Structural Performance of Glass Façades Exposed to Fire

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Abstract

Glass façades are commonly used in the modern construction industry. The thesis starts by providing a general background about glass façades, their design criteria, and related previous research studies. The common concern among the previous studies was the inadequate performance of glass façades during fire incidents, which accelerates the spread and severity of the fire. This concern is magnified by the recent worldwide increase in wildfires. Thus, it is critical for engineers to be able to assess the structural performance of glass façades at elevated temperatures. The thesis addresses this need by presenting a simplified technique to model single skin façades during fire exposure and evaluating the structural performance of typical glass facades during fire exposure.

The development of the simplified technique involved estimating the temperatures of the façade elements using the governing convection and radiation equations. The temperatures are then used to evaluate the properties of the materials of the façade as well as the thermal strains. Suitable elements are chosen to model the façade utilizing a widely used structural analysis program (SAP2000). The analysis steps are then summarized. The proposed simplified technique was found to be able to predict the behavior of glass façades during fire exposure with good accuracy.

Three main glass façade systems (vertical, inclined, and oversized) were then examined by exposing them to elevated temperatures and wind loads. The floors exposed to the fire experienced the highest lateral deformations. The vertical façade system acted as a continuous system, where the lateral deformations of the floors, which were unexposed to fire, increased. This behaviour did not occur in the inclined façade system, in which each floor acted independent of the other floors. Out of three examined systems, the inclined system experienced the lowest deformations, and the oversized system experienced the highest deformations.
Keywords

Glass façade systems; Steel frames; Aluminum frames; Mullion; Transom; Fire incidents; Simplified modelling; Numerical studies; Thermal analysis.
Summary for Lay Audience

Safety of the occupants needs to be ensured during fire incidents, which are either developed within the building or outside (wildfire). This thesis addresses this point by focusing on glass façades, which are critical to stop the supply of oxygen to an internal fire or keep a wildfire outside the building. The thesis provides engineers with a simplified technique to estimate the behaviour of glass façades during fire exposure, which will allow them to ensure the occupant safety. The thesis also compares the performance of three glass façade systems and draws important conclusions, which can help engineers and architects during the planning stage for a new construction.
Co-Authorship Statement

All the numerical work presented in this thesis is performed by Mohamed Badr. Work was reviewed by Dr. Maged A. Youssef and Dr. Salah El-Fitiany. Chapters 4 and 5 will be submitted to scholarly journals as manuscripts co-authorized by Mohamed Badr, Maged A. Youssef, Salah El-Fitiany, and A. Vedrtnam. Dr. Vedrtnam from India is collaborating with Dr. Youssef in research addressing fire safety of glass façades.
Acknowledgments

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List of abbreviation and symbols

\( C \)  Specific heat (J/kg. K)

\( C_{al} \)  Aluminium specific heat (J/kg. °C)

\( C_{st} \)  Steel specific heat (J/kg. °C)

\( E_{al} \)  Aluminium elastic modulus (N/mm\(^2\))

\( E_{st} \)  Steel elastic modulus (N/mm\(^2\))

\( F/V \)  Element shape factor

\( F_y \)  Yield force (kN)

\( h_c \)  Convective heat coefficient (W/m\(^2\)K)

\( K_{sh} \)  Shadow correction factor

\( T_{al} \)  Aluminium temperature (°C)

\( T_f \)  Fire temperature (K)

\( T_s \)  Element temperature (K)

\( T_{st} \)  Steel temperature (°C)

\( \Delta t \)  Time increment (sec)

\( \varepsilon_{st} \)  Steel strain ratio

\( \varepsilon_y \)  Yield strain ratio

\( \lambda_{al} \)  Aluminium thermal conductivity (W/m. °C)

\( \lambda_{st} \)  Steel thermal conductivity (W/m. °C)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>$\sigma$</td>
<td>Boltzmann constant (W/m². K⁴)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density (kg/m³)</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>Section curvature (Rad/mm)</td>
</tr>
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</table>
Chapter 1

1 Introduction

The use of glass façades (curtain walls) has significantly increased in mid- and high-rise buildings. Façade is a French word, which means the front face. In case of buildings, façade is the front element that completes the overall form and enhances the architecture character of the building [1]. Metal glass façades are widely used because of their advanced technologies, features, and rapid installation. A typical glass façade system is shown in Figure 1.1 and mainly consists of an outer frame with vertical members known as mullions and horizontal members known as transoms, glass panel, and insulation gaskets [2]. Sometimes spandrels are used to hide the structural edges and can be made of glass, metal, stone, or compressed cement. Glass façades are typically designed for gravity and wind loads [3]. Their fire performance is not usually considered.

![Figure 1.1: Typical glass façade system](image)

During internal fire incidents, glass façades are expected to prevent the spread of fire between floors. This function was not achieved during the Grenfell tower fire, shown in Figure 1.2, which led to 72 deaths and 74 non-fatal injuries [4]. Other recent major facade fire incidents include Marco Polo Tower (Honolulu city, USA), in which fire started at the mechanical room located on the 26th floor and spread throughout the building (Figure
1.3) [4] and Tamweel Tower (Dubai, UAE), in which fire burned the full height of two separate curtain walls (Figure 1.4) [4,5].

Figure 1.2: Fire at Grenfell Tower, London [6]

Figure 1.3: Fire at Marco Polo tower, USA [7]
The recent worldwide increase in the frequency and size of wildfires is concerning. The wildfires, which have been happening in Canada, USA, Australia, Greece, and other countries have led to the destruction of many homes/cities and the injury/death of many people. For such fires, glass façades are expected to keep the fire outside the building. Figure 1.5 shows a burning building because of a wildfire in Kelowna, Canada [8].
1.1 Research Impact

With the recent increase in fire incidents and wildfires, engineers need to ensure the safety of the occupants by limiting the spread of an internal fire and preventing wildfires from penetrating the building façade. This research provides engineers with a simplified analysis technique that allows them to achieve this goal. The thesis also provides an assessment of the structural performance of typical glass façades during fire exposure. This assessment provides architects with critical data, which will allow them to have better safer designs.
1.2 Objectives

This study aims to provide engineers and researchers with better understanding of the structural performance of glass façades during fire exposure. To achieve this goal, the following objectives are addressed.

- Conduct a comprehensive literature review to understand the current state of knowledge.
- Develop a simplified model that can help assess the thermal and mechanical behavior of single panel glass façades during fire exposure.
- Assess the structural performance of commonly used glass facades systems during fire exposure.

1.3 Outline of The Thesis

The thesis is divided into five chapters that cover the introduction, literature review, development of a numerical technique to assess the fire performance of glass façades during fire exposure, examining the structural performance of typical glass façades during fire exposures, and summary and conclusions.

Chapter 1 presents an overall introduction of the thesis in terms of general background, research objectives and scope.

Chapter 2 provides a literature review discussing the types of glass facade systems, fire temperatures, behaviour of glass panels during fire exposure, and previous research which address glass façades.

Chapter 3 presents a simplified technique to model single skin façades during fire exposure. The development of this technique involved: (1) defining the typical components of curtain walls, (2) identifying suitable models to account for their thermal and mechanical properties, (3) conducting non-linear finite element analyses of glass façades during fire exposure, and (4) identifying potential simplifications in the models.
and applying them. The proposed simplified technique was found to be able to predict the behavior of glass façades during fire exposure with good accuracy.

Chapter 4 presents a numerical study of different glass façade systems during exposure to fire. The used modeling technique was validated against experimental and numerical studies by others in Chapter 3. The considered façade systems have vertical, inclined, and oversized panels. The inclined panel system showed the best performance under combined thermal and mechanical loads.

Chapter 5 provides the overall conclusions of the research as well as the limitations and recommendations for future work.
1.4 References


Chapter 2

2 Literature Review

This chapter presents a literature review on topics related to the thesis scope. In the first section, background information and definitions as well as classification of curtain wall systems and different types of glass panels are given. Then, the structural design of glass façades is discussed, while focusing on the basic parameters that affect the overall structural performance. The last section covers fire temperatures, behaviour of glass panels during fire exposure, and previous research addressing glass façades.

2.1 Historical Background

Modern engineers discarded the decorative styles of the nineteenth century and merged architectural features with innovative industry products. This change has resulted in a simple, logical, and functional building styles. The first curtain wall (façade) was designed in 1926 by a German architect, Walter Gropius (1883-1969). The design provided an exterior wall of glass. Mr. Gropius was a teacher in North America and a founder of the international style in architecture, which greatly influenced the construction industry [1]. Nowadays, Curtain walls became far more sophisticated than their early counterparts. The developments, which were made over the past 50 years, have eliminated the installation and design difficulties, leading to better façade products [1].

2.2 Classification of Glass Façade System According to Construction Technique

Curtain walls can be divided into five main categories: stick (frame), semi-panels, full panels, oversized panels, and window panels.

2.2.1 Stick Construction Type

The most widely used construction method for building façades is the stick method. It is based on a defined grid system, which consists of vertical (mullions) and horizontal (transoms) frame members [4]. The rectangular spaces between the grid members are
filled with a solid or glass panels, as shown in Figure 2.3. Patterson et al. [5] described the technique in which those prefabricated vertical and horizontal frame members are installed and connected on site. Glass or other cladding panels are then attached to these members. The connections between the frame members and the building floors should have adequate tolerance to eliminate the effects of building deformations on the façade.

The pros and cons of the system are explained by Murray et al. [6]. Most stick systems are standard, off-the-shelf products, which means that they have relatively low material cost. Moreover, the efficient packaging technique for separate system components provides low expenses for handling and transportation. However, the main disadvantage for this system results from the method of installation as it takes time, requires highly skilled labors, generally results in quality issues, and can be delayed by weather.

![Figure 2.1: Typical stick (frame) construction technique [4]](image-url)
2.2.2 Semi Panel Construction Type

The semi-panel construction can be described as the improved version of the stick (frame) construction technique. Members of the semi-panel system are produced as vertical strips, which allow the pre-assembled panels to slide inside their cavities, as shown in Figure 2.2. This system was utilized in iconic buildings including the World Trade Center and Sears Tower because of its lower installation time as compared to the stick system.

![Diagram of semi-panel construction technique](image)

**Figure 2.2: Diagram of semi-panel construction technique [8]**

2.2.3 Panel construction type

The panel construction technique is considered the most contemporary method. This system consists of a series of pre-assembled units, which are assembled and glazed in the factory, and then shipped to the construction site for installation [7]. Figure 2.3 shows a typical bracket used to connect the panels to the floor slab. Figure 2.4 shows the installation process, which is speedy and eliminate all problems of the previous systems.
2.2.4 Oversized Panel Construction Type

The oversized panel system is similar to the panel construction type. However, the panels in this system are bigger and either cover more than one floor or have a wider width. This system is not popular due to construction difficulties associated with handling bigger panels. However, it is usually used on small, specialized projects [3].
2.2.5 Window Panel Construction Type

This façade is placed within the space between the floors, as shown in Figure 2.6. This system is only used in some residential applications, especially in inclined curtain walls [3].
2.3 Classification of Glass Façade System According to Design Method

Curtain wall systems can be divided into single skin, structural glazing, point-fixed glass, and double skin [2].

2.3.1 Conventional Curtain Wall System (Single Skin Façade)

Conventional curtain wall system is well-known and widely utilized. It is usually constructed using the stick (frame) construction technique and is often called pressure equalization system. It was developed by the Building Technologies Research Institute of Norway in the late 1960s [9]. The initial version of this system consisted of mullions, transoms, and glazing parts with pressured plates [2]. The standard conventional curtain wall system has both horizontal and vertical cover caps, which can be produced in various forms and sizes. It provides linearity effect to the building façade. In this system, the vertical mullions are anchored to the floor slab, and the horizontal transoms are installed. Then the glass panels and extruded-aluminum pressure plates are installed [6]. The extruded-aluminum pressure plates, which are intermittently screwed into the mullions, exerts pressure on the gaskets to mechanically fix the glass to the frame. Lastly, the cover caps, which are usually made from aluminum, are placed on the pressured plates to conceal the fasteners, as shown in Figure 2.7 [2].

![Figure 2.7: Conventional curtain wall system](image-url)
2.3.2 Structural Glazing Curtain Wall System

Structural glazing curtain wall system, which symbolizes transparency and lightness, is widely used in high-rise buildings. The construction method of this system depends on frame construction technique. In this system, the glazing and structural details are done such that they provide a flat surface. Thus, eliminating the need for cap plates. As the aluminum section cannot be seen from the outside (Figure 2.8), this system provides an aesthetic solution [10]. Structural glazing is constructed by mounting the glass panels to the aluminum frames through a high-strength and high-performance silicone gasket sealant. The silicone sealant adhesive is used to bond the glass to the frame without the need for mechanical anchors [11].

Figure 2.8: Structural glazing curtain wall systems [11]

2.3.3 Point-Fixed Glass Curtain Wall System

Innovations in steel and glass industry have resulted in glass curtain walls, which are lightweight. This system is preferable in term of visual aspects, because of its transparent effect. Glass curtain wall systems can be coordinated with all types of steel structures. The spider fittings, shown in Figure 2.9, are used to support the glass panels [12].
2.3.4 Double-Skin Curtain Wall System

The double skin façade (DSF) emerged across Europe, Asia, Canada, and the United States in the end of the twentieth century as a mean to save energy. It also provides access to daylight and natural ventilation. Although it started in low-rise buildings, numerous high-rise applications were completed in the early 1990’s [2]. The categories of Double-Skin Façade, in terms of partitioning the cavity, are summarized in Figure 2.10. For box window type, the horizontal and vertical partitioning divide the façade in smaller independent boxes. The shaft box type provides vertical connection between the cavities to ensure an increased stack effect (chimney effect). In the corridor façade type, the cavities are connected in the horizontal direction for acoustical, fire resistance, and ventilation reasons. The multi storey double skin façade type provides connection of the cavities throughout the façade. Table 2.1 [13] summarizes the advantages and disadvantages of each system.
Figure 2.10: Double Skin Façade Configuration
<table>
<thead>
<tr>
<th>Table 2-1: Advantages and disadvantages of DSF categories</th>
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<tbody>
<tr>
<td><strong>Box window type</strong></td>
</tr>
<tr>
<td><strong>Sound Insulation</strong></td>
</tr>
<tr>
<td><strong>Natural ventilation and air quality</strong></td>
</tr>
<tr>
<td><strong>Fire protection</strong></td>
</tr>
</tbody>
</table>
2.4 Classification of Glazing types

Glass façade systems consist of nearly 80-85% glass and 10-15% metal frames. The appropriate selection of the glass type has a direct influence on the overall performance of the curtain wall system. Moreover, there is a wide range of existing and emerging glazing technologies, many of which break new grounds with respect to innovative structural use of glass. The importance of the thermal conductivity and performance of glass in curtain wall systems is discussed by Atalay et al. [7]. The main types of glass panels, which are commonly used in curtain walls, are summarized in the following subsections.

2.4.1 Insulating Glass Types (IGU)

An insulated glazing unit (IGU), Figure 2.11, consists of two or more ordinary glass panes enclosing a hermetically sealed air space [15]. The most important function of an IGU is to reduce heat loss by preventing heat transfer between the external and internal environments. The glass panes are connected by a spacer and sealants to reduce water-vapor penetration. Insulating glass can help in reducing the external noise pollution when it is made up of glass panes of the same thickness.

![Figure 2.11: Typical Insulated Glass Cross Section](image)

2.4.2 Security Glass Types

There are two main types of security glass: toughened glass and laminated glass.
Toughened Glass (Tempered Glass)

Tempered glass is an extremely tough glass, which is heat treated to a uniform temperature and rapidly cooled to induce internal compressive stresses of 770 kg/m² to 1462 kg/m² [11]. This process results in four to five times stronger glass, which breaks into small relatively harmless fragments. Thus, it minimizes the risk of injury. It also provides greater thermal strength and can tolerate sudden temperature changes.

Laminated Glass

Glass is a fragile material and has low resistance to impact. By increasing the thickness of glass, its resistance improves but its fragility remains a problem. Laminated glass is made by laminating two or more sheets of equal or unequal glass thicknesses with a flexible plastic interlayer (e.g., PVB-poly vinyl butyral). The transparent plastic film (PVB) enables significant improvements in post breakage behavior of the glass [15]. If one or both layers of glass are exposed to an impact or increased thermal stresses, the fragments of the glass adhere to the interlayer. Thus, the broken pieces of glass remain bonded. Laminated glass elements retain a particularly high structural capacity as compared to annealed and heat-strengthened glass.

2.5 Design of Glass Façade Systems

Engineers design glass façades while accounting for their installation method. The design should give details about the frame structure, glass panes, and spandrels if applicable and should address the structural integrity, deformations of the support structure and deformations within the façade, weather tightness, moisture control, and thermal insulation.

2.5.1 Structural Integrity

The structural integrity of the curtain walls can be checked using the same methods for designing typical structures. The applied loads include the gravity and lateral loads. It should be noted that wind and seismic loads, acting on the skin of the building, are of different character and magnitudes than those governing the design of the building itself.
The façade is expected to see higher intensity loads, which can change more drastically [1]. Standards that can be related to structural design include: NBCC-2015 [17], Eurocode EN 1990 [18], Aluminum Design Manual [19], and Metal Curtain Walls [20].

2.5.2 Deformations

An important consideration in designing curtain walls is the necessity of having ample provision for movement. Buildings are not static and do deform. Movements can be within the façade or relative between the façade and the building. These movements are caused by temperature changes, lateral forces, gravity loads, creep, and ground settlements. Having adequate clearance in the joints, connecting the façade to the building, and connecting the façade elements together, allows for such movements to happen without affecting the façade structure.

2.5.3 Weather tightness

Weather tightness means protection against both water leakage and air infiltration. It is closely related to proper joint design. Undoubtedly, a major share of difficulties experienced with metal curtain walls is related to the loss of weather tightness. Water leakage was a common problem in earlier walls, due to faulty designs, materials, or workmanships. This problem does not exist anymore.

2.5.4 Moisture Control

Metal and glass are impermeable to moisture, and thus act as highly efficient vapor barriers. However, they have low heat retention capacity, which means that the design of the façade system should provide control of condensation.

2.5.5 Thermal Insulation

Glass inherently has low resistance to heat flow. Thus, with proper attention to details curtain walls can be designed to provide good thermal performance by utilizing rubbers and gaskets. Generally, this is accomplished by minimizing the portion of metal framing members exposed to the external temperatures, eliminating thermal short circuits by
means of thermal breaks, using double rather than single glazing, and providing good insulation in the large opaque areas of the wall.

2.6 Development of Compartment Fire

Structures are usually divided into vertical, horizontal, or combined compartments. This division limits the spread of fire. It also allows phased evacuation of multi-story structures. A typical compartment fire, Figure 2.12, can be divided into four phases: growth, flashover, post-flashover, and the decay period [21].

![Figure 2.12: Fire developments and stages [21]](image)

2.7 Standard Time Temperature Curves

To standardize testing, a standard fire was specified by different codes to simulate severe fire, which is fully developed with no decay period [21]. The most widely used standard temperature-time relationships, Figure 2.13, are ASTM-E119 [22] and ISO 834 [23] to simulate an internal fire within a building, Eurocode Hydrocarbon fire [24] to simulate fire caused by chemical gas, and external fire [25] to simulate wildfire.
2.8 Glass Façade Fire Exposure

While research addressing fire spread between floors through the building façade dates back to the 1960’s [26], fire testing of building façades started in the 1990’s [26]. Such testing is continuing to date for new products and materials.

During fire, the first element, which is expected to break, is the glass panel. The flames emitting from the created openings can extend higher than 5 m above the top of the window as reported by Yokoi et al. [27]. Flames can, thus, be found to spread from floor to another through the building façade. This phenomenon was called the leapfrog phenomenon [26]. Babrauskas et al. [28] divided thermal exposure to glass to two types based on the exposure if it is internal or external. Wildfires spread by a combination of a radiant heat, moving flames, and dry bushes (Figure 2.14).

Figure 2.13: Standard fire curves
Babrauskas et al. [28] stated that when a glass panel is first heated, it tends to crack when the glass reaches a temperature of about 150-200 °C. The first crack initiates from one of the edges. Pagni et al. [29] mentioned that glass breaks when exposed to fire as the temperature difference between the exposed pane and its shaded perimeter produces a thermal strain at the edge. Shields et al. [30] conducted several room fire tests using 6 mm thick float glass and showed that first cracking does not occur until the bulk glass temperature reached around 110 °C. This corresponds to a heat flux of around 3 kW/m².

Many studies have conducted full scale real fire tests to observe the behaviour of the curtain wall system as whole unit. Gandhi et al. [31] conducted a full-scale test on a three-storey building by exposing the curtain wall system to fire from inside the building. The façade system included aluminum composite panels (ACP), toughened glass, pressure tapes, and silicon glazing sealant. Breakage of the glass panes due to failure of pressure tapes and silicon sealant in addition to exposure of aluminum composites to elevated temperature was observed. Dréan et al. [32] performed a fire test on two rooms and concluded that CFD simulations were able to predict the gas temperatures and the heat flux on the tested façade. Sędłak et al. [33] assessed the temperature of vertical aluminum frames (mullions) of a glazed partition and assessed the effect of using insulation inserts.
2.9 Conclusions

The glass façade is a system of complex components which has developed over the past few decades starting from grid systems to unitized panel systems. Their safety is a major concern for many design engineers. Thus, there are many design provisions to produce efficient glass panels. However, to understand the issues associated with their weak performance during fire, several experimental studies were conducted to study their behaviour during fire exposure. Very few studies included numerical simulations, which relied on the use of sophisticated models. Engineers are in-need of simplified models that can be used to analyze glass façades during fire exposure to assess their vulnerability and behaviour.

2.10 References


[24] Standard fire curves from Eurocode [33]: Hydrocarbon Temperature-time fire curve


Chapter 3

3 Simplified Modelling of Single-Skin Façade Exposed to Fire

Undoubtedly, glass façades are widely used worldwide. Their design is usually controlled by the wind loads [1]. Figure 3.1 shows the components of a typical glass façade, which include vertical Mullions, horizontal transoms, glass panels. The connection between the mullions and the transoms is shown in Figure 3.2. While the connection shown in Figure 3.2(a) allows for rotation, the one shown in Figure 3.2(b) is considered rigid. Gaskets are usually used in the connection between the glass panels and the metal frame for moisture and sound insulation. A clearance of 5 to 10 mm is typically used to allow for the expansion of glass panels.

Figure 3.1: Cross section of a typical aluminum glass facade
Fire safety of the structural elements is addressed in the design stage. Façade elements are considered non-structural elements, and their fire safety is usually ignored [2]. Grenfell Tower fire, UK, clearly highlighted that this design approach needs to be revised [3].

Sędłak et al. [4] highlighted that the fire resistance of glazed partitions depends on many factors including frame material and shape, type and volume of used insulation inserts, type of glazing, and glazing fixing method. Their experimental work emphasized the need to consider different fire scenarios, while assessing the fire safety of façade elements. Ni et al. [5] experimentally evaluated the fire performance of double-skin façades using three fire intensities and evaluated the damage corresponding to each intensity. Through an experimental-numerical investigation, Quinn et al. [6] evaluated the effect of localized fire on the development of cracks in glazing façades with vertical and inclined glass panels. Kinowski et al. [7] compared the effect of glazing fixing methods on the fire resistance of curtain walls. Song et al. [8] numerically examined the thermal performance of different types of curtain-wall framings. Scagliola frame, which is made of selenite, glue and natural pigments including marble and other stones, was found to have the lowest temperature difference.
The conducted studies relied either on experiments or sophisticated modeling techniques, which are expensive and time consuming. This paper proposes a simplified, yet reliable, modeling technique to predict the performance of single skin glass facades during fire incidents. The following sections provides details about the proposed modeling technique and its validation.

3.1 Proposed Modelling Technique

The simplified modeling technique involves the use of the widely available SAP 2000 software to predict the fire performance of framed glass facades. The following steps are proposed.

1. Heat transfer material properties are first estimated.
   a. For aluminum, the specific heat, $C_{al}$ (J/kg.°C) can be determined using Equation 3.1 [9]. The thermal conductivity, $\lambda_{al}$ (w/m.°C), can be determined using Equation 3.2 [9]. Where $T_{al}$ is the aluminum temperature (0°C < $T_{al}$ < 500°C).

   \[
   C_{al} = 0.41 T_{al} + 903 \quad (3.1)
   \]

   \[
   \lambda_{al} = \begin{cases} 
   0.07 T_{al} + 190 & \text{for 3xxx and 6xxx alloys} \\
   0.10 T_{al} + 140 & \text{for 5xxx and 7xxx alloys} 
   \end{cases} \quad (3.2)
   \]

   b. For steel, the specific heat, $C_{st}$ (J/kg.°C), can be determined using Equation 3.3 [10]. The thermal conductivity, $\lambda_{st}$ (w/m.°C), can be determined using Equation 3.4 [10], where $T_s$ is the temperature of the steel.

   \[
   C_{st} = \begin{cases} 
   425 + 0.773 T_{st} - 1.69 \times 10^{-3} T_{st}^2 + 2.22 \times 10^{-6} T_{st}^3 & \text{20°C < } T_s < 600°C \\
   666 + \frac{13002}{738-T_{st}} & \text{600°C < } T_s < 735°C \\
   545 + \frac{17820}{T_{st}-731} & \text{735°C < } T_s < 900°C \\
   650°C & \text{900°C < } T_s < 1200°C 
   \end{cases} \quad (3.3)
   \]
c. For aluminum, steel, and glass, the density ($\rho$) 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 panels for an assumed fire temperature. The temperatures of the different elements can be evaluated using the governing convection and radiation heat Equation 3.5 [11]. The solution starts by assuming that $T_s$ and $T_f$ are equal to the ambient temperature, then $\Delta t$ is increased incrementally. For each increment, $T_f$ is first estimated from the standard fire curve and used to evaluate $\Delta T_s$.

$$\Delta T_s = K_{sh} \left( \frac{F/V}{\rho \cdot C} \right) [h_c(T_f - T_s) + \sigma E (T_f^4 - T_s^4)] \Delta t$$ (3.5)

Whereas $\Delta T_s$ represents the temperature rise in the considered element, $F/V$ 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 is taken equal to 20 w/m$^2$K [12], $K_{sh}$ is a correction factor for shadow effects and can be taken equal to 1 [11], $\Delta t$ represents the time increment in seconds, and $T_s$ and $T_f$ are the element and fire temperatures, respectively.

3. Stress-related material properties at a specific temperature are defined as shown below.

a. The initial modulus of elasticity of aluminum and steel typically degrades with elevated temperatures. Tables 3.1 and 3.2 present the modulus of elasticity values at different temperatures as recommended by the European standard [9,10].

b. The stress-strain curve of aluminum and steel at elevated temperatures can be defined using the Ramberg-Osgood formulation curves, as shown Figures 3.3 [13] and 3.4 [14], respectively.
c. The ordinary glass was modeled as an elastic material with young’s modulus of 70 GPa. Glass is assumed to collapse when its temperature reaches 200 °C [15].

![Figure 3.3: Aluminum stress strain curve at elevated temperatures](image1)

![Figure 3.4: Steel stress strain curve at elevated temperatures](image2)

4. The material stress-strain curves are used to predict the moment-curvature diagrams for the mullions and transforms. SAP 2000 [16] section-design tool can be utilized to complete this step.
5. Each of the mullions and transoms is modeled using elastic frame elements, having modulus of elasticity and thermal properties corresponding to the assumed fire temperature. The properties of each section can be estimated using the section designer tool. The elastic frame elements are connected using SAP 2000 [16] plastic hinges, which model the moment-curvature diagrams. The plastic hinge length can be considered equal to the element length.

6. The glass panels are modeled using shell elements with an equivalent thickness. The mesh size for different cases was examined and an optimum mesh was found to range from 150 to 200 mm.

7. The glass panels are connected to the mullions/transoms by non-linear gap links to model the gaskets and the provided clearance. Figure 3.5 shows a schematic of the used model.
   a. A gap link is used to represent the provided clearance between the glass and mullions/transoms. A clearance of 6 mm can be assumed [17].
   b. Elastoplastic elements are used to simulate the gaskets. The elastic stiffness and yield force are assumed equal to 0.5 kN/mm and 0.24 kN [17]. The gaskets are assumed to melt at 200 °C [18].

![Figure 3.5: Modelling of gaskets and provided clearance](image_url)
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3.2 Model Validation

This section presents four validation cases that test different aspects of the proposed technique.

3.2.1 Validation Case 1

Maljaars et al. [19] 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 3.6. 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.

The frame was modeled using the technique described in section 3.1, and its behaviour was predicted at ambient temperature and elevated temperatures. Figure 3.7 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. [19]. Regarding the behaviour at elevated temperatures, the experimental research showed that the frame failure occurs at a temperature of 300 °C. In the proposed technique, a temperature of 300 °C was applied and then the load causing failure was identified. Failure occurred at a load of 11.86 kN due to reaching the ultimate curvature. The small error in predicting the failure load can be due to the assumptions of rigid connections and constant temperature for the entire frame. The variation of the frame deformation with fire temperature in the second test is shown in Figure 3.8. The curve shows that the frame stiffness was reduced significantly at a fire temperature of about 170 °C.
Figure 3.6: Schematic layout of the frame

Figure 3.7: Load-deflection curve of aluminum frame at ambient temperature
3.2.2 Validation Case 2

An aluminum frame was analyzed using the finite element program ELSAFIR98A to determine its resistance when exposed to ISO fire curve [20]. The frame is shown in Figure 3.9 and is made of standard European sections. The frame deformation was found to be 4.6 mm at ambient temperature. The frame collapsed after 6 minutes of exposure to ISO standard fire.

The frame was modeled using the technique described in section 3.1, and its behaviour was predicted. The temperature of the frame was first estimated using Equation 3.5. Figure 3.10 shows the variation of the temperature of the frame with time, as well as the ISO fire temperature. Nonlinear force-static analysis was performed at a fire temperature of 250 °C, which corresponds to 6 minutes of ISO standard fire. The load was increased until the frame became unstable, which happened at a load of 14.73 kN/m as compared to the 15.00 kN/m experimental load. The variation of the frame deformation with fire temperature is shown in Figure 3.11. The curve shows that the frame stiffness was reduced significantly at a fire temperature of about 250 °C.
Figure 3.9: Modelled frame exposed to ISO fire curve

Figure 3.10: Temperature of ISO fire curve and aluminum frame
3.2.3 Validation Case 3

A glass façade made of an aluminum transom-mullion frame and insulated glazing systems, shown in Figure 3.12, was experimentally tested to examine its cyclic behaviour at ambient temperature [21]. The façade was fixed at the bottom end. Actuator beams were used to apply the lateral loads.

The components of the examined façade (aluminum frame with 150 mm by 50 mm HSS sections, glass panes with 32 mm thickness, glass clearance of 5 mm, and rubber gaskets) were modeled using the technique proposed in section 3.1. The increasing lateral load was applied, and the obtained lateral load-deformation behaviour was compared with the experimental envelope for the cyclic lateral load-deformation behaviour. The comparison is shown in Figure 3.13. The proposed modeling technique was able to predict the lateral deformation with good accuracy.
Figure 3.12: Facade dimensions and geometry

Figure 3.13: Maximum load displacement comparison
3.2.4 Validation Case 4

The validation cases presented in the previous sections have their limitations, as cases 1 and 2 only addressed the frame behaviour during fire exposure and case 3 addressed the façade behaviour at ambient temperature. Del la rose et al. [22] modeled a typical Hilti curtain wall, Figure 3.14, using ANSYS. The same curtain wall was modeled using ABAQUS and the proposed simplified technique. The modeled wall is 4.2 m in width and is used for 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. They were used to model the stainless-steel mullions and transoms (HSS 100×60×4.1), glass panels (13 mm thick), and the concrete slabs (150 mm thick). A schematic showing the curtain wall model is given in Figure 3.15. A fire source was located 1 m from the glass panes. The facade was assumed to be laterally supported by the floor slabs. 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.

**Figure 3.14: Curtain wall**
Figure 3.15: HILTI curtain wall model in ABAQUS

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 rose et al. [22]), 9.3 mm (ABAQUS), and 9.5 mm (simplified technique by SAP 2000). The differences in the predictions of the three analysis methods are minor (maximum difference 3.2 %). Figure 3.16 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 by SAP 2000). 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 3.17 shows the comparison between the mullion temperature as predicted by ANSYS by Del la rose et al. [22], ABAQUS, and Equation 5. The predictions of the three methods are closely matched.
Figure 3.16: Deformed shape due to wind pressure at ambient temperature

Figure 3.17: Thermal analysis comparison
Finally, 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 at different fire durations. Figure 3.18 shows the variation of the lateral deformation of the façade with time as predicted by ABAQUS and the proposed technique. Figure 3.19 show the mullion deformation from the SAP2000 model approach at 100 °C. The proposed technique provided good predictions for the lateral deformations during fire exposure. The middle 1.85 m of the mullion experienced inelastic deformations. Increasing the wind pressure from 57.5 kPa to 115 kPa, increased 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, from 81 to 86 mm (ABAQUS) and 63 mm to 80 mm (proposed technique) at 200°C, and from 144 to 153 mm (ABAQUS) and 142 to 152 mm (proposed technique) at 400°C.

Figure 3.20 compares the lateral deformation considering wind loads of 57.5 and 115 kPa. At low temperatures, the deformations for the 57.5 kPa were double of that for the 115 kPa case indicating a linear elastic behavior. These deformations were relatively (less than 300 mm). The fire temperature increased these deformations significantly. At a temperature of 300 °C, the lateral deformations were almost equal for the two cases as the thermal deformations had higher contribution than the wind deformation. The frame lost stability at a temperature of 982 °C.
Figure 3.18: Coupled mechanical thermal analysis

Figure 3.19: Lateral deformation using the proposed technique at 100 °C
3.2.5 Validation Case 5

A vertical glass-façade system made of HILTI curtain wall panels with dimensions of 4.2 m wide and 5.4 m high, is assumed to be covering a 16.8 m wide three-storey building. The ABAQUS model, shown in Figure 3.21, includes 12 stainless-steel mullions, 16 stainless-steel transoms, 9 glass panes, and 6 half glass panes. The ABAQUS model utilized 8-node bricks with three translational degrees of freedom per node, following the assumptions of De la Rosa [22]. Tie constraints were used to attach the glass panels to the framing systems. The facade is assumed to be laterally supported by the floor slabs. The same vertical glass façade system was further modelled including wind pressure/suction at ambient temperature using the proposed technique. The wind load was assumed to be equal to 2.4 kPa [23].

For the vertical panel façade system, the lateral deformations measured at mid-height of the first, second, and third floors are 0.123 mm (SAP model) and 0.126 mm (ABAQUS Model). Figures 3.22 and 3.23 show the lateral deformations obtained from SAP and ABAQUS models, respectively. All elements of the examined façades remained in the elastic range for the ambient temperature case. Under wind loading, the gap links...
between the glass and frame elements opened indicating that glass panels will not be affected by the façade deformations.

Figure 3.21: ABAQUS model
Figure 3.22: Lateral deformation of mullion at first floor (SAP model)

Figure 3.23: Lateral deformation of mullion at first floor (ABAQUS)
3.3 Conclusion

This chapter proposes a simplified technique that can be utilized to estimate the lateral deformations of glass façades during fire exposure. The proposed technique was validated using experimental and numerical research by others and found to provide accurate predictions. The proposed technique starts by estimating the frame and glass temperatures using the governing convection and radiation equations. The temperature is then used to evaluate the material properties. The frame is modeled using the plastic hinge approach of SAP2000. The deformations of the gaskets are accounted for using nonlinear spring elements. At a temperature of 200 °C, the glass and gaskets lose their function, while the façade frame keeps resisting the loads. The proposed technique is limited to the presented glass and façade materials, and the examined loads and systems.

3.4 References


Chapter 4

4 Behaviour of Glass Façade Systems during Fire Exposure

Undoubtedly, glass façades are widely used around the world. Daniel et al. [1] emphasized on the risk of fire spread through glass façades. Quin et al. [2] examined the effect of localized fire on single glazing façades, with different orientations, in terms of crack initiation and crack pattern. Gandhi et al. [3] conducted full scale experimental test on a 3-storey glass façade system and highlighted the vulnerability of combustible façade panels in case of fire. Zhaopeng et al. [4] presented an experimental study to understand the effect of cavity width on the fire spread and glass breakage of a double skin façade in a two-storey building.

Façade systems can utilize vertical, inclined, or oversized panels. The vertical glass panel system is shown in Figure 4.1. It consists of a series of pre-assembled units, which cover the height of one story of the building, as shown in Figure 4.2. This system is assembled and glazed in the factory, and then shipped to the construction site for installation [5]. The vertical panels can be either: (1) single skin, which includes mullions, transoms, glass panes and gaskets, or (2) double skin, which includes the previous components in addition to a cavity to save energy in hot and cold climates [5]. Inclined glass panel system is shown in Figure 4.3. The inclination can be either backward or forward. Backward inclination can diminish the ability of fire flames to reach the glass façade in upper floors [1]. This system is mainly composed of inclined mullions, transoms, and glass panes. The supporting frames for this system are typically supported by anchor brackets, which are connected to floor system, as shown in Figure 4.4. The oversized panel system is shown in Figures 4.5 and 4.6. In this system, a glass panel covers more than one floor, which makes it an efficient system with respect to installation. This system usually includes mullions, transoms, and high strength glass panes [6].

The previous research did not provide details about the performance of façade systems during fire exposure. This chapter addresses this shortcoming by examining the
mechanical behaviour of vertical, inclined, and oversized façade systems during fire exposure.

Figure 4.1: Vertical glass facade system

Figure 4.2: Vertical panel system installation
Figure 4.3: Backward inclined glass facade system

Figure 4.4: Inclined panel system assembly
Figure 4.5: Oversized glass facade system

Figure 4.6: Oversized glass panel in the factory
4.1 Design of assumed Façade Systems

In this study, 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 4.7, 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 panels. Following the assumptions of De la Rosa [7], the standard panels consist of stainless-steel mullions, glass panels, and aluminum transoms. The system, shown in Figure 4.7, includes 12 mullions, 16 transoms, 9 glass panes, and 6 half glass panes. Figure 4.8 shows the cross section for the typical mullions and transoms.

The curtain wall is 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 [9]. As curtain wall installation takes place after floors have been constructed, they must tolerate movements resulting from short- and long-term column shortening and floor deflections. These deformations are accounted for in the bracket. It was suggested to estimate movements during and after construction as 0.6 and 2.2 mm for column shortening and 3.2 and 25 mm for floor deflections [10]. These deformations were imposed on the façade in the analysis stage assuming a stepped deformation shape, Figure 4.9.

The load combination given by the Eurocode [11], (1.0 D + Fire Effect + 0.33 Wind load), was utilized to examine the 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 fire within the building or external fire.
Figure 4.7: Facade system dimensions

Figure 4.8: Mullion and transom cross sections
4.2 Modeling

The assumed façades are modeled using the simplified technique, explained in the previous chapter. For the simplified technique, the utilized moment curvature diagrams are shown in Figure 4.10. The elastic modulus values for glass, aluminum and steel are given in Table 4-1. Gap clearance of 6 mm was used between glass and façade framing.
Figure 4.10: Moment curvature diagrams
Table 4-1: Elastic moduli of the glass facade components in kPa [12,13,14]

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4.3 Ambient Temperature Results

For the vertical panel façade system, the 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 loading, the gap links between the glass and frame elements opened indicating that glass panels will not be affected by the façade deformations.

4.4 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. Three fire durations of 2.5, 10.0, and 30.0 minutes were evaluated. Figure 4.11 shows the change in the temperature of the mullions and glass panels with time. As mentioned in the previous chapter, the glass panels are assumed to break at a temperature of 200 °C. This temperature is reached after eight minutes of exposure to ASTM E119 standard fire.
A typical SAP model is shown in Figure 4.12. Figures 4.13 and 4.14 show the maximum lateral deformations for different fire durations considering wind pressure and wind suction, respectively. The values of deformations for both wind pressure and wind suction were similar, indicating that the performance is controlled by the change in material properties due to the fire temperature. 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 4.15. It is obvious that the mullions experienced inelastic deformations when exposed to elevated temperatures.
Figure 4.12: SAP Model showing the mullion lateral deformation at 100 °C

= ASTM E119 (2.5 min) ≡ ASTM E119 (10 min) ≡ ASTM E119 (30 min)

(a) Fire exposure at first floor
(b) Fire exposure at second floor

(c) Fire exposure at 1st and 3rd floors.

Figure 4.13: Mullion deformation due to wind pressure (inward deformation is positive)
a) Fire exposure at first floor

(b) Fire exposure at second floor
(c) Fire exposure at 1st and 3rd floors

**Figure 4.14:** Mullion deformation due to wind suction (inward deformation is positive)

**Figure 4.15:** Temperature-strain variation of the first-floor mullions for the case of first floor fire exposure
4.5 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 4.16 shows the utilized SAP model.

Figure 4.17 shows the maximum lateral deformations for different fire durations considering wind pressure and wind suction. Figure 4.18 compares the lateral deformations of the vertical façade and inclined façade systems. 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 the first floor being exposed to fire. Similar to the vertical façade system, the wind suction and wind pressure results were similar. Also, the mullions of the first-floor experienced inelastic deformations. The variation of the mullion strains with the temperature for the case of fire exposure at the first floor is shown in Figure 4.19.

![Figure 4.16: Mullion deformation at 400 °C from SAP model](image-url)
Figure 4.17: Mullion deformations during fire exposure (inward deformation is positive)
Figure 4.18: Comparison between mullion maximum deformation for the vertical and inclined systems

Figure 4.19: Temperature strain ratio of the mullions on the first floor for the case of first floor fire exposure.
4.6 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 4.20 shows the used SAP model. 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 Figures 4.21, 4.22, and 4.23.

Figure 4.20: SAP Model for oversized panels showing mullion deformation at 100 °C considering first floor fire exposure
Figure 4.21: Mullion deformation due to wind pressure (inward deformation is positive)
Figure 4.22: Mullion deformation due to wind suction (inward deformation is positive)
Three main glass façade systems were examined at elevated temperatures while being exposed to wind pressure/suction. The floors exposed to the fire experienced the highest lateral deformations. The vertical façade system acted as a continues system, where the lateral deformation of the floors, which were unexposed to fire, increased. This behaviour did not occur in the inclined façade system, in which each floor acted independent of the other floors. Out of three examined systems, the inclined system experienced the lowest deformations, and the oversized system experienced the highest deformations.

Figure 4.23: Comparison between mullion deformations for oversized panels

4.7 Conclusions
4.8 References


Chapter 5

5 Summary and conclusions

The thesis examines the structural performance of glass façades during exposure to internal or external fire. It starts by providing a literature review about the topic, then proposes a simplified technique to analyze glass façades during fire exposure and applies this technique to evaluate the performance of three glass façade systems. The following sections summarized the main conclusions for each chapter of the thesis. This chapter ends by recommendations for future work.

5.1 Literature Review

A literature review, covering the historical background on the glass façades, and their classifications is presented. The current design criteria for glass façades are also summarized. These criteria account for structural integrity, allowance for relative displacement between the façade system and the building, weather tightness, moisture control, thermal insulation, and sound transmission. It was clear that existing studies have focused on experimental techniques, and that methods to accurately model a glass façade are missing in the literature.

5.2 Simplified Modelling of Single Skin Façade Exposed to Fire

A simplified technique, which can be utilized to estimate the structural performance of glass façades during fire exposure, is proposed. The proposed technique starts by estimating the temperatures of the façade elements using the governing convection and radiation equations. The temperature is then used to evaluate the material properties. The frame is then modeled using the plastic hinge approach of SAP2000. At a temperature of 200 ºC, the glass and gaskets lose their function, while the façade frame keeps resisting the loads. The proposed technique was validated using experimental and numerical research by others and found to provide accurate predictions.
5.3 Behaviour of Glass Façade Systems During Fire Exposure

The structural performance of three glass façade systems during exposure to fire was examined in this chapter. The floors, which were exposed to fire, experienced the highest lateral deformations due to the applied wind loads. The vertical façade system acted as a continuous system. In this system, the lateral deformations of the floors, which were not exposed to fire, increased as well. The behaviour of the inclined façade system was different, as each floor acted independently from the other floors. This system yielded the lowest deformations. On the opposite, the oversized panel system experienced the highest deformations.

5.4 Thesis Limitations

The proposed technique is limited to:

1. The presented single skin glass panes.
2. The conventional façade materials including steel, aluminum, and glass.
3. The examined lateral loads: i.e., static wind loads.

Furthermore, the Proposed technique considered uniform temperature across the entire element and does not consider heat transfer between floors.

5.5 Recommendations for Future Work

This thesis has revealed that additional analytical studies are needed including:

1. Extending the numerical work to cover the seismic behaviour of fire damaged glass facade systems.
2. Understanding the effect of the building deformations on the glass façade behaviour and evaluating if the current allowance for deformations is adequate.
3. Applying the proposed technique on other innovative glass systems.
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