical loads).

In this regard, the present study aims at exploring the structural performance of ordinary glass beams composed of monolithic or even laminated (LG) glass sections, under conventional in-plane bending setup and exposed to standard fire loading (ISO time–temperature scenario). Most importantly, the attention is given to FE numerical models and their potential to support the definition of fire endurance parameters of practical use in the structural glass field. To this aim, based on simple case-study configurations and earlier validation to experiments, parametric FE numerical simulations carried out in ABAQUS/Standard (Simulia, 2019) are presented to address the combined effect of thermal and mechanical aspects in glass beams and simple components. Based on the comparative numerical outcomes, the validity/applicability of conventional fire endurance approaches of typical use for load-bearing components made of traditional constructional materials are taken into account for possible adaptation to fire exposed glass members.

2. State of art and research methodology

2.1 Problem formulation

Structural members made of traditional constructional elements are often designed and verified against fire loading. The fire endurance (or resistance) of building and load-bearing elements represents a major obstacle to the spread of a fully developed fire, and a primary task for safety of building occupants. Modern building codes, in this regard, require building constructions and components to have varying degrees of fire endurance, depending on the quantity of combustible material normally found in the occupancy for which the building is designed. Experimental analysis can be carried out in support of fire endurance assessment, based on established setup configurations and loading protocols (see for example ISO 834-1 (1999) and EN 1363-1 (2000) documents).

For timber (Wang *et al.*, 2020), steel (Laím *et al.*, 2022), concrete (Wang *et al.*, 2018), steel-concrete (Kang *et al.*, 2018) or timber-concrete (Hozjan *et al.*, 2019) load-bearing components, specific modelling assumptions have been validated in the years, to efficiently reproduce the experimental conditions and support/extend expensive experimental tests. In most of cases, it is generally recognized that FE numerical tools can efficiently support the analysis and verification.

From a practical point of view, the conventional approach for the evaluation of the expected fire endurance and performance follows few basic procedural steps that include:

(1) the selection of the relevant design fire scenarios and the determination of the corresponding design fires;

(2) the determination of the reference time–temperature curve;

(3) the calculation of temperature evolution within the structural member to verify;

(4) the analysis of the corresponding mechanical behaviour of the structural member exposed to fire;

(5) the analysis and quantification of fire endurance in presence of mechanical loads, which are representative of components and systems in ordinary operational conditions.

In doing so, a major attention must be paid for the description of boundaries (i.e. to reflect the real restraints) and to thermal exposure, as well as the sensitivity and response of constituent materials to temperature variations. In most of cases, the standard ISO time–temperature curve from ISO 834-1 (1999) is generally used in fire exposure description, while literature thermo-physical and mechanical properties of materials can be described as a function of temperature. Overall, the most important procedural steps can be summarized as in Figure 2 (example adapted for glass).

In this paper, a detailed analysis is thus presented for monolithic and LG members with in-plane bending setup, which are subjected to fire exposure and different amplitudes of sustained mechanical loads. With the support of original FE numerical models validated to past studies, the procedural steps as in Figure 2 are developed with a specific attention to fire endurance assessment.

2.2 Mechanical analysis of glass elements in cold conditions

Structurally speaking, the mechanical analysis and verification of structural glass elements is based on conservative assumptions on the side of material characterization and loading, see for example CEN TC/250 (2019a, b), ASTM WK8056 (2022) and others.

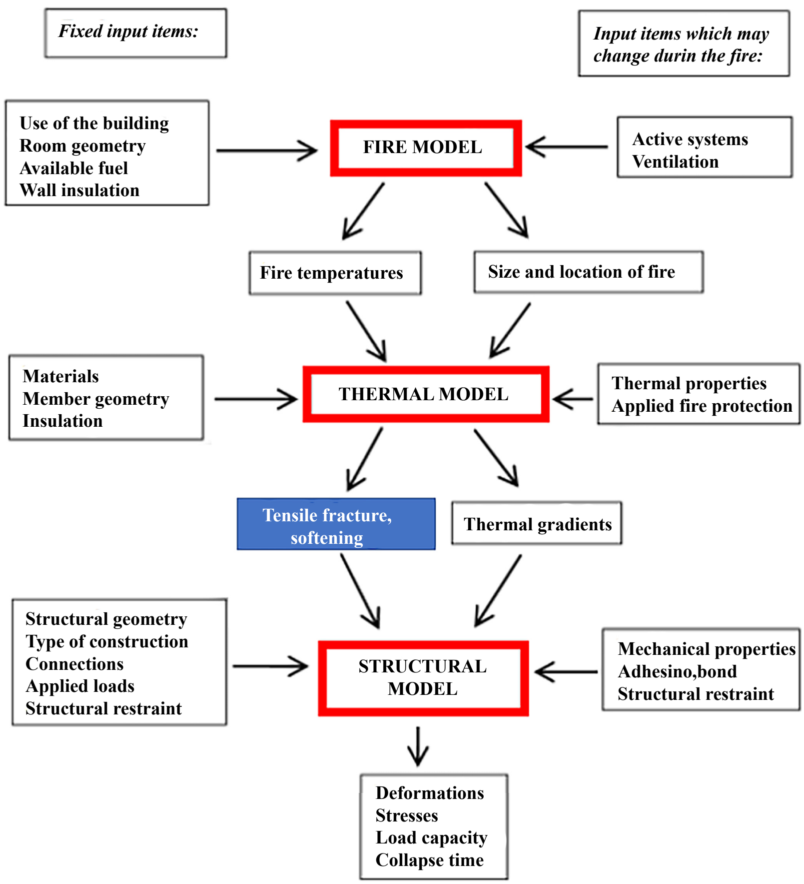

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Figure 2.
Classical procedural steps for thermo-mechanical numerical analysis of load-bearing components and structures in fire conditions

Following the probabilistic State Limit design approach, major challenges for glass elements in cold conditions are represented by stress verification at the Ultimate Limit State, that is:

$$\sigma_{max} \leq \sigma_{Rd} \quad (1)$$

for the most unfavourable loading combination, where σ_{Rd} is the design material strength, and analysis of maximum deflections at the Serviceability Limit State, that is:

$$w_{max} \leq w_{lim} \quad (2)$$

with w_{lim} a specific limit value.

Key mechanical properties for glass are reduced to a linear elastic material model with limited tensile strength (with characteristic value in the order of σ_{tk} = 45 MPa, 70 MPa or 120 MPa for annealed (AN), heat-strengthened (HS) and fully tempered (FT) glass types, respectively (EN 572–2:2004)), relatively high compressive strength and modulus of elasticity (MoE) in the order of 70 GPa in cold conditions (EN 572–2:2004; CEN TC/250, 2019a, b). Equation (1) is certainly mostly affected by the limited tensile strength and by the brittle elastic behaviour of glass material, so that several reinforcement techniques have been elaborated in the years to provide post-fracture load-bearing capacity (see for example (Bedon and Louter, 2014) and Figure 3). Major attention in material characterization can be also required by description viscoelastic bonding interlayers, especially for LG applications in out-of-plane bending (Hána *et al.*, 2018; Hänig *et al.*, 2019), where equivalent secant stiffness and equivalent linear elastic constitutive assumption are conventionally taken into account for structural analysis.

2.3 Thermo-mechanical analysis of glass elements

The fire endurance numerical analysis issue derives from the large use of glass components in buildings (in the form of structural, secondary structural or even non-structural elements) and by the high vulnerability of glass elements to possible failure. Most importantly, for fire-related issues, a major challenging issue compared to Section 2.2 is represented by glass material degradation in terms of thermo-physical and mechanical properties with high temperature, as also emphasized in review discussion from Bedon (2017). From a practical point of view, this suggests that relatively brittle and vulnerable building components are

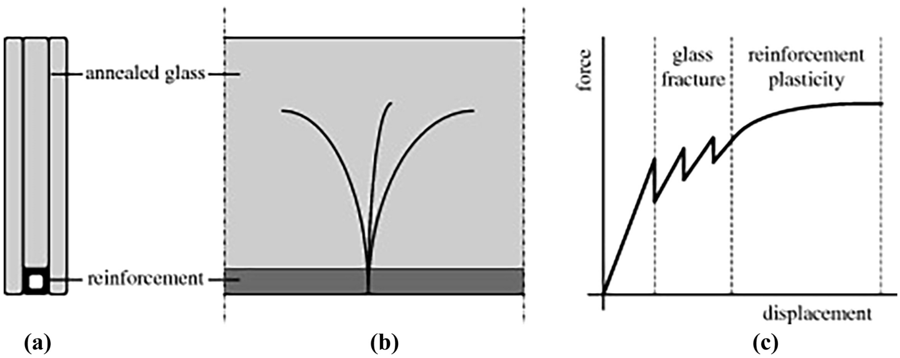

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Figure 3. Enhanced load-bearing mechanical performance analysis of LG beams with steel reinforcement at the tensile edge: (a) cross-section; (b) side-view of a cracked reinforced glass beam; (c) force–displacement diagram, with significant post-fracture residual capacity due to steel tendon

even more criticalities to fire exposure, compared to other systems, and thus necessitate for specific verification tools, performance indicators, guideline recommendations, which can derive from extensive experimental analyses and possibly by dedicated numerical investigations. Typical material performances for commercial glass elements in fire, in this regard, are expected to be affected by relevant modifications due to a relatively low glass-liquid transition temperature, which is around $T_g \approx 550$°C (490°C–585°C) and depends on the amount of silica, sodium oxide and calcium oxide (Sehgal and Ito, 1998). Also, soda-lime glass has softening point $T_d \approx 650$–700°C, and thus slumps over its own weight at a minimum rate of 1 mm/min (Musgraves *et al.*, 2019). This means that fire-related issues involve additional and progressive softening phenomena, which are superimposed to mechanical loads.

In this regard, a major effort can derive from dedicated experimental investigations on full-scale specimens in fire (Sjöström *et al.*, 2020; Louter *et al.*, 2021) or material analysis (Kerper and Scuderi, 1966). Similarly, FE methods and simulations can represent a valid support for extended studies in fire conditions (Bedon and Louter, 2018).

For simple glass panels in out-of-plane bending setup proposed in Kozlowski and Bedon (2021), it was shown for example that the quantification of overall load-bearing effects due to temperature-dependent glass material properties is a major aspect of numerical analyses. However, special attention for the definition of simplified verification protocols should necessarily take into account further relevant aspects such as:

(1) the quantification of thermal exposure and/or mechanical loading effects (i.e. superimposed stress peaks) on a given glass panel variably restrained;

(2) and the definition of generalized observations and performances for glass elements variably loaded and restrained, which is of course a major challenging issue and cannot be easily addressed.

In this regard, the current investigation takes inspiration from past literature efforts (Kozlowski and Bedon, 2021; Louter *et al.*, 2021), where simple monolithic or LG beam elements have been explored in fire conditions. More precisely, the analysis in Kozlowski and Bedon (2021) included FE numerical investigations to explore the thermo-mechanical behaviour of monolithic glass panes under sustained constant load (out-of-plane bending setup like in Figure 1(a)) and fire. It was shown how the failure of glass panel – namely associated to the first achievement of a maximum tensile stress exceeding the material strength – can be affected by different loading combinations, in which a given fire thermal load interacts with ordinary mechanical loads. Most importantly, the numerical study in Kozlowski and Bedon (2021) gave evidence that simplified numerical tools are generally efficient and accurate for a limited number of geometrical, loading and boundary configurations, which are not representative of structural glass solutions in buildings. Another relevant aspect pointed out in Kozlowski and Bedon (2021) was represented by the necessary description of temperature-dependent thermo-physical and mechanical properties for glass and related components (gaskets, supports, etc.), which is often disregarded by some simplified numerical tools, with major effects on resistance and failure predictions.

The study in Louter *et al.* (2021) explored both experimentally (in laboratory conditions) and numerically the thermo-mechanical response of LG beams under sustained mechanical load and fire loading (see Figure 1(b)). The experimental analysis of deflection in time and temperature evolution in time, as well as the typical failure mechanism observation, was used for assessment and validation of thermo-mechanical FE numerical models developed in ABAQUS (Figure 4).

For both the numerical studies reported in Kozlowski and Bedon (2021) and Louter *et al.* (2021), the modelling strategy was developed in accordance with preliminary considerations summarized in Bedon and Louter (2018), where the analysis was again focused on simple

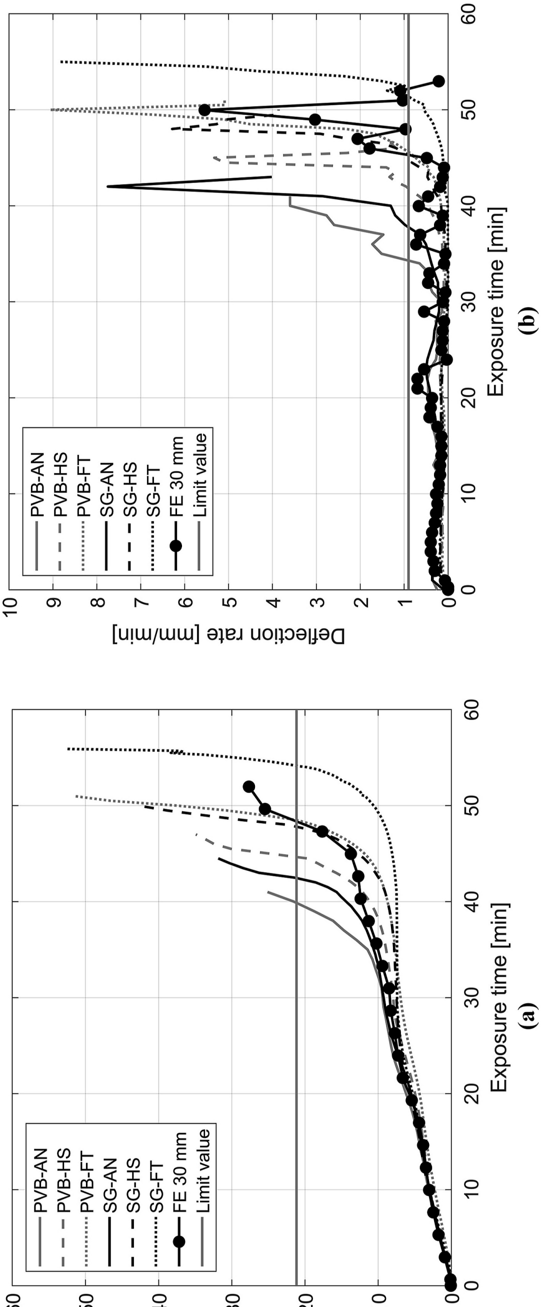

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Figure 4.
Numerical model validation (ABAQUS) toward full-scale experimental tests for LG beams in furnace: (a) deflection and (b) deflection rate, in relation to the exposure time

monolithic glass panels (experimentally tested in furnace conditions) and numerically explored in ABAQUS, for out-of-plane bending failure considerations. In that case – due to lack of insulation components – it was shown that premature fracture can be severely affected by temperature gradients in the region of restraints.

To note that non-uniform temperature exposure should be also taken into account especially for vertically oriented glass elements (Vedrtnam *et al.*, 2020, 2021), because representative of additional influencing parameters in terms of local stress peaks and progressive evolution of material degradation with temperature. The thermo-mechanical simulations reported in Vedrtnam *et al.* (2020) for small-scale samples, in this regard, gave evidence of robust potential of FE methods for glass analysis in fire conditions. To note, in any case, that this last issue is particularly relevant for building glass components like walls, windows, façade systems, rather than horizontal beam-like elements which are object of study in the present investigation.

Following the above studies reported in Louter *et al.* (2021) and Figure 3, the present investigation extends in fact the original FE numerical analysis, by considering a set of additional setup configurations (monolithic glass or laminated glass sections) and loading conditions (mid-span of distributed), and focuses on typical performance indicators and thermo-mechanical performance observations which should be taken into account for derivation of possible useful details in fire endurance analysis of glass elements.

2.4 Reference structural system

The present numerical analysis takes inspiration from the experimental setup described in Louter *et al.* (2021) and Figure 5. To avoid multiple influencing parameters and uncertainties in material calibration and thermo-mechanical response interpretation, a monolithic glass element in agreement with the nominal geometry discussed in Bedon and Louter (2018) is first taken into account, with a total span $L = 1.36$ m, $H = 0.3$ m the height, $t = 10$ mm the nominal thickness of glass. Also, a protection layer is used in accordance with the experimental setup in Louter *et al.* (2021) and Figure 5, with $L_p = 125$ mm and $H_p = 50$ mm.

The in-plane bending response of glass beams is thus numerically explored under an imposed sustained mechanical load F (at the mid-span section) and a standard ISO time–temperature curve.

From a mechanical point of view, it is important to remind that the structural verification of a load-bearing system like in Figure 5 is mostly governed by tensile stress analysis. Also, the in-plane bending performance of a given glass beam in cold conditions is directly proportional to the number of glass layers/glass thickness for the resisting cross-section, given that the maximum tensile stresses at mid-span can be roughly assumed (disregarding any possible interlayer foil) that:

$$\sigma_{max} = \frac{M_{max}}{W_g} \tag{3}$$

where:

$$W_g = \frac{t\,H^2}{6} \tag{4}$$

is the elastic resistant modulus of glass, for a cross-section with t the total glass thickness, and M_{max} the maximum bending moment due to mechanical loads.

A mostly different thermo-physical and mechanical performance takes place under fire exposure, and even more under combined fire exposure and sustained mechanical loads, thus requiring dedicated studies and procedures for verification.

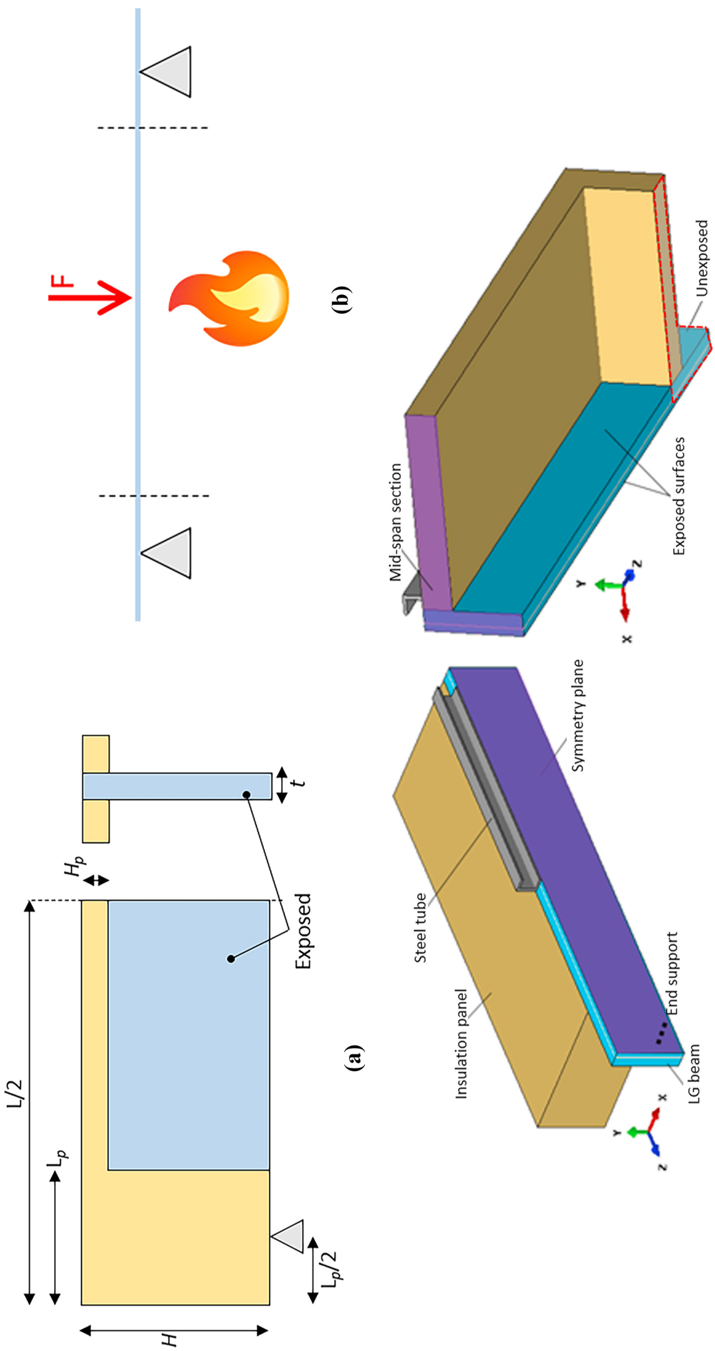

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Figure 5.
Schematic representation of the reference numerical setup for thermo-mechanical analysis: (a) beam geometry and (b) loading, with (c) example of numerical model of LG beam in fire, as assembled in ABAQUS

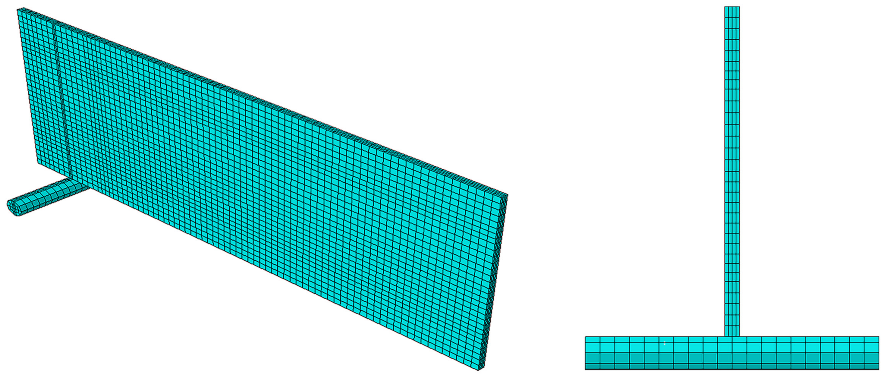
3. Finite element numerical modelling

3.1 Background and modelling assumptions

The present FE numerical investigation was carried out in ABAQUS with the same modelling assumptions of previous studies recalled in Section 2.3. Most importantly, the typical FE simulation consisted of two uncoupled steps, in which the response of the examined glass beams was assessed under the effects of combined thermal exposure and sustained mechanical loads. In doing so, a key role was assigned to the modification of thermo-physical and mechanical properties of the constituent materials in use (i.e. glass and interlayers), to properly reproduce a realistic response.

The first step of reference numerical analysis consisted of a “heat transfer” simulation (with a total step time of 3,600 s). This was carried out to calculate the time-varying thermal state of the reference beam model, when subjected to a standard fire ISO curve. More precisely, a transient heating stage was taken into account for fire exposure, with an initial time increment set equal to 0.01 s and a maximum allowable temperature change set in 50°C per increment. Under a variable/automatic time increment configuration, the maximum allowable time increment was set in 10 s (over a total of 3,600 s). The “heat transfer” step parameters were applied in the corresponding “static general” mechanical simulation to account for fire exposure effects on load-bearing capacity of the examined beams. A direct equation solver was used for both steps.

To this aim, the “predefined field option” was used in the mechanical step, so as to import (increment by increment) the nodal temperatures due to the imposed ISO time–temperature curve. Accordingly, an identical mesh scheme was used for “heat transfer” and “static general” steps (Figure 6). Regarding the fire exposure simulation, more in detail, the mesh was composed of three-dimensional, linear heat transfer brick elements (DC3D8 type from ABAQUS library), with 8-node hexahedral layout. DC3D8 elements, with full Gauss integration, belong to the family of diffusive heat transfer elements and are characterized by the availability of a single degree of freedom, which corresponds to the temperature at each node. The mesh layout (with four solid brick elements in the thickness of each described instance) was selected based on previous numerical validations on fire exposed glass systems with identical layout (Bedon and Louter, 2018; Louter *et al.*, 2021).



(a) **(b)**

Note(s): Exposed and unexposed surfaces described as in Figure 5

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Figure 6.
Reference mesh pattern for “heat transfer” and “static general” steps, for the FE assembly representative of 1/4th the beam geometry (ABAQUS): (a) axonometry and (b) cross-section detail

The experimental scenario was numerically described in the form of radiation and convection interactions for all the fire exposed and unexposed surfaces of the FE model components ("surface radiation" and "surface film condition" from ABAQUS library), based also on previous validation experiences (Bedon and Louter, 2018; Louter *et al.*, 2021). For all the fire exposed surfaces, the convective heat transfer coefficient was kept uniform for the full-time interval of ISO thermal loading, and set equal to 25 W/m^{2}K (ISO 10077-2, 2012). For the unexposed surfaces of the model, at the same time, a convective heat transfer coefficient of 8 W/m^{2}K was used (ISO 10077-2, 2012). Radiation to ambient was taken into account based on emissivity coefficient equal to 0.95 (Quinn Brewster, 1992; Louter *et al.*, 2021). For the total interval of 3,600 min under ISO thermal exposure, the corresponding temperature distribution and evolution in time of step was separately collected from the transient simulation, for all the FE elements and mesh nodes.

In the subsequent simulation stage, where the "static general" mechanical analysis was carried out on a FE model assembly like in Figure 6, the attention was focused on representing the response of the examined glass beams under the imposed mechanical load F, in combination with the effects on materials due to the temperature variations of the first (transient heat transfer) step. Basic modifications of the heat transfer, thermal FE model were thus made in terms of solid element definition. DC3D8 elements were in fact replaced by C3D8R, general purpose, linear isoparametric bricks characterized by reduced integration and 8-node hexahedral layout, to match the original mesh scheme as in Figure 6. After preliminary trials, the reduced integration option was preferred to increase computational efficiency without affecting the accuracy of FE simulations. Under these assumptions, the examined glass beam geometry was described as simply supported at the ends (linear nodal support for the bottom edge of glass layers). Similarly, additional symmetry nodal restraints were distributed over the middle planes of the reference FE model, in both the principal directions of the system, so as to efficiently analyse the bending response of 1/4th the total nominal geometry (Figures 5 and 6).

3.2 Material properties

When numerical methods are used to predict the fire endurance of load-bearing construction elements and systems composed of traditional materials like timber or steel, basic modelling assumptions can take advantage of conventional material properties (especially in mechanical terms) which are consolidated in literature standards, handbooks, research documents (Kang *et al.*, 2018; Hozjan *et al.*, 2019). At the moment, this is not the case of load-bearing applications of ordinary soda-lime structural glass, where standardized experimental and numerical protocols for reliable fire endurance analysis are not established yet. As such, a major effort is required in similar applications especially for the realistic description and characterization of a typical brittle elastic in tension material (with MoE of 70 GPa at room temperature and nominal density of 2,500 kg/m^3, with 0.23 the Poisson' ratio (EN 572–2:2004)), which is also highly sensitive to temperatures.

Overall, the material properties already adopted in (Bedon and Louter, 2018; Louter *et al.*, 2021) from previous experimental evidences of material and component glass samples were taken into account for the present FE model calibration (see for example Figure 4). Typical experimental trends of basic thermo-physical and mechanical properties of ordinary glass with temperature, such as MoE, density, specific heat, thermal conductivity and thermal expansion coefficient are reported in Figure 7(a)–(e). In the implementation of such a FE material input, a primary attention was paid especially for the characterization of stress–strain response of glass material under increasing temperature, according to Figure 7 and also to the previously reported ranges of T_g and T_d parameters for commercial glass. Most importantly, basic modelling assumptions were elaborated to account for the relaxation and

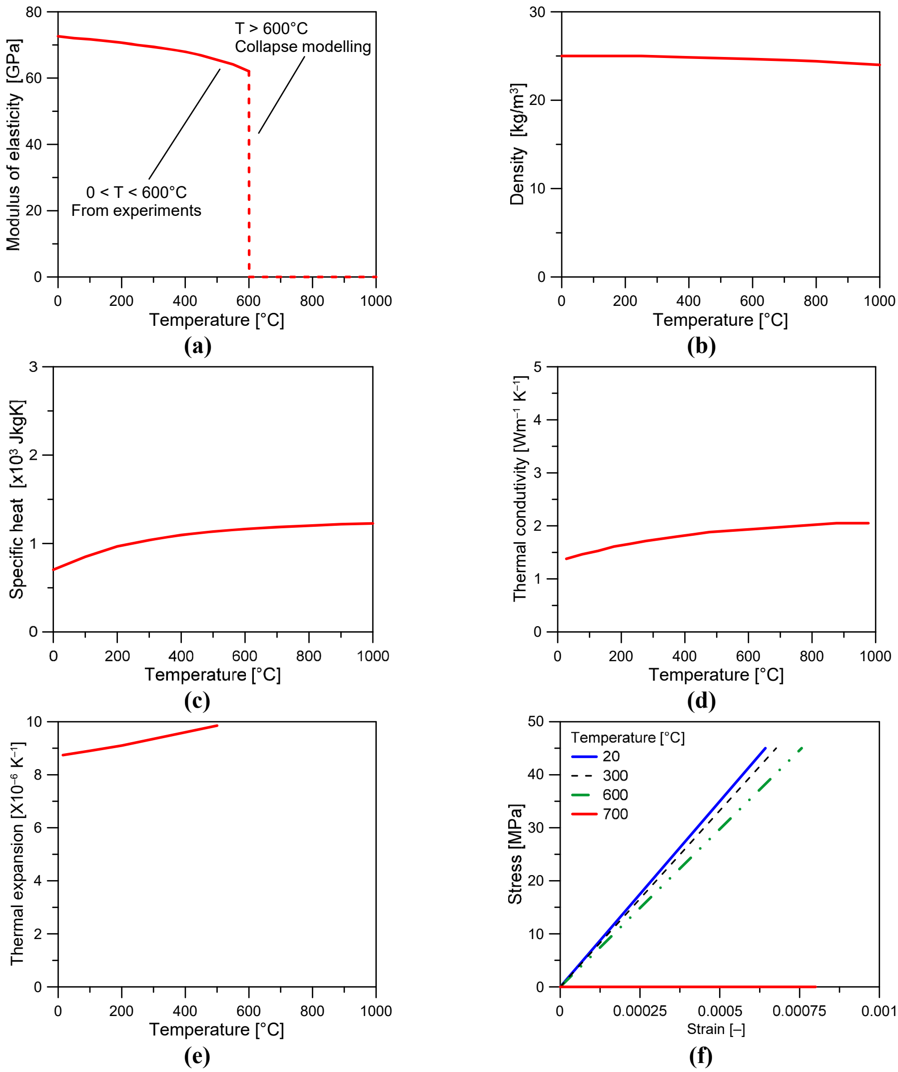


Figure 7.
Selected mechanical and thermo-physical material properties for ordinary glass, with evidence of their sensitivity to temperature variations: (a) modulus of elasticity; (b) density; (c) specific heat; (d) thermal conductivity; (e) linear thermal expansion coefficient; (f) example of numerically implemented stress–strain response for AN glass type at different temperatures

Source(s): Literature experimental data in use for FE numerical simulations (figure created by authors)

softening of glass from its original solid state, which has major effects on the reduction of elastic bending stiffness of glass members in fire, and consequently on their overall load-bearing capacity to sustain mechanical loads.

To this aim, the variation of its MoE was numerically described in accordance with Figure 7(a). To note that – compared to cold conditions – the MoE in fire conditions is expected to decrease in the order of -5% at 300°C, -10% at 500°C and -15% at 550–600°C. For temperatures above 600°C (that is higher than T_g), literature evidences and experimental observations report a rather null residual stiffness for the MoE extrapolation of fire exposed ordinary glass samples (Kerper and Scuderi, 1966; Bedon, 2017). For this reason, a significant drop in MoE for the viscous state of glass was numerically accounted for temperatures above 600°C, by assuming zero residual stiffness in the FE models. To note that such a simplified modelling assumption was privileged, based also on previous validation toward experimental findings (see for example (Louter *et al.*, 2021), to reproduce the progressive glass softening and conservatively disregard any possible residual capacity for the examined FE assemblies, which are expected to slump over their own weight for temperatures higher than $T_d \approx$ 650–700°C (Section 2.3).

In order to assess the thermo-mechanical performance of various glass types, a material tensile strength σ_{tk} = 45 MPa, 70 MPa or 120 MPa was considered for AN, HS and FT glass types. For the purpose of present study, and in absence of further experimental feedback, any possible degradation of material strength with high temperature was disregarded, and parametric calculations were carried out by taking into account the above characteristic strength values for AN, HS and FT glass types in cold conditions.

This choice was numerically justified by negligible strength decrease that can be in general experimentally observed for glass samples exposed up to above 400–500°C (Kerper and Scuderi, 1966; Bedon, 2017). At the same time, for temperatures exceeding 600°C (and thus T_g), any possible strength degradation (and consequent beam collapse) was implicitly accounted by the prevailing relaxation and softening of glass (i.e. MoE degradation), which was implemented by means of the temperature-dependent material properties as in Figure 7(a)–(e). Examples of corresponding stress–strain responses under uniform temperature scenarios are reported in Figure 7(f).

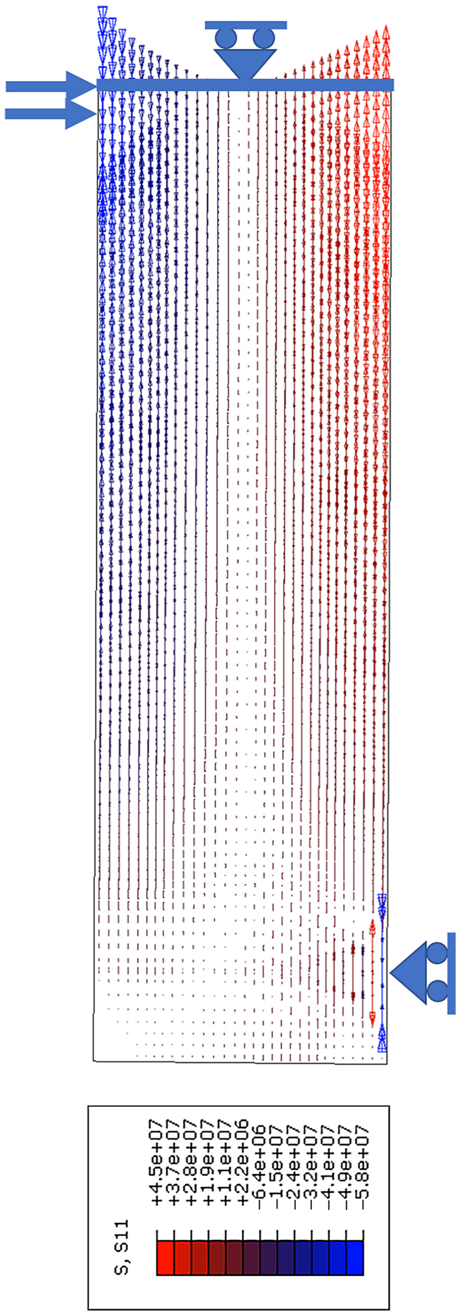
3.3 Loading strategy

For each examined scenario, the load-bearing capacity of glass beam in cold conditions was first numerically calculated (F_{20}, in the following, for the beam setup with mid-span concentrated load). According to the loading scheme in Figure 5(b), F_{20} represents the mechanical load associated to maximum tensile stresses $\sigma_{\max}$ in glass which equal the material strength (for AN, HS or FT glass types respectively). To note that, according to the MoE modification as in Figure 7(a), the load-bearing performance assessment in ambient conditions is largely different from the stress-deflection analysis of the same glass beam specimen under fire, as a major stress peak transition phenomenon which derives from material modification (Louter *et al.*, 2021). The typical stress distribution is proposed in Figure 8 for the beam specimen under in-plane bending setup at room temperature.

Boundaries and loading definitions are also schematized for the side view of 1/4th the beam assembly. A simple roller was introduced to replace the steel support from Figure 5. In the thickness of glass section, this nodal restraint was extended to 5 nodes in total (4 brick elements). At the mid-span region, mesh nodes of brick elements (160 in total) were prevented to translate in the longitudinal direction. Finally, the vertical load was reproduced in the form of a uniform pressure distributed over a 50 mm wide portion of the top surface of glass. To note that possible out-of-plane displacements were also restrained, to reproduce the lateral bracings of the reference in-plane bending experimental setup.

For fire scenarios, under the imposed standard time–temperature curve from ISO 834-1, the in-plane bending analysis is still focused on the effects of sustained mechanical loads F as in Figure 5(b). Differing from cold conditions, however, a sustained mechanical load F_{fire} is numerically imposed at the mid-span section as a fraction of the collapse load F_{20} in cold conditions.

To this aim, various combinations of ISO time–temperature curve and different amplitude of mechanical loads are also taken into account for the same beam geometry, that is variable magnitudes of sustained loads are considered, where M-FX% denotes the numerical model



Note(s): Example of AN glass type at collapse, for the determination of F20, with schematic reproduction of boundaries and loads (legend values in Pa)

Source(s): Figure created by authors

Figure 8.
Normal stress distribution in the longitudinal direction, for a monolithic glass beam in cold conditions and under in-plane bending setup, subjected to the action of mid-span mechanical load *F* (ABAQUS)

with a X% part of failure load in cold conditions (F_{20}). Table 1 summarizes the selected mechanical and loading configurations for the set of monolithic glass beams under mid-span concentrated load F. To note that the exposed and unexposed surfaces of glass were defined according to the schematic representation of Figure 5.

3.4 Fire endurance analysis

In accordance with Section 3.1, the fire endurance analysis was carried out by subjecting each FE assembly to ISO thermal exposure (transient heat transfer simulation) and by the subsequent mechanical analysis (with input time–temperature nodal fields). In general, based on step features as in Section 3.1, the maximum imposed time increment of 10 s was achieved approximately after 50 s of fire exposure, and thus each simulation (3,600 s) resulted in around 400 increments for each model assembly/loading configuration.

From a structural point of view, the fire endurance of selected glass systems was carried out by local and global analysis of principal stress peaks over the time of analysis/fire exposure, based on material properties in Section 3.2. The maximum tensile stress in glass σ_{max} due to the imposed thermo-mechanical loads (ISO time–temperature curve and F_{fire} mechanical loading as in Table 1) was monitored in the time of analysis and compared to the material strength σ_{tk}, so that the overall mechanical collapse of glass beams could be detected as the first exceedance of material resistance:

$$\sigma_{max} = f(ISO\,time - temperature; F_{fire}) = \sigma_{tk} \tag{5}$$

In parallel, special care was spent for the analysis of deformations under fire exposure. For flexural loaded members, the EN1363-1 standard recommends for example that the deformation and deformation rate limits should be estimated as given in Eqs. (6)-(7) respectively:

$$D_{lim} = \frac{L^2}{400d}\,[mm] \tag{6}$$

$$DR_{lim} = \frac{L^2}{9000d}\,[mm/min] \tag{7}$$

where L is the bending span (in millimetres) and d the distance between the extreme fibre of the cold design compression zone and the extreme fibre of the cold design tension zone (in millimetres).

In the present parametric simulations, based on Eqs. (5), (6) and (7), the corresponding failure time t_f was separately collected in each examined configuration, so as to support a quantitative comparative analysis of possible failure configurations. Also, the attention was

Model	Section	Glass type	Fire loading	Mechanical load
M-F20	Monolithic	AN, HS or FT	No fire (cold conditions)	F_{20} *
M-F75%			ISO	0.75 F_{20}
M-F50%				0.50 F_{20}
M-F25%				0.25 F_{20}
M-F10%				0.10 F_{20}
M-F5%				0.05 F_{20}
M-F0.5%				0.005 F_{20}

Note(s): (*) = numerically estimated as the collapse load in cold conditions (i.e. Figure 8).
Source(s): Table created by authors

Table 1. Summary of examined configurations for the set of monolithic glass beams under mid-span concentrated load F ("M-F" series)

paid on the sequential analysis of the above possible collapse conditions, and thus to quantify the minimum t_f and the corresponding conservativeness of possible standardized procedures based on a traditional stress verification check as in Eq. (5) or conventional deformation approaches as in Eqs. (6)–(7).

4. Discussion of numerical results

4.1 Stress and temperature analysis

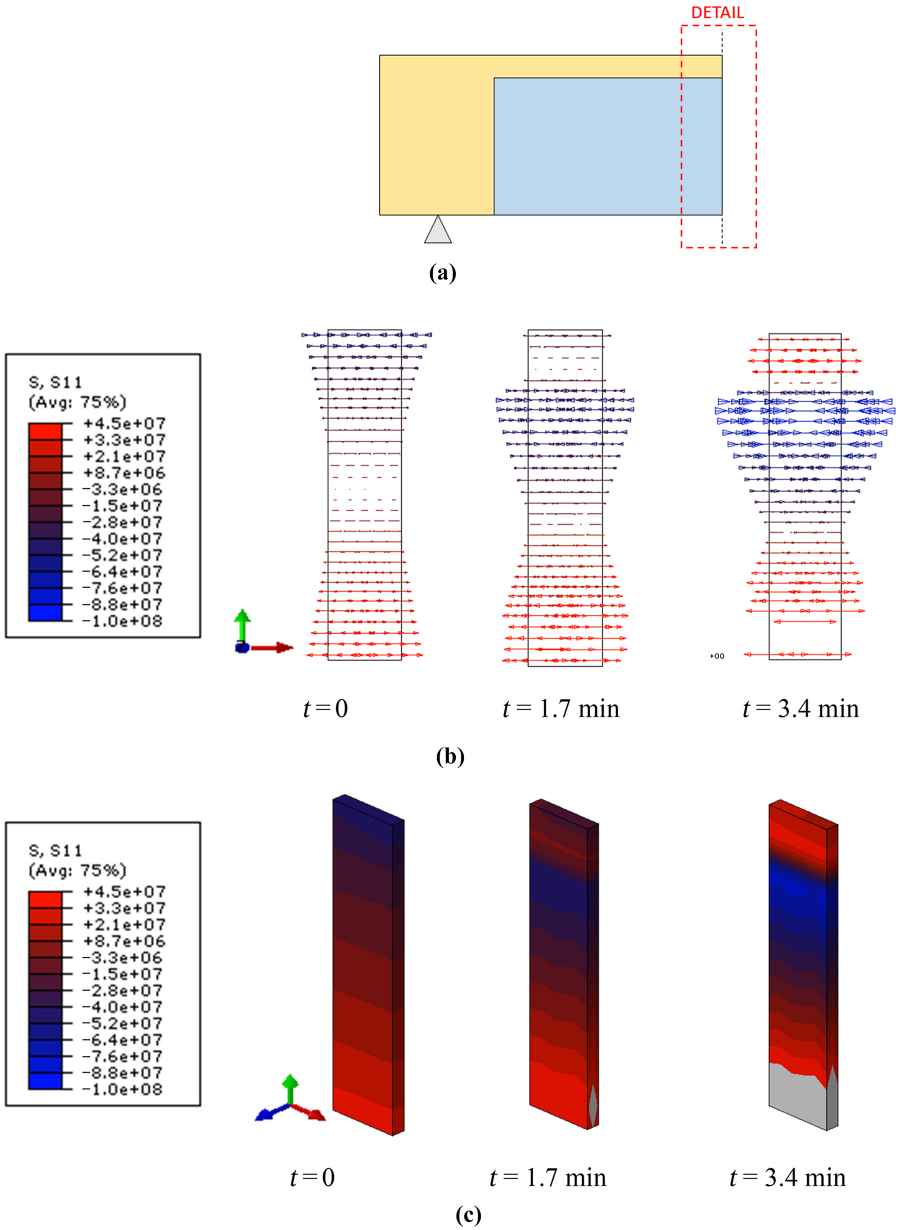
Differing from the bending analysis in cold conditions, the first remarkable effect of combined fire exposure is represented by the migration of stress peaks in the glass beam, from the typical tensile (bottom) edge like in Figure 8 toward the coldest regions of the member. It is important to note that such an effect derives from temperature-dependent material properties (especially the modulus of elasticity of glass) and thus confirms the need of temperature-varying material properties for more realistic simulations. At the same time, a major challenge for similar configurations is represented by the detection of stress peaks in glass and corresponding failure time as in Eq. (5), due to the modification in time of temperature in glass, and thus material stiffness, and consequently stress distribution. A typical example is shown in Figure 9 for selected time intervals of analysis in fire conditions.

Both graphical items represent the stress distribution in glass for the mid-span region of a monolithic beam, with evidence of vectorial representation or contour plot distribution. It is worth to be noted the mostly different distribution in the height of glass beam, compared to the analysis in cold conditions. As also discussed in (Louter *et al.*, 2021), this effect derives from the progressive degradation of modulus of elasticity for glass, with a consequent redistribution of internal stresses, but also to the bridge effect due to the presence of the protection insulating layer on the top/end regions of glass beam, to preserve a minimum stiff thickness for the member object of study.

Following Figure 9, it is clear that the condition in Eq. (5) requires a more detailed stress distribution and stress peak evolution analysis of the glass member, both in terms of geometry (evolution in thickness, length and height) and in time (due to progressive temperature increase and material degradation), and should necessarily consider multiple key control points for the beam, as well as the maximum envelope of stress peaks.

Figure 10(a), in this regard, illustrates few selected control points on the examined beam geometry. The mid-span control point P1, in particular, is expected to carry on most of the imposed mechanical load F_{fire} for analogy with cold condition performances in Figure 8. On the other side, major modifications can be observed from the mechanical analysis of stress evolution in fire conditions, see Figure 10(b). A relevant initial decrease of measured stress values can be noted in the initial stage of fire exposure, which is counterintuitive from a traditional mechanical analysis of glass beam under in-plane bending setup and cold conditions. Such an effect is a consequence of the increasing temperature due to fire and the progressive relaxation of glass MoE. In Figure 10(b), most importantly, it can be noted that the average glass-liquid transition temperature $T_g \approx 550°C$ is achieved at the tensile edge of beam in around ≈ 7 min, while the softening point $T_d \approx 650–700°C$ is achieved in ≈9 min. This means that the MoE assumption for numerical modelling, based on simplifications as in Figure 7, disregards a possible residual stiffness degradation of glass (and thus any residual load-bearing capacity) in the order of 2 min of fire exposure.

After ≈2 min of fire exposure, the case-study member in Figure 10(b) is subjected to a further increase of stress peaks in P1, and the material strength for HS glass is achieved after ≈ 8 min of fire exposure. However, the simultaneous relaxation of glass material manifests in a progressive increase of tensile stress peaks in the coldest regions of the beam (i.e. P3 control point). After ≈8 min of fire exposure, the temperature in P1 is in fact higher that 400°C, and the mid-span tensile region of beam has no residual mechanical capacity. The



Note(s): Stress values in Pa (example for the M-F75% model)

Source(s): Figure created by authors

Figure 9. Stress analysis for a monolithic glass beam under fire exposure and sustained mechanical load (detail of mid-span region), as a function of time exposure (ABAQUS): (a) schematic detail; (b) vectorial representation (front view of beam geometry) and (c) corresponding contour plot (axonometric view)

typical result is a “stress failure condition” that is frequently governed by the coldest regions in the top of the beam, rather than at its mid-span bottom region. This condition necessarily requires a careful analysis of stress distributions in time, both in the span of the beam but also in the thickness of monolithic or laminated glass layers.

4.2 Fire endurance analysis

As highlighted in Section 4, the fire endurance analysis of glass members is a challenging task which is strongly sensitive to intrinsic material properties, thus requiring specific calculation assumptions and performance indicators. This is carried out in present study in terms of stress failure detection (i.e. tensile strength limit for glass as in Eq. (5)), but also typical deformation limit values in use for traditional constructional materials in beams (Eqs. (6) and (7)). Moreover, the magnitude of imposed mechanical loads represents a further challenging task for failure detection, given that mechanical stress is superimposed to thermal effects on material degradation and softening, with additional deflection and corresponding stresses (see for example Figure 11(a)).

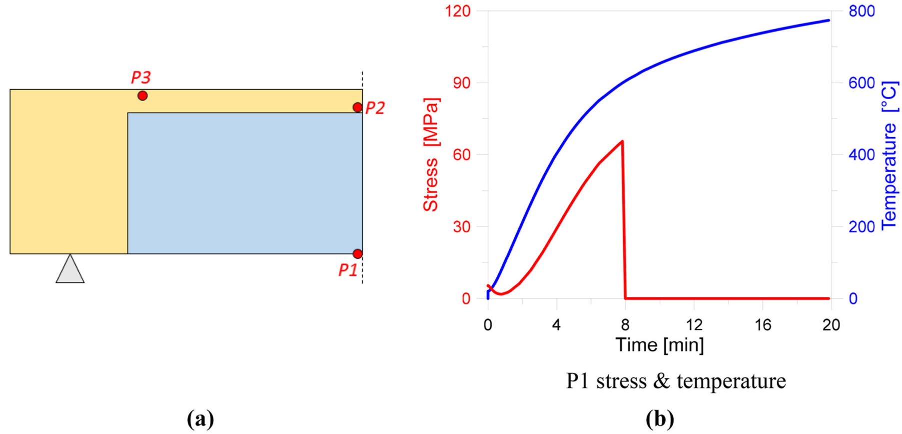


Figure 10. Stress and temperature analysis for a monolithic glass beam under fire exposure (ABAQUS): (a) reference control points and (b) example of evolution of tensile stress and temperature in P1, as a function of exposure time (example for the M-F10% model)

Source(s): Figure created by authors

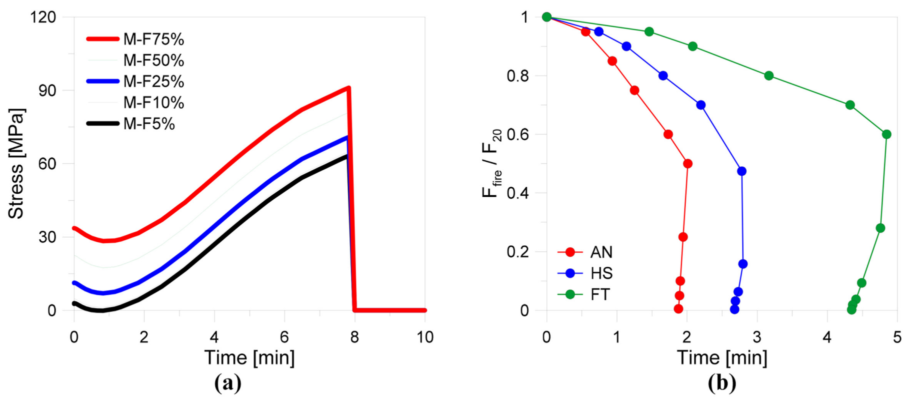


Figure 11. Calculated failure time for a monolithic glass beam under fire exposure (ABAQUS), based on stress analysis and Eq. (5): (a) stress evolution in P1 (AN glass type) and (b) calculated failure time based on maximum envelope of stress peaks in glass, as a function of AN, HS or FT glass types

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Given that the stress analysis in P1 control point as in Figures 10 and 11 is not meaningful and sufficient for fire loading conditions, the maximum envelope calculation is required for failure detection in terms of stress peaks. The latter assumption reveals that most of the configurations from Table 1 are characterized by fracture of glass that is theoretically propagated from the mid-span region, as in cold conditions but also to the top edge region (P3).

The final result can take the form of the resisting domain reported in Figure 11(b), where the effect of different glass types (AN, HS or FT) is also emphasized for a given setup. It is worth to be noted, as also expected, that as far as (F_{fire}/F_{20}) ratio of imposed mechanical load decreases from the unitary value, the corresponding failure time progressively increases for all the examined conditions. This suggests that a given geometry can fail due to “major mechanical loading effects” rather than “major thermal effects” due to softening from fire exposure, for a general thermo-mechanical combination of loads. On the other side, Figure 11(b) shows also that the failure time starts to decrease for sustained loads of limited amplitude ($F_{fire}/F_{20} < \approx 0.5$, in present investigation). This last effect depends again on the critical role of the cold/protected top region of glass (due to the presence of insulation layer), in combination with the progressive relaxation of tensile region and migration of stress peaks in the beam (i.e. from P1 toward P3) due to fire and confirms the complexity of calculation approaches for fire endurance of structural glass members.

When the deflection limits from Eqs. (6) and (7) are taken into account for the same geometrical and mechanical configurations, typical results as in Figure 12 can be obtained from thermo-mechanical simulations. In this case, it is possible to notice that both the deformation trend (Figure12 (a)) and the deformation rate trend (Figure 12(b)) are slightly sensitive to the magnitude of sustained mechanical load. For the examined configurations in Table 1, after ≈8 min of fire exposure, the beam geometry has rather null residual capacity and thus a major drop in measured deflection or deformation rate can be noted.

This finding suggests, in combination with the stress failure analysis like in Figure 11, a prevailing role of thermal load on the mechanical one, and thus a major manifestation of glass relaxation (i.e. MoE degradation as in Figure 7(a)), which was also observed in the full-scale experiments reported for example in Figure 4 and (Louter *et al.*, 2021). At the same time, it is important to note that the monolithic glass members discussed in Figures 11 and 12 are not specifically designed to resist ordinary design mechanical loads or even fire. From Figure 12(a) and (b), it is also possible to note that deformation parameters achieve a maximum plateau after ≈ 9 min. This effect derives from the bridge capacity of top (unexposed) compressive region of beams, which provides a minimum capacity until final collapse (Louter *et al.*, 2021).

A direct effect of prevailing thermal effects can be better quantified in terms of predicted failure time for deformation limit as in Eq. (6), see Figure 12(c), where numerical dots are reported from Eq. (6) for all the thermo-mechanical loading configurations.

In particular, it can be noted that M-F20 or M-F0.5% configurations differ for less than ≈0.3 min in overall failure time. While such a numerical quantification can be affected by the simplified description of MoE degradation as in Figure 7(a), such a qualitative behaviour is in line with structural failure mechanisms of laminated glass beams and members, which are typically characterized (in absence of specific reinforcement as for example in Figure 3) by a post-fracture performance with rather null residual load-bearing capacity.

Similarly, Figure 12(d) shows the calculated deformation rate at the exceedance of material strength (Eq. (5)) for the same geometrical and mechanical configurations. This last parameter is particularly useful for comparisons toward conventional performance indicators like in Eqs. (6) and (7) and suggests that D_{lim} and DR_{lim} limit values tend to overestimate (for the examined configurations) the actual fire endurance of glass beams. In other words, the thermal effects due to fire exposure are prevailing on mechanical load effects

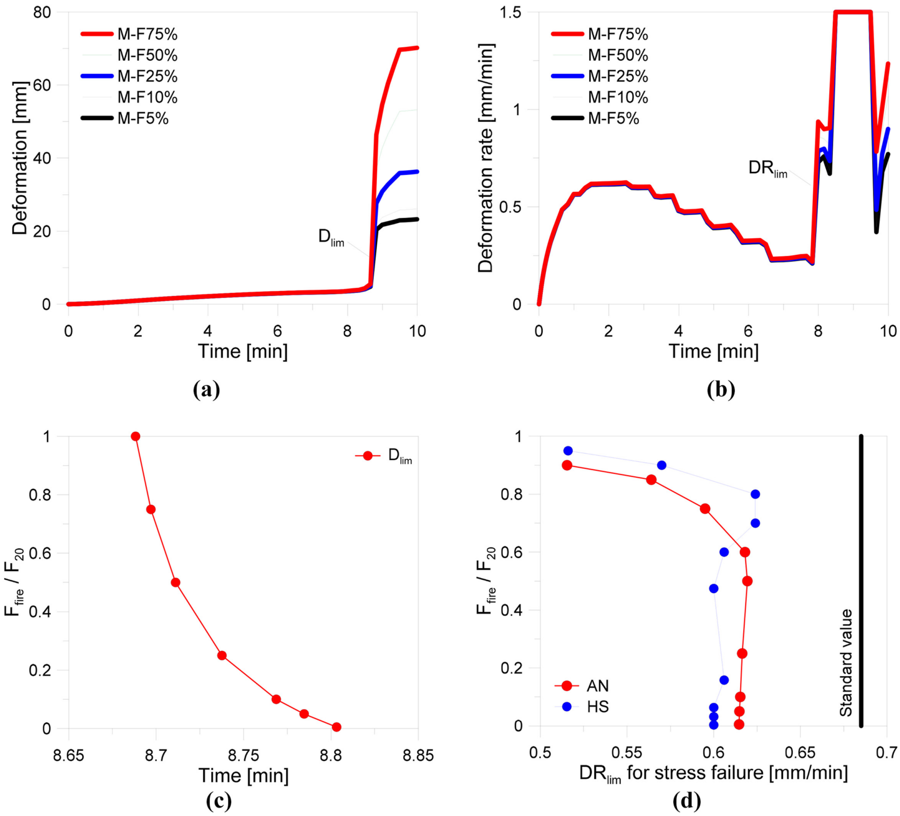


Figure 12.
Failure time for monolithic glass beams under fire exposure, based on deformation analysis (ABAQUS): (a) mid-span deflection; (b) deformation rate and (c) calculated deformation limit, with (d) corresponding calculation of deformation rate based on maximum stress envelope in glass (from Eqs. (5) and (7))

Source(s): Figure created by authors

in cold conditions, but stress failure is still premature to recommended D_{lim} and DR_{lim} limit values from Eqs. (6) and (7). In terms of deformation rate, for example, numerical results in Figure 12(d) show that the stress failure is detected for DR_{lim} values in the range of ≈0.6 mm/min, which are markedly lower than the standard limit from Eq. (6), and this suggests additional studies for specific calibration toward structural glass applications.

4.3 Effect of mechanical load distribution

Another relevant aspect is certainly represented by the distribution of sustained mechanical loads, and the corresponding bending response of the examined beams, given that major modifications are introduced in terms of stress evolution in glass. For the present investigation, the beam configurations as in Table 1 were subjected to a distributed load q to replace the mid-span concentrated load F, see Figure 13(a).

In practical terms, the thermo-mechanical numerical analysis was carried out as for the configurations in Table 1, with the exclusive modification of mechanical load definition. As also schematized in Figure 8, the vertical load q was in fact described in terms of uniform pressure acting on the top surface of glass. Differing from the previous setup with mid-span load F, however, this last pressure was extended to cover the fire exposed span of the examined glass beams (with the exclusion of L_p region from the beam ends, like in Figure 5). Nodal boundaries were kept identical to the reference FE model in Section 3.

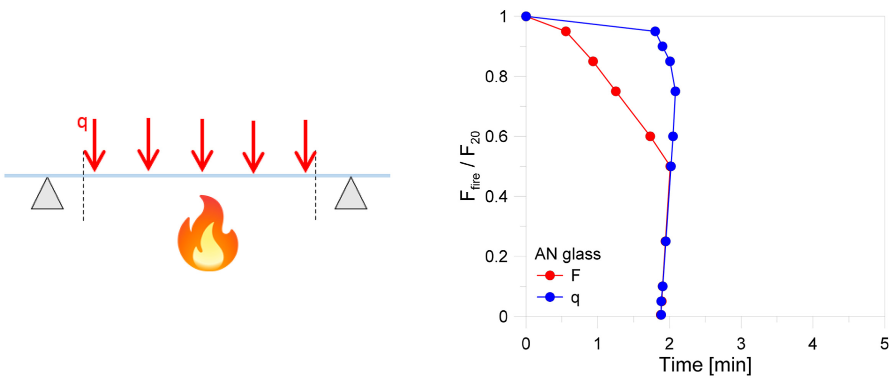
In quantitative terms, exemplificative comparisons are proposed in Figure 13(b) for the beams composed of AN glass. The resisting domains (for F or q setup configurations) are representative of calculated failure time in terms of stress analysis (like in Eq. (5)), as a function of various mechanical loading combinations in fire. It is worth to be noted, for example, that the effect in terms of stress failure detection for the presently investigated configurations can be markedly perceived under F or q mechanical loads for high $F_{fire}/F_{20} > \approx 0.5$, that is for beams in which the imposed mechanical load is close to the failure load F_{20} in cold conditions. Similarly, no remarkable modifications can be noticed in terms of deformation limit and corresponding failure time, compared to Figure 12.

Again, such a numerical output confirms that the deformation rate value leading to stress failure is calculated in the order of ≈0.6 mm/min, which is lower than the standard value from Eq. (7). A similar finding confirms a rather stable response of the beam under mid-span F or distributed q sustained loads, but at the same time emphasizes the current overestimation of expected failure time based on deformation parameters rather than stress peak analysis.

4.4 Effect of cross-section features

In conclusion, the numerical analysis was further extended to focus on the performance of glass members still in agreement with configurations in Table 1, but characterized by LG cross-section in place of monolithic panel setup, see Figure 14(a). Under identical geometrical size and loading setup, the number of glass layers for LG beams was set in $N_{LG} = 2$, 4 or 6 respectively. Such an input assumption is strictly related to Eqs. (3) and (4), where the use of LG sections with 2, 4 or 6 glass layers for present simulations is associated to proportionally enhanced in-plane bending capacity in cold conditions (in the order of $R_B = 2$, 4 or 6 times respectively) compared to the same monolithic beam as in Table 1.

The thermo-mechanical analysis of LG beam sections in fire and under sustained mechanical loading is indeed more complex and affected by multiple influencing parameters (Louter *et al.*, 2021). Typical comparative numerical results can be summarized as in Figure 14(b), where the failure time of various geometrical and mechanical configurations is calculated based on maximum envelope of stress peaks in glass (based on Eq. (5)). It is worth to be noted that the stress failure detection for LG members is certainly characterized by



(a) **(b)**

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Figure 13. Failure time for monolithic or LG beams under different mechanical load distribution (ABAQUS): (a) loading scheme and (b) calculated failure time based on maximum stress envelope in glass due to mid-span F or distributed q sustained load

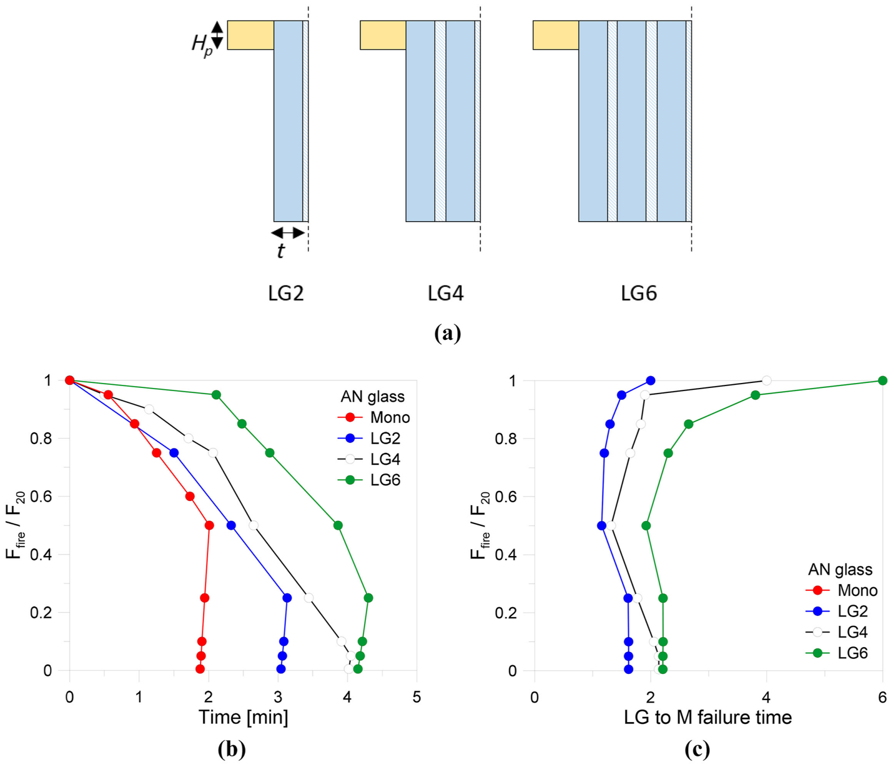

Figure 14.
Failure time for monolithic or LG beams under mid-span sustained load (ABAQUS): (a) reference cross-section layouts and (b) calculated failure time based on maximum stress envelope in glass, with (c) laminated-to-monolithic failure time ratio (examples for AN glass layers)

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relatively higher failure time compared to the monolithic configurations from Table 1, and this LG failure time increases with N_{LG}.

The same calculated increase in failure time for LG members, however, is less pronounced than the expected resistance increases in bending with N_{LG} in cold conditions, and follows a nonlinear trend toward the mechanical loading parameter (F_{fire}/F_{20}). Such an evidence can be seen in Figure 14(c), where the failure times derived from parametric numerical analyses in fire conditions for LG sections are correlated to monolithic beam estimates (as a function of total glass thickness). It can be noted in Figure 14(c) that for LG beams in bending in cold conditions, in accordance with Eq. (4), the failure time ratio is proportional to the number of LG layers. The parametric analysis on LG members under fire exposure shows that the individual glass layer is responsible of "failure" detection for stress verification as in Eq. (5), and this depends on the non-uniform distribution and evolution of temperature in the thickness and height of glass sections under fire. Accordingly, the parametric outcomes in Figure 14(c) confirm that the presence of thermal loading for fire exposure strongly affects the failure time estimates and the load-bearing potential of LG sections, and this is a major difference compared to stress design assumptions in cold conditions.

It is also to note that the predicted deformation rate (for tensile stress failure in glass) for the examined LG beam configurations, compared to the conventional value in Eq. (7), was calculated in around ≈0.35 mm/min. As also observed for monolithic beams, this last outcome overestimates the assumption from Eq. (7) and can be again seen as a direct effect of local stress distributions, that are highly non-uniform in the span and in the thickness of multiple glass layers, and further evolute in the time of exposure, with major effects on material degradation and consequent thermo-mechanical performance of beams.

5. Conclusions

Ordinary (or commercial) soda-lime glass is largely used in buildings, but limited attention is given to its mechanical performance under extreme design loads such as fire. This paper explored the in-plane bending response of glass beams under fire, giving evidence of current issues in their fire endurance analysis. Compared to other traditional constructional materials like timber or steel in fire, where dedicated recommendations are provided by standards for realistic fire endurance assessment based on experiments or numerical methods, this is not the case of structural glass. Major efforts are thus required for (1) reliable thermo-mechanical material characterization and (2) definition/assessment of efficient and conservative failure detection approaches of general use.

As shown, the attention should be focused both on the local and global analysis of stress peaks in glass (including time-dependent material degradation) and deformation parameters (i.e. deformation and deformation rate trends), which are sensitive to various mechanical and geometrical properties. Compared to the structural analysis of glass elements in cold conditions, however, several modifications can be observed in their bending response and overall capacity, due to combined/superimposed fire effects and progressive material softening.

In this regard, the use of Finite Element (FE) numerical models for transient heat transfer and mechanical simulations proved to represent – based on experimental validation – an efficient tool for structural glass applications in fire. At this stage, however, material parameters under high temperature are still not well defined, and such a characterization uncertainty can be addressed by means of conservative degradation assumptions. From a practical point of view, additional experimental studies are hence required for enhanced material characterization under high temperatures.

In terms of failure time detection for the examined glass beams, it was also shown that the traditional verification of glass members against tensile stress peaks (like in cold conditions) cannot be disregarded for fire endurance purposes. At the same time, however, existing deformation parameters which are in use for load-bearing members suggest that additional studies are required to characterize the failure detection of glass in fire. In this regard, it is expected that the present theoretical predictions could be further extended and provide support for generalized fire endurance assessment of structural glass members in fire, so as to cover several configurations of technical interest, and possibly facilitate the derivation of general recommendations and procedural steps of practical use.

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