Structural performance of single-skin glass façade systems exposed to fire

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ABSTRACT

Purpose

Understanding the structural performance of external glass curtain walls (façades) during fire exposure is critical for the safety of the occupants, as their failure can lead to fire spread throughout the entire building. This concern is magnified by the recent increase in fire incidents and wildfires. This paper presents the first simplified technique to model single skin façades during fire exposure, and, then utilizes it to examine the structural behaviour of vertical, inclined, and oversized façade panels.

Design/methodology/approach

The proposed technique is based on conducting simplified heat transfer calculations, and, then utilizing a widely used structural analysis software to analyze the façade. Validation for the proposed technique with reference to available experimental and numerical studies by others are presented. A parametric study is then conducted to assess the structural performance of different glass façade systems during exposure to fire.

Findings

The proposed technique was found to provide accurate predictions of the structural performance of glass façades during fire exposure. The structural performance of inclined façade systems during fire exposure was found to be superior to vertical and oversized façade systems.

Originality

This research paper is the first to provide a simplified technique that can be utilized to model single skin facades under fire. The presented technique along with the conducted parametric study will

improve the understanding of the fire behaviour of single skin glass facades, which will lead to safer applications.

Keywords: Glass façade, Steel, Aluminum, Heat transfer, Nonlinear numerical analysis, Fire incident, Simplified modeling, Vertical panel system, Inclined panel system, Oversized panel system.

1. Introduction

Undoubtedly, glass façades are widely used worldwide. Their design is usually governed by wind loads (Santos *et al.*, 2014). However, façade elements are considered non-structural elements, and their fire safety is usually ignored (Bedon, 2017). Grenfell Tower fire, UK, clearly highlighted that this design approach needs to be revised (Nguyen, *et al.*, 2016).

Components of a typical aluminum glass façade are shown in Figure 1. They include vertical mullions, horizontal transoms, and glass panes. Gaskets are usually used in the connections between the glass panes and the metal frame for moisture and sound insulation. A clearance of 5 to 10 mm is typically used to allow the expansion of the glass panes. Façade systems can utilize vertical, inclined, or oversized panels. The vertical glass panel system is shown in Figure 2(a). It consists of a series of pre-assembled units, each unit is covering the height of one story of a building. This system is assembled and glazed in the factory, and then shipped to the construction site for installation (Şengün Doğan, 2013). Inclined glass panel system is shown in Figure 2(b). The inclination can be either backward or forward. Backward inclination can diminish the ability of fire flames to reach the upper floors (O'Connor, 2008). This system is mainly composed of inclined mullions, transoms, and glass panes. The oversized panel system is shown in Figures 2(c).

In this system, the glass panes cover more than one floor, which significantly speeds the construction process. This system usually includes mullions, transoms, and heat-strengthened glass panes.

The performance of glass panes during fire exposure was examined by many researchers. Ni *et al*. (2012) experimentally evaluated the fire performance of double-skin façades for different fire intensities. Quinn *et al*. (2013) experimentally evaluated the effect of localized fire on the development of cracks in glazing façades with vertical and inclined glass panels. Sędłak *et al*. (2015) highlighted the factors affecting the fire resistance of glazed partitions, which include frame material and shape, type and volume of used insulation inserts, type of glazing, and glazing fixing method. Kinowski *et al*. (2016) compared the effect of glazing fixing methods on the fire resistance of curtain walls. Bedon (2017) and Bedon *et al*. (2018) highlighted the design and research issues for structural glass systems exposed to fire. The structural response of fire-exposed glass beams was examined by Louter *et al*. (2021). Kozłowski and Bedon (2021) examined the sensitivity of failure prediction of glass panels exposed to fire to the various input parameters. Their experimental work emphasized the need to consider different fire scenarios while assessing the fire safety of façade elements. Although simplified techniques to analyze glass panes during fire exposure can be found in the literature (Sabsabi *et al.,* 2021), similar techniques cannot be found for the façade system. Previous research for façade systems relied on either experiments or sophisticated modeling techniques, which are not suitable at the design stage.

This paper proposes a simplified, yet reliable, modeling technique to predict the performance of single skin glass facades during fire incidents. The following sections provide details about the proposed technique and its use to assess different glass façade systems during fire exposure.

2. Proposed Modelling Technique

The simplified modeling technique to predict the fire performance of framed glass façades is applied using SAP2000 (2017). Similar Finite Element software can be used for the analysis. The analysis steps for the proposed technique are summarized below.

1. Heat transfer material properties are first estimated.
   a. For aluminum, the specific heat, C_{al} (J/kg. °C) can be determined using Equation 1 (EN 1999-1-2, 2007). The thermal conductivity, λ_{al} $(w/m.°C)$, can be determined using Equation 2 (EN 1999-1-2, 2007) . Where, T_{al} is the temperature of the aluminum in °C (0 °C < T_{al} < 500 °C).

$$C_{al} = 0.41\ T_{al} + 903 \qquad (1)$$

$$\lambda_{al} = \begin{cases} 0.07\ T_{al} + 190 & \text{for 3xxx and 6xxx alloys} \\ 0.10\ T_{al} + 140 & \text{for 5xxx and 7xxx alloys} \end{cases} \qquad (2)$$

   b. For steel, the specific heat, C_{st} $(J/kg.°C)$, can be determined using Equation 3 (EN 1993-1-2, 2005). The thermal conductivity, λ_{st} $(w/m.°C)$, can be determined using Equation 4 (EN 1993-1-2, 2005), where T_s is the temperature of the steel in °C.

$$C_{st} = \begin{cases} 425 + 0.773\ T_{st} - 1.69x10^{-3}\ {T_{st}}^2 + 2.22x10^{-6} & 20°C < Ts < 600°C \\ 666 + \frac{13002}{738 - Tst} & 600°C < Ts < 735°C \\ 545 + \frac{17820}{Tst - 731} & 735°C < Ts < 900°C \\ 650\ °C & 900°C < Ts < 1200°C \end{cases} \qquad (3)$$

$$\lambda_{st} = \begin{cases} 54 - 3.33 \times 10^{-2}\ T_{st} & 20\ °C < T_s < 800\ °C \\ 27.3 & 800\ °C < T_s < 1200\ °C \end{cases} \qquad (4)$$

c. For aluminum, steel, and glass, the density (ρ) is independent of the temperature and can be assumed equal to 2700 kg/m^3, 7750 kg/m^3 and 2500 kg/m^3, respectively.

2. Heat transfer analysis is conducted to evaluate the temperature of the mullions, transoms, and glass panes for an assumed fire temperature. To simplify this step, it is proposed to estimate the temperature of the different elements using Equation 5, which governs the convection and radiation heat transfer (Incropera *et al.*, 2007). The proposed solution starts by setting the temperatures of the element T_s and the fire T_f equal to the ambient temperature, then the time increment Δt is increased incrementally. For each increment, the fire temperature T_f is first estimated from the standard fire curve and used to evaluate the temperature rise in the considered element ΔT_s.

$$\Delta T_s = K_{sh} \left(\frac{F/V}{\rho . C}\right) [h_c(T_f - T_s) + \sigma \mathcal{E} \, ({T_f}^4 - {T_s}^4)] \, \Delta t \qquad (5)$$

Where F/V is the element shape factor that can be evaluated as the perimeter divided by the cross section, h_c is the convective heat coefficient considering free convection heat transfer through gas and can be taken equal to 20 w/m^2K (Kothandaraman, 2006), K_{sh} is a correction factor for shadow effects and can be taken equal to 1 (Incropera *et al.*, 2007), σ is Boltzmann constant and can be taken equal to $5.67{\times}10^{-8}$ W/m^2K^4 (Incropera *et al.*, 2007), and $\mathcal{E}$ is the emissivity coefficient and can be taken equal to 0.02, 0.07, 0.9 for aluminum, steel and glass, respectively (Incropera *et al.*, 2007) .

3. Stress-related temperature-dependent material properties are defined as follows:

   a. The initial modulus of elasticity of aluminum and steel typically degrades with elevated temperatures. Tables I and II present values for the modulus of elasticity at different temperatures as recommended by Summers *et al.* (2015) and Chen and Young (2006).

b. The stress-strain curves of aluminum and steel at elevated temperatures can be defined using the Ramberg-Osgood model (Summers *et al.,* 2015; Chen and Young, 2006) .

c. The ordinary glass can be modeled as an elastic material with young's modulus of 70 GPa. Glass is assumed to collapse when its temperature reaches 200 °C (Babrauskas, 2012).

4. The material stress-strain curves are used to predict the moment-curvature diagrams for the mullions and transforms.

5. The façade system is modeled using SAP2000 (2017).

   a. Each of the mullions and transoms are modeled using number of elastic frame elements, having modulus of elasticity and thermal properties corresponding to the assumed fire temperature. The elastic frame elements are then connected using plastic hinges, which utilize the moment-curvature diagrams obtained in step 4. The plastic hinge length can be considered equal to the element length.

   b. The glass panels are modeled using 20 mm by 20 mm shell elements. This mesh size was found to result in good accuracy (Sabsabi et al., 2021).

   c. The glass panels are connected to the mullions/transoms by elastoplastic gap links, which model the gaskets and the provided clearance, Figure 3. A clearance between the glass and mullions/transoms of 6 mm can be assumed (Aiello *et al.*, 2018). The elastic stiffness and yield force of the links are assumed equal to 0.5 kN/mm and 0.24 kN, respectively (Aiello *et al.*, 2018) . The gaskets are assumed to melt at 200 ºC (Sadykov *et al.*, 2019).

3. Model Validation

This section presents four validation cases that test different aspects of the proposed technique. The first two cases provide validation for the structural performance of the façade framing at ambient and elevated temperatures. The third and fourth cases provide validation for the full façade system considering lateral deformations at ambient and elevated temperatures.

Maljaars *et al*. (2010) conducted an experimental-numerical investigation to examine the performance of aluminum frames during exposure to elevated temperatures. The geometry of the examined frames is shown in Figure 4. A test was first conducted at ambient temperature, where the applied loads were increased incrementally, while monitoring the deformations. A second test was then conducted, where the loads were kept constant at 12.5 kN and the frame temperature was increased. Figure 5 shows the variation of the beam deflection with the applied force at ambient temperature. The figure shows good agreement between the predictions of the proposed technique and the experimental and numerical results by Maljaars *et al*. (2010). Regarding the behaviour at elevated temperatures, the experimental research showed that the frame failure occurs at a temperature of 300 °C. Failure at the same temperature was predicted by the proposed technique to occur at a load of 11.86 kN. The small error (5.4%) in predicting the failure load can be due to the assumptions of rigid connections and/or uniform frame temperature.

The second validation case involved an aluminum frame, which was analyzed using a finite element program (ELSAFIR98A) assuming exposure to ISO fire curve (Faggiano *et al.*, 2004). The frame is shown in Figure 6. The frame collapsed after 6 minutes of exposure, which corresponds to a temperature of 250 °C. The simplified technique was applied at this temperature. Failure load was then found to be 14.73 kN/m, as compared to the experimental 15.00 kN/m.

The third validation case involved a glass façade made of an aluminum transom-mullion frame and insulated glazing systems, as shown in Figure 7. The façade was experimentally tested to examine its cyclic behaviour at ambient temperature (Caterino *et al.*, 2017). Actuator beams were used to apply the lateral loads. The components of the examined façade are aluminum frame made of 150 mm by 50 mm HSS sections, 32 mm thick glass panes, 5 mm glass clearance, and rubber gaskets. These components were modeled using the proposed technique. An increasing lateral load was then applied, and the obtained lateral load-deformation behaviour was compared with the experimental envelope for the cyclic lateral load-deformation behaviour (backbone curve), Figure 8. The proposed modeling technique was able to predict the lateral deformation with good accuracy.

The 4.2 m wide curtain wall, Figure 9, analyzed by Del la rosa and Lu (2017) using ANSYS was utilized as the fourth validation case. Two models were developed for this curtain wall using ABAQUS and the proposed simplified technique. The modeled wall was used in a façade system with a floor height of 5.2 m. ABAQUS meshing utilized 8-node thermally coupled bricks with three translational degrees of freedom per node. The optimum mesh size was found to be 50 mm. The brick elements were used to model the stainless-steel mullions and transoms (HSS 100×60×4.1), glass panes (13 mm thick), and the concrete slabs (150 mm thick). Tie constraints were used to attach the mullions and the transoms to the glass panes. A schematic showing the curtain wall model is given in Figure 10. A fire source was located 1 m from the glass panes and followed ASTM E-119 fire exposure curve. The facade was assumed to be laterally supported by the floor slabs. As for the heat properties, ideal gas constant of 273.15 K and Boltzmann constant of $5.67\times10^{-8}\ \mathrm{W/m^2K^4}$ were utilized (EN 1993-1-2, 2005). Three main analysis cases were conducted, which involved: (1) applying a wind pressure at ambient temperature, (2) conducting thermal analysis, and (3) applying a wind pressure at elevated temperature.

Considering the lateral behaviour at ambient temperature, the Hilti curtain wall was exposed to static wind load of 57.5 kPa. The maximum lateral deflection was found to be 9.6 mm (ANSYS by Del la rosa and Lu (2017)), 9.3 mm (ABAQUS), and 9.5 mm (simplified technique). The differences between the predictions of the three analysis methods are minor (maximum difference 3.2 %). Figure 11 shows the deformed shape obtained using ABAQUS. To further examine the validity of the proposed technique, the analysis was repeated assuming a static wind load of 115 kPa. The lateral deflection increased from 9.3 mm to 18.6 mm (ABAQUS) and from 9.5 mm to 19.0 mm (simplified technique). The frame is clearly still behaving in the linear elastic range.

A thermal analysis was then performed to predict the temperature of the mullion assuming ASTM E-119 fire. Figure 12 shows the comparison between the mullion temperature as predicted by ANSYS (Del la rosa and Lu, 2017), ABAQUS, and Equation 5. The predictions of the three methods are closely matched.

The façade is then tested for combined mechanical and thermal loads. A coupled mechanical-thermal analysis was conducted using ABAQUS by applying the wind pressure while the façade is exposed to an internal fire. Analysis was also conducted by the simplified technique~~, Figure 13,~~ at different fire durations. Figure 13 shows the SAP2000 model for the proposed technique, which includes elastic frame elements representing the mullions and transoms, shell elements representing the glass panels, and elastoplastic gap links representing the gaskets. The point experiencing the maximum lateral deformation at temperature of 100 °C is highlighted in the figure. Figure 14 shows the variation of the lateral deformation of the façade with time as predicted by ABAQUS and the proposed technique. The wind pressure was then increased from 57.5 kPa to 115 kPa for three fire temperatures (100, 200, and 400 °C). This increase has resulted in increasing the maximum lateral deformation of the mullion from 23 mm to 30 mm (ABAQUS) and 21 mm to 28 mm (proposed technique) at 100 °C, 65 to 86 mm (ABAQUS) and 63 mm to 80 mm (proposed technique) at 200 °C, and 144 to 153 mm (ABAQUS) and 142 to 152 mm (proposed

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technique) at 400 °C. It is clear that the proposed technique was able to predict the deformations with good accuracy. The results also indicate that the fire temperature has resulted in non-linear behaviour of the façade system.

4. Structural Performance of Façade Systems

Vertical and inclined glass-façade systems made of HILTI curtain wall panels with dimensions of 4.2 m wide and 5.4 m high, Figure 15, are assumed to be covering a 16.8 m wide three-storey building. For the oversized panel system, a 16.8 m wide two-storey building is assumed to be covered by 4.2 m by 10.8 m glass panes. Following the assumptions of De la Rosa and Lu (2017), the standard façade panels consist of stainless-steel mullions, glass panes, and aluminum transoms. The system, shown in Figure 15, includes 12 mullions, 16 transoms, 9 glass panes, and 6 half glass panes. Figure 16 shows the cross section for the typical mullions and transoms.

Curtain walls are designed to resist the imposed gravity and wind loads, accommodate deformations, and provide weather tightness. The loads imposed on the curtain wall are transferred to the building structure through the supporting brackets. The gravity loads include the own weight of the frame and the glass panels. The wind load was assumed to be equal to 2.4 kPa for an area of high wind intensity (CCBFC, 2015). As the installation of curtain walls takes place after the construction of the floors, they must tolerate movements resulting from the short- and long-term column shortening and floor deflections. It was suggested to estimate these movements to include 2.2 mm column shortening and 25 mm floor deflection (EN 1993-1-1, 2005). These deformations were imposed on the façade assuming a stepped deformation shape as shown in Figure 17.

The load combination given by the Eurocode (EN 1990, 2002), "1.0 D + Fire Effect + 0.33 Wind load", was utilized to examine different façade systems. A standard fire curve, ASTM E119, was assumed. Three main cases were considered in the analysis, which involved: (1) applying the wind pressure/suction at ambient temperature, (2) applying the wind pressure at elevated temperatures, and (3) applying the wind suction at elevated temperatures. Results of cases 2 and 3 are valid for cases of a fire within the building or an external fire. The assumed façades are modeled using the simplified technique, explained in section 2. The utilized moment curvature diagrams are shown in Figure 18. The elastic modulus values for glass, aluminum and steel are given in Table III. Gap clearance of 6 mm was assumed between the glass panes and the façade framing. To represent the different stages of load resistance, three fire durations of 2.5, 10.0, and 30.0 minutes were evaluated.

4.1 Ambient Temperature Results

For the vertical panel façade system, the maximum lateral deformation measured at mid-height of the first, second, or third floors is 0.123 mm (SAP model) and 0.126 mm (ABAQUS Model). The inclined system showed a much lower deformation of 0.07 mm. The lateral deformation of the oversized panel system, measured at the level of the first floor, is 0.16 mm. All elements of the examined façades remained in the elastic range for the ambient temperature case. Under wind load, the gap links between the glass and frame elements opened indicating that glass panels will not be affected by the façade deformations.

4.2 Vertical Façade System at Elevated Temperatures

For the vertical façade system, three fire scenarios were assumed, (1) fire at the first floor, (2) fire at the second floor, and (3) fire at the first and third floors. At 2.5 minutes, the glass façade system resisted the applied loads as a whole system. The glass panels are assumed to break at a temperature of 200 °C, which happened after five minutes of exposure to ASTM E119 standard fire. At 10 minutes of exposure, the lateral loads were only resisted by the frame elements. After 30 minutes, the mullions behaved inelastically due to degradation of the material properties. Figure 19 shows the change in the temperature of the mullions, transoms, and glass panes with time.

A typical SAP model is shown in Figure 20 considering fire temperature of 100 °C. The figure shows the value and location of maximum lateral deformation in meter of the first-floor mullions. Figure 21 shows the maximum lateral deformations for different fire durations at the first floor, the second floor and at the first and third floor considering wind pressure or wind suction. The deformations and stresses of the exposed floors were significantly increased. The deformations of the unexposed floors were slightly increased because of the continuity of the façade system. The case of fire exposure at the first and third floors produced the highest deformations in these floors. The maximum deformation at the second floor was observed for the case of fire exposure at the second floor. The variation of the mullion strains with the temperature for the case of fire exposure at the first floor is shown in Figure 22. The mullions started to experience inelastic deformations after reaching a temperature of 400 °C.

4.3 Inclined Façade System at Elevated Temperatures

For the inclined façade system, only one case is considered as each floor is expected to behave independently from the other floors. The studied case involved exposing the first floor to fire and wind loads. Figure 23 shows the utilized SAP model and the analysis results at 400 °C.

Figure 24 shows the maximum lateral deformations for different fire durations considering wind pressure or wind suction. In general, it is obvious that the inclined panels have better performance than the vertical panels, as they have resulted in lower lateral deformations. Additionally, the system is considered discontinuous from floor to another, and thus the upper floors were not affected by exposure at the first floor. The mullions of the first-floor experienced inelastic deformations while those in the second and third floor experienced elastic deformations of 0.07 mm. Figure 25 compares the lateral deformations of the vertical façade and inclined façade systems, and it is obvious that the inclined mullion have better performance than the vertical one. The variation of the mullion strains with the temperature for the case of fire exposure at the first floor is shown in Figure 26. As shown, the mullions yielded at 400 °C and experienced nonlinear deformations. However, these nonlinear deformations are still lower than vertical panel system.

4.4 Oversized Façade System at Elevated Temperatures

Two cases were considered for the oversized panel system that involved: (1) exposing the first floor to elevated temperatures, and (2) exposing both the first and second floors to elevated temperatures. Figures 27 shows the used SAP model and the mullion deformation at 400 °C considering first floor fire exposure. The mullion's temperature was assumed to be constant along its height because of the high conductivity of its material. The oversized panels showed significant higher deformations than the vertical and inclined panels. As shown in Figure 28, the highest deformations were captured at the first-floor storey level as the oversized panel system was only laterally supported at the ground and the second-floor storey levels. Figure 29 shows that the double floor exposure case experienced higher deformations than the first-floor exposure case. Regardless, both cases show significantly higher deformations than the vertical and the inclined panel systems. Although this system is rapid in installation, attention should be given to its structural performance during fire exposure.

5. Conclusions

This paper proposes a simplified technique that can be utilized to estimate the lateral deformations of glass façades during fire exposure. The proposed technique starts by estimating the frame and glass temperatures using the governing convection and radiation equation. These temperatures are then utilized to evaluate the material properties. The frame is modeled using the plastic hinge approach of SAP2000 (2017). The deformations of the gaskets are accounted for using nonlinear spring elements. At a temperature of 200 ºC, the glass and gaskets are assumed to lose their function, and the loads are resisted by the façade frame. The proposed technique was validated using experimental and numerical research by others and found to provide accurate predictions for the temperature, deformation, and failure load of the façade elements. Three main glass façade systems (vertical, inclined, and oversized) were then examined at elevated temperatures while being exposed to wind pressure/suction. The main conclusions of the conducted analyses can be summarized in the following points.

1. At ambient and at elevated temperatures, the oversized panel system had the highest lateral deformations, and the inclined system had the lowest lateral deformations.
2. At ambient temperatures, the lateral deformations for the three façade systems were relatively low (less than 0.003% of the floor height).
3. After 30 minutes of standard fire exposure, the lateral deformations of the fire exposed floors increased significantly for the three systems reaching values of about 2.5% of the floor height for the vertical and inclined façade systems and about ~~1.8~~3.6% of the floor height for the oversized façade system.
4. The vertical façade system acted as a continuous system, where the lateral deformation of the unexposed floors increased. For the floors above or below the fire exposed floors, the deformation direction also changed simulating the deformation behaviour of a continuous beam and indicating that the deformations resulting from fire exposure are much higher than the original ambient deformations.
5. In the inclined floor system, the deformation of each floor is independent of the other floors.
6. ~~Out of three examined systems, the inclined system experienced the lowest deformations, and the oversized system experienced the highest deformations.~~

This research was limited to single-skin glass façade system utilizing normal glass panes and uniformly exposed to standard fire temperatures. Future research is needed to (1) explore the use of different types of façade systems and glass panes including high strength panes, (2) examine the effect of gaskets on the temperature distribution of the façade system as highlighted by Bedon and Louter (2018), (3) experimentally examine the structural performance of gaskets during fire exposure, (4) examine the performance of the façade system during simulated realistic fire scenario, which will be affected by the breakage of the glass panes and subject the façade system to non-uniform temperature exposure along its height as highlighted by Vedrtnam et al. (2021), and (5) provide engineers with quantitative methods to assess the structural fire performance of façade systems.

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