Fire Safety Façade Design and Modelling

The Case Study of the Libeskind Tower

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Abstract
Nowadays, the construction industry is characterised by high-rise, multifunctional, and complex buildings with innovative façade systems. Unlike a simple prescriptive approach in accordance with standards and codes, a performance-based design allows us to: define safety levels and goals, evaluate heat transfer to the structure and the structure's response based on fire behaviour, model different fire scenarios using Computational Fluid Dynamics (CFD) software, and personalise the design of any specific project in order to reach the required level of safety. Through a significant case study, the Libeskind Tower in Milan's City Life district, this paper describes the Fire Safety Engineering (FSE) performance-based design approach. The analysis demonstrates consistent results between the CFD fire modelling output and the laboratory test on a full-scale façade mock-up. Moreover, a Finite Element Analysis (FEA) performed on a section of the façade mullion, identifies and highlights the façade system's critical issues in different fire scenarios.

Keywords
Computational fluid dynamics (CFD), finite element analysis (FEA), façade modelling, Fire Safety Engineering (FSE), building façades

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1 INTRODUCTION

Nowadays, the construction industry is characterised by high-rise, multifunctional, and complex buildings with innovative façade systems (Fig. 1). The need to comply with European energy efficiency regulations has led to research and design advanced building envelopes (Rigone, & Giussani, 2019; Romano, Aelenei L., Aelenei D., & Mazzucchelli, 2018), for which innovative materials and systems are continuously developed and introduced (Aelenei L., Aelenei D., Brzezicki, Mazzucchelli, Rico Martinez, & Romano, 2018; Mazzucchelli, Alston, Brzezicki, & Doniacovo, 2018), calling for an improvement of regulations and testing standards (Anderson, Boström, McNamee, & Milovanović, 2017).

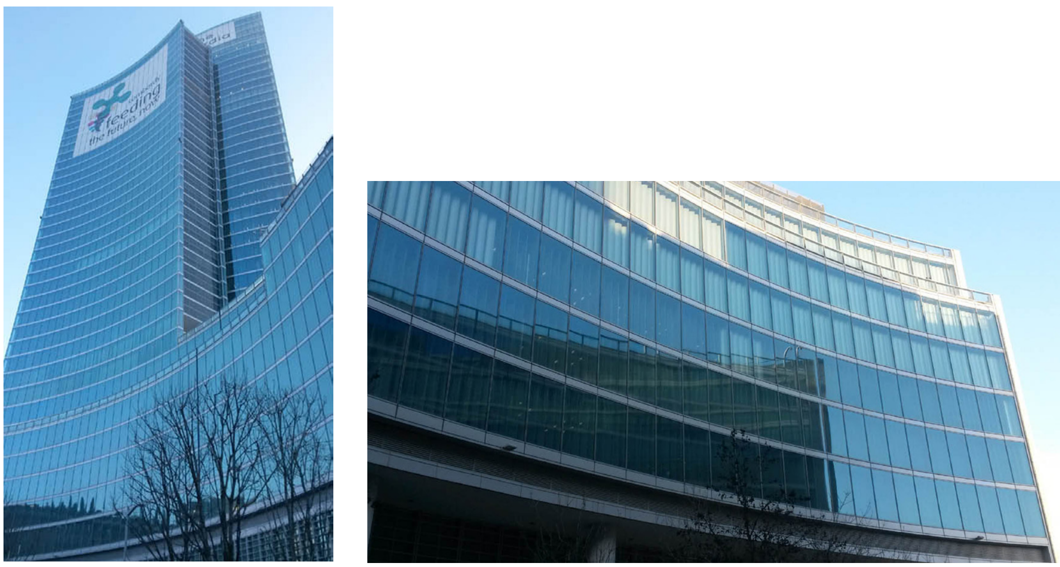

FIG. 1 Example of high-rise building with advanced façades: Palazzo Lombardia, Milan, Italy

However, the architectural quality and thermal performance of a façade system must be in accordance and consistent to guarantee other requirements, such as fire safety. Many recent fire events demonstrate that the need to improve the technical knowledge and practical procedures in high-rise buildings façade systems design, especially those concerning fire vulnerability, is still very strong (Mazzucchelli, Lucchini, & Stefanazzi, 2019). In this regard, unlike a simple prescriptive approach in accordance with standards and codes, a performance-based design allows us to define safety levels and goals, evaluate heat transfer to the structure and the structure's response based on fire behaviour, model different fire scenarios using Computational Fluid Dynamics (CFD) software, and personalise the design of any specific project in order to reach the required level of safety. Therefore, an appropriate selection and use of materials, a Fire Safety Engineering (FSE) analysis, and laboratory tests (Fig. 2) become fundamental (Bjegović, Pečur, Milovanović, Rukavina, & Alagušić, 2016).

The paper, after introducing the general issue of fire safety pertaining to building façades, focuses on a case study where a performance-based FSE design approach has been followed. In particular, the CFD modelling process and the Finite Element Analysis (FEA) analysis, as tools to evaluate different fire scenarios and the façade system's critical issues in case of fire, are described in detail. The analyses carried out demonstrate results consistent with those of a laboratory test on a full scale façade mock-up, showing that such an approach can be conveniently used in assessing the fire performance of façade systems, especially in the case of new buildings with complex shapes.

FIG. 2 Images of laboratory tests to evaluate the fire behaviour of an opaque façade solution: ignition phase (left) and steady phase after 10 minutes (right)

2 FIRE SAFETY CONSIDERATIONS

In the construction field, fire events in façades are the less likely to occur. Nevertheless, in Europe many national guidelines regarding opaque façades (Rukavina, Carevic, & Pečur, 2017; Mazzucchelli et al., 2019) are available, while new transparent curtain wall systems undoubtedly call for an improvement in the standards.

In general, the typical scenarios for the fire spread over façades are of three types (Fig. 3):

- spread of an external fire onto a combustible façade by radiation from a neighbouring, separate building;
- spread of an external fire due to radiative effect or due to direct fire effect from a source of fire located next to the façade (for example fire developed on a balcony or fire from a car parked near the façade);
- internal fire, started in a space inside the building, spreading through openings in the façade (windows, doors, etc.) onto upper or lower floors.

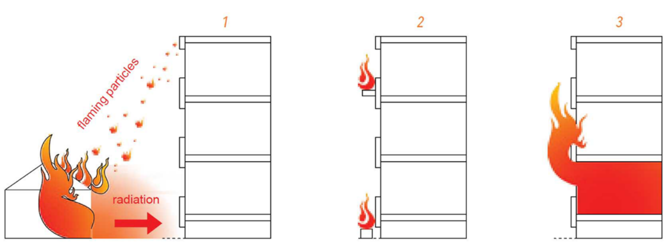

FIG. 3 Typical scenarios of fire spread across façades (Rukavina et al., 2017)

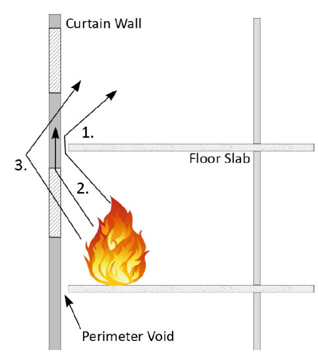

FIG. 4 Curtain wall façades' main fire spread mechanisms (Mazziotti & Cancelliere, 2013)

Considering a curtain wall system, where normally there are no combustible materials on the external surface of the façade, the typical fire spread scenarios are summarised in Fig. 4, where no. 1 represents the fire spread through the space between the slabs and the internal façade surface, no. 2 the fire spread within the façades cavities or ventilation chambers, and no. 3 the fire spread through façade windows and openings.

In any case, many aspects should be considered to guarantee the fire safety in building façades, such as the connection requirements between fire compartments and façade elements, the fire behaviour of materials, the absence of obstacles to the fire spread on the façade and/or to neighbouring façades, the possibility of detachment of burnt façade portions and involvement of still intact portions of the façade, the risk of glass units and façade components to fall, etc. Fire vulnerability can be reduced if the fire load within building compartments is maintained at moderate levels. Moreover, fire protection for buildings can be achieved not only by passive methods, but also by active systems (e.g. sprinklers) that can minimise the risk of fire propagations. Therefore, fire safety is related to many variables and must be assessed, investigated, and solved, case by case, through a specific FSE analysis, taking into account many parameters (e.g. spatial distribution of the combustible materials, development and fire spread over the façades, Heat Release Rate - HRR, temperature distribution, smoke composition, air movement and diffusion or ventilation). Furthermore, fire safety aspects are not limited to the control of fire spread, but also concern the structural safety of the building components.

In the past, the fire resistance performance of components could be determined only by laboratory tests. In recent years however, the use of numerical methods for the fire resistance calculation of various structural components is growing and spreading, since it is far less costly and time consuming, thus significantly contributing to the modern development of fire safety science and engineering. Nowadays, appropriate numerical simulations allow a performance-based approach to be followed in a much faster and more convenient way, in which the modelling is combined with full scale fire tests carried out to evaluate the behaviour of different solutions, materials, and effects due to different geometries and configurations of façade openings (Kotthoff, Hauswaldt, Riese, & Riemesch-Speer, 2016; Northe, Riese, & Zehfuß, 2016; Bjegović et al., 2016).

Thus, numerical modelling is commonly used for a major parameter analysis, especially in the case of buildings characterised by complex façades, such as those of the Libeskind Tower. Moreover, for a large-scale test method, modelling is required for simulations as undergoing a laboratory test can be complex due to factors that can influence the results (e.g. wind direction and speed).

3 CASE STUDY: THE LIBESKIND TOWER

The Libeskind Tower is located in the City Life district in Milan (Italy). The main highlighted issues of the office tower are the concave bending of its elevations and the top crown (Fig. 5). The building core is divided into two separate blocks, symmetrical as far as the structure is concerned, but asymmetrical with regards to the location of the escape routes (Fig. 6).


FIG. 5 Render of the Citylife district in Milan (Italy). The Libeskind tower is the one on the left

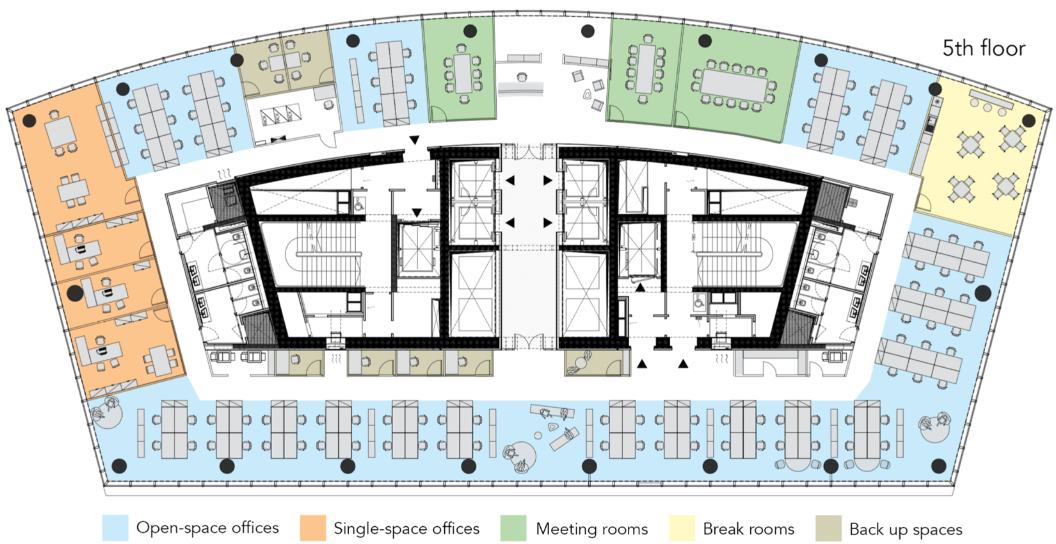

FIG. 6 Tower layout of the 5th floor

From the first to the twenty-eighth floor, indoor spaces are occupied by offices (Fig. 6), while at the twenty-seventh floor a double-height office and conference rooms are located. The crown's façade is characterised by a glass structure, whose geometrical lines complete the building, closing the spherical tendency, which is crucial to the tower concept. It is possible to simplify and to model the façade's design geometry into a toroid and cylinders, relatively simple shapes defined with a limited number of panel families. The façade units have a typical size of about 1500mm x 4100mm (Fig. 7), although it is not possible to identify a standard module because of the tower's geometry. Despite having the same performance requirements, the different types of façade units differ for geometric characteristics, type of components, and installation method (Fig. 7 and Fig. 8).

FIG. 7 Construction phases of the Libeskind tower façade

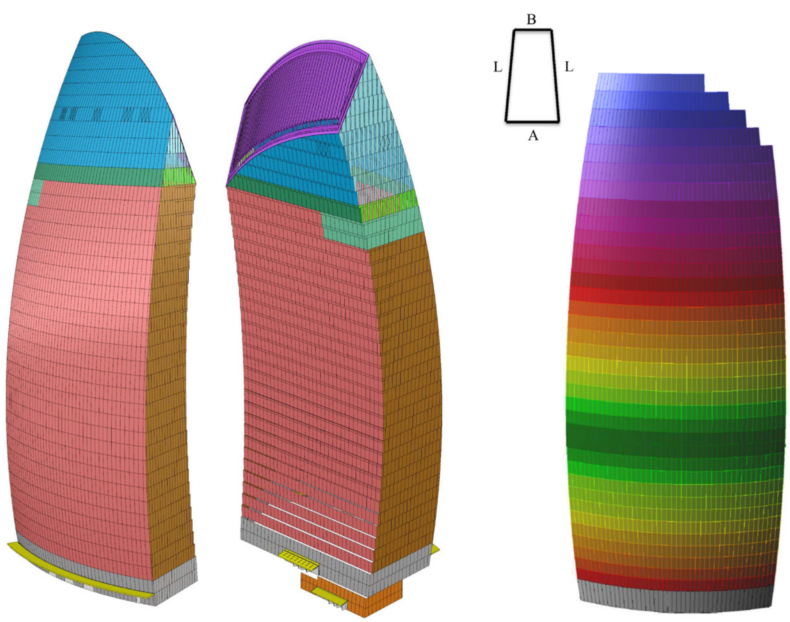

FIG. 8 Façade type and façade module shape. Despite having the same performance requirements, the different types of façade units differ for geometric characteristics, type of components, and installation method

The geometric rules of the module shape generation (Fig. 9 and Fig. 10) are the following:

- north façade: the shape is generated by a portion of spindle with horizontal oriented rotation axis. The center of the toroid is located at the 11th floor of the tower, defining a geometric rule that reduces the number of different panels. The horizontal stack joint between the flat units allows the vertical rotation of the panels;
- south façade: the shape is obtained from a portion of cylinder on the horizontal axis, discretised by vertical, inclined, and horizontal flat panels. The centre of the toroid is located at the 14th floor of the tower. To reduce the solar radiation of the façade to the public square, the façade module was modified, including the projected windowsill;
- east and west façades: the shape is given by two radial planes that cut the volume of the entire building. The panels are flat, rectangular-shaped, and the “jolly” panels are cut at the edges of the tower.

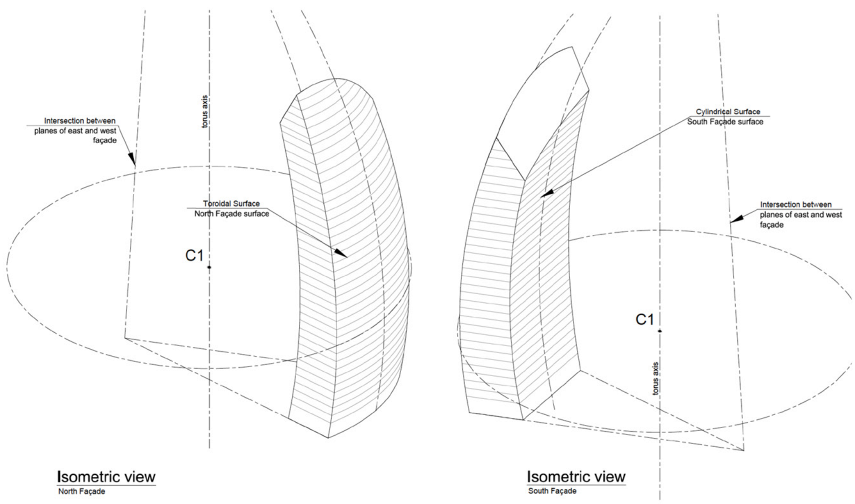

FIG. 9 Geometrical rule of module shape generation (De la Fuente, 2019)

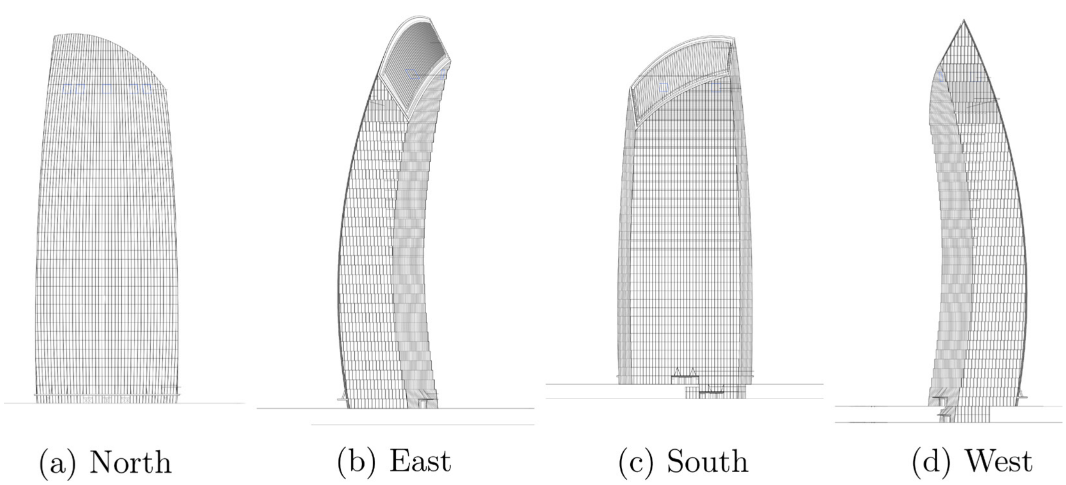

FIG. 10 Elevations of the tower (De la Fuente, 2019)

FIG. 11 Façade - south-east corner, low rise

From a functional point of view, the crown hides the cooling towers, the service lifts, and the façade's Building Maintenance Unit (BMU) system. The triple glazing façade fixed units (Fig. 11) comply with the thermal (overall U-Value U_{cw} = 1.1 ÷ 1.3 W/m²K), air permeability (class A4 - EN 12152), and acoustic insulation ($D_{2m,nT,w}$ = 42 dB) performance values required by Italian national standards, as well as the protection from solar radiation in compliance with the current building regulations. Most of the glazing units of the single skin façade are Triple Glazed Units (TGU), with low-E and solar coating, air cavity filled with Argon gas and a "warm edge" spacer type. The connection to the slab is fire resistant and the details include insulating material and specific calcium silicate fire-board installed between the façade and the concrete decking (Fig. 12).

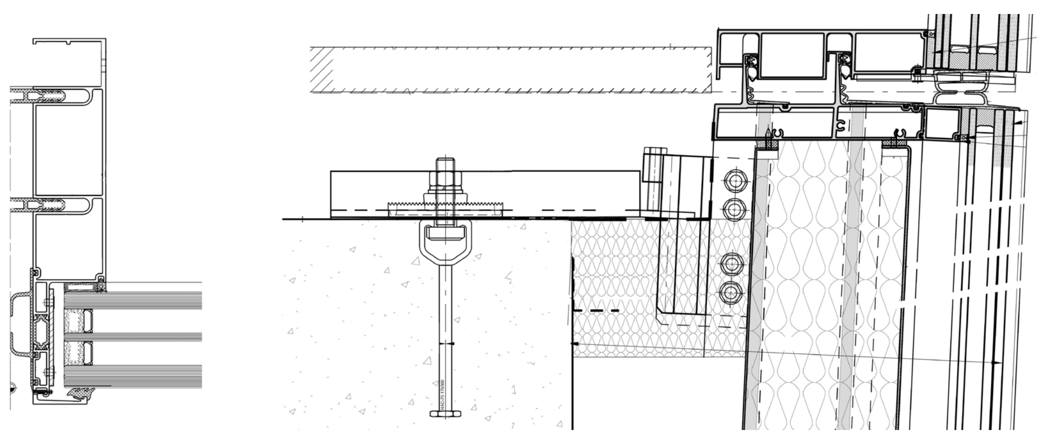

FIG. 12 Typical horizontal section of façade unit – half mullion aluminium frame (on the left) and typical vertical section of stack joint between units (on the right)

The connection joint is also very high performance for acoustic insulation. An internal natural light control system is achieved with automatic blackout roller blinds powered by a step-by-step electric driver controlled by a Building Management System (BMS). The potential overheating of the glass interlayer induced by the roller blind radiant effect is controlled by suitable slow natural ventilation through a perimetral air gap between the curtain walling framing and the roller blind.

3.1 METHODOLOGY AND MODELLING

The aim of the analysis here presented is the evaluation of the façade system's behaviour in case of fire, carried out through a CFD simulation (to assess the temperatures reached in a standard room and on the façade surface) and thermal and FEA modelling on a façade mullion (to assess critical issues in case of fire).

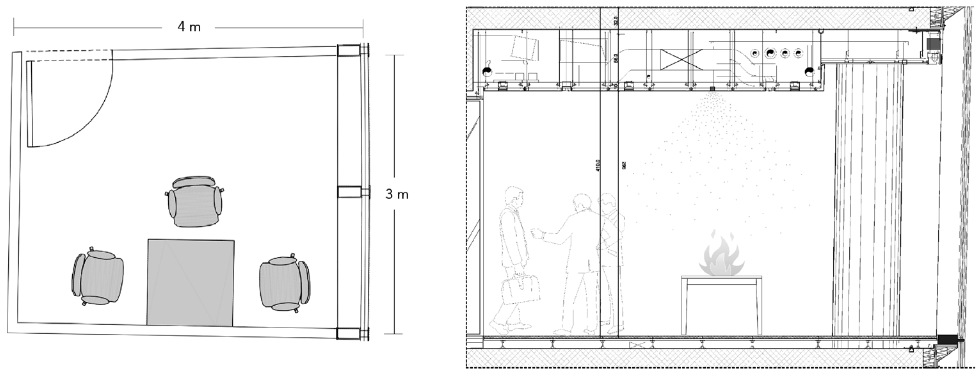

FIG. 13 Layout and vertical section of the analysed 7th floor north-facing room

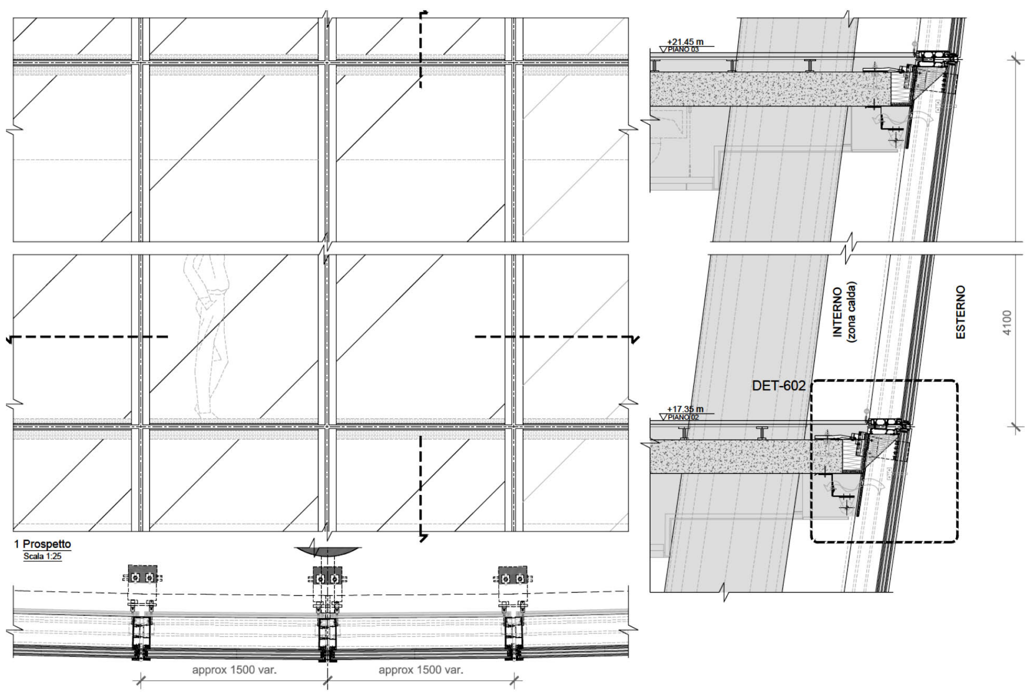

FIG. 14 North façade details: front view, vertical and horizontal sections

Different room configurations on different floors and with different orientations have been analysed (De la Fuente, 2019), but only the results for a north-facing office (Fig. 13) are presented here. This because the north façade is the most critical due to its architectural curvature (Fig. 14) and where, in case of failure, a façade module is more likely to fall onto pedestrian zones.

The fire simulations allow the identification of the thermal loads acting on a façade and evaluation of the components' performance after flame and smoke propagation. In further detail, fire dynamics take into account physical and chemical interactions, including fluid dynamics, thermodynamics, combustion, and radiation. While in simplified fire models (such as one zone model), the gas temperature of a compartment is considered uniform and it is represented by a temperature-time relationship, without considering smoke movement and fire spread, advanced ones are normally theoretical computer models that simulate the heat and mass transfer process associated with fire in a compartment. This allows gas temperatures to be predicted in a more detailed and precise way, and to provide a space- and time-dependent gas temperature distribution, smoke movement, and fire spread.

In accordance with PD 7974-1 (Application of fire safety principles to the design of buildings, 2003), the design of fire is characterised in terms of HRR, smoke production rate, and time to key events like flashover and fire size or duration. Some preliminary assessments were performed to evaluate the fire scenario (Rigone, Mazzucchelli, & De la Fuente, 2020), such as ventilation conditions and possible variations during the fire (FSC Engineering report Torre Tcc, 2018), automatic suppression systems, and performance of each of the safety measures (De la Fuente, 2019), location, type, quantity, and distribution of combustible materials, materials fire reaction, considering BS 7479 (Application of fire safety principles to the design of buildings - Code of Practice, 2001) as a technical reference.

In the case study, an automatic sprinkler system was considered. The system aims to stabilise the maximum flow rate of the flames, once activated; still, the possibility of a system failure has been studied. Therefore, the following fire scenarios have been analysed:

- SN1: Fire located close to a mullion with a standard response sprinkler. The purpose of the standard response sprinkler is to pre-wet materials around the fire, removing the fuel source. Containing the fire in its original location and suppressing its growth are the main goals;
- SN2: Fire located close to a mullion with a quick response sprinkler. It has similar fire-control benefits as a standard response sprinkler, but it sprinkles more water on walls to control fire growth and to maintain lower temperatures at ceiling level, reducing the likelihood of flashover and slowing the fire growth within the building;
- SN3: Fire located close to a mullion with a sprinkler failing. This scenario aims to assess the behaviour of the room and to investigate the timing failure for the different components of the building façade.

For a typical office room, a fire with a medium growth rate parameter (0.012 kJ/s^3, as recommended in BS 7974 and in accordance with NFPA 92B) is considered (Table 1). The fire is located at 0.5 m distance from one of the mullions, allowing the maximum effect of the fire on the façade structure to be analysed. The interaction between water and air heated by the fire is not directly modelled, but it is assumed that the sprinkler activation interrupts the fire development and stabilises it, maintaining a horizontal growth curve (FSC Engineering report Torre Tcc, 2018). Hence, when the fire growth value becomes constant, it corresponds to the sprinkler system activation. To evaluate the activation time for the two different sprinkler systems, B-Risk software (provided by BRANZ and the University of Canterbury) has been used. The output of this pre-assessment phase is necessary for the definition of the fire curves and the HRR.

TABLE 1 Summary of the main HRR curves inputs

	SPRINKLER STANDARD RESPONSE (SN1)	SPRINKLER QUICK RESPONSE (SN2)	UNCONTROLLED FIRE (SN3)
Room temperature [°C]	20	20	20
Sprinkler activation temperature [°C]	68	68	-
Space height [m]	3.0	3.0	3.0
Fire detector spacing [m]	2.9	2.9	-
Fire growth rate [kW/s²]	0.012	0.012	0.012
Activation time [s]	175	140	300
Heat Release Rate, HRR [kW]	375	225	1,080
Heat Release Rate Per Unit Area, HRRPUA [kW/m²]	284	220	818

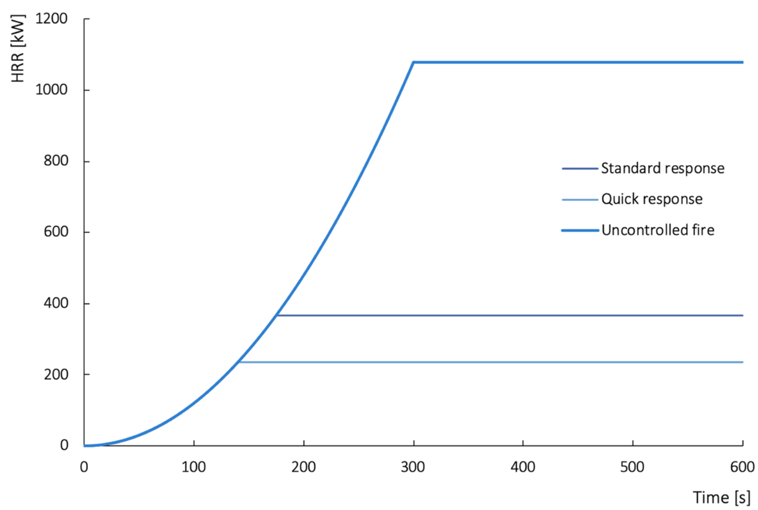

FIG. 15 Input HRR curves for the identified fire scenarios: sprinkler standard response (SN1), sprinkler quick response (SN2), uncontrolled fire (SN3) (De la Fuente, 2019)

The HRR curves for the proposed scenarios were calculated according to the equation of time-squared fire growth curve (specified in PD 7974-1). For SN3, following EN 1991-1-2 (Eurocode 1: Part 1-2: General actions – Actions on structures exposed to fire, 2002), which states that at 300 seconds (from ignition) the maximum rate of heat release is reached in an office occupancy, it is assumed that the curve stabilises at a fully developed fire and the decay phase would follow. The HRR curves for the identified fire scenarios and the main inputs are summarised in Table 1 and Fig. 15 (De la Fuente, 2019). Finally, the HRR curves have been used as a CFD software input, through the specific area (representing a localised fire) and the Heat Release Rate Per Unit Area (HRRPUA).

To analyse the specific façade system performance and to evaluate the temperatures of the framing mullions and glazing within the hypothesised fire scenarios, "Fire Dynamics Simulator" (provided by the National Institute of Standards and Technology - NIST) and "PyroSim 2018" (provided by Thunderhead Engineering), based on the Fire Dynamics Simulator 6.6.0 CFD calculation algorithm (McGrattan, Hostikka, McDermott, Floyd, Weinschenk, & Overholt, 2013), have been used. The modelling is characterised by the subdivision of the area of interest into a large number of much smaller domains, called mesh or cell grid. In this way, complex geometries and time-dependent flows can be easily managed. The output consists of parametric values of the flows of interest, such as speed, smoke concentration, and the level of radiation calculated in each of the cells of the grid.

The temperature monitoring was carried out through specific detectors positioned on the façade module. The number of sensors, called Adiabatic Surface Temperature (AST), total 95 on the mullions and 208 on the glass panes, giving a total of 303 (Fig. 16). The modelling and the experimental test have been carried out to verify if the temperatures reached within the room could rise up to critical values, compromising the stability of the aluminium structure and the glass panes. In this regard, the CFD modelling output has been used as input for the Transient Thermal Analysis (TTA) of the mullion section, carried out through Straus7 (provided by G+D Computing and HSH Srl) and ANSYS (provided by ANSYS, Inc.) software, taking into account convection, radiation, and conduction effects. Both pieces of software use a finite elements analysis (FEA) method and, for the case study, a non-linear analysis section has been considered. To further elaborate, for the TTA of the mullion, a simplified section (Fig. 17) was analysed, considering the exposure of the mullion for 40 minutes to the natural fire curves obtained by CFD simulations. The triple glazing was modelled in Window and THERM software (provided by Lawrence Berkeley National Laboratory) to analyse the temperatures on each glazing pane surface. Finally, the modelling results were compared with the laboratory test results to evaluate the real model reliability.

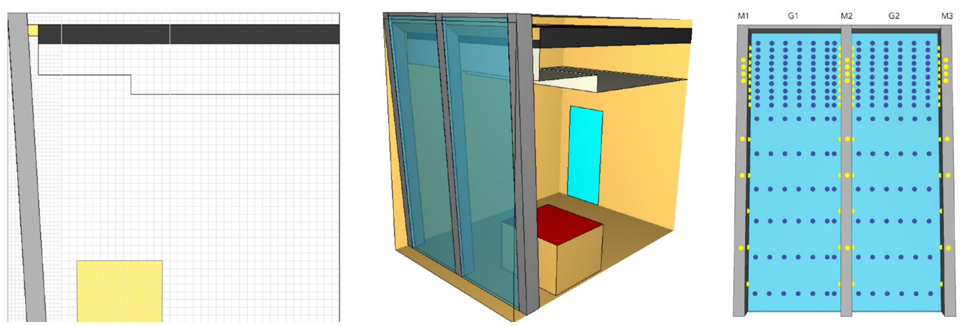

FIG. 16 Office model vertical section (left), 3D view (in the centre), and Adiabatic Surface Temperature (AST) sensors position (on the right, façade indoor view). M1: mullion no. 1, M2: mullion no. 2, M3: mullion no. 3, G1: glazing no. 1, G2: glazing. no. 2

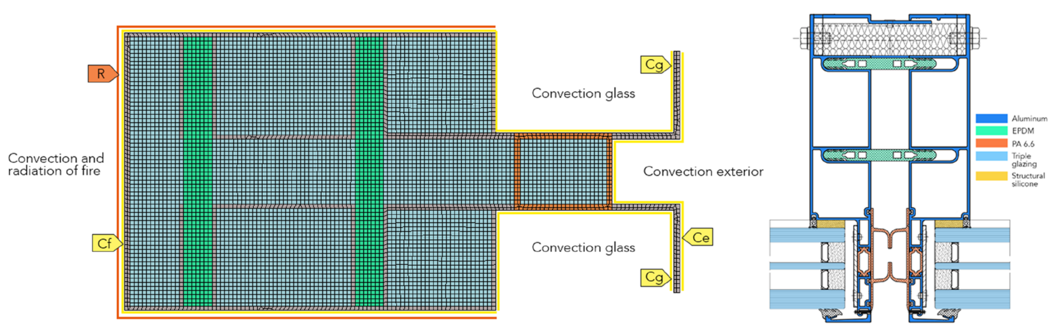

FIG. 17 ANSYS mullion model with mesh and boundary conditions (left) and mullion section with components (right)

3.2 NUMERICAL RESULTS

The overall behaviour of the office room proves the benefit of providing the sprinkler system. The temperature distribution on the façade (Fig. 18) reaches its highest values after 600 seconds of fire exposure. As can be seen according to what is detected by AST sensors, the façade is subject to temperatures between 50°C and 600°C, where the ranges differ according to the scenario. Considering SN1 and SN2, the mullions are locally subjected to temperatures equal to or higher than 250°C at the M1 and M2, while having temperatures between 120°C and 250°C in two thirds of the total area, and temperatures lower than 120°C for about one third of each mullion. For SN3, the mullion temperatures drastically increase, approximately doubling.

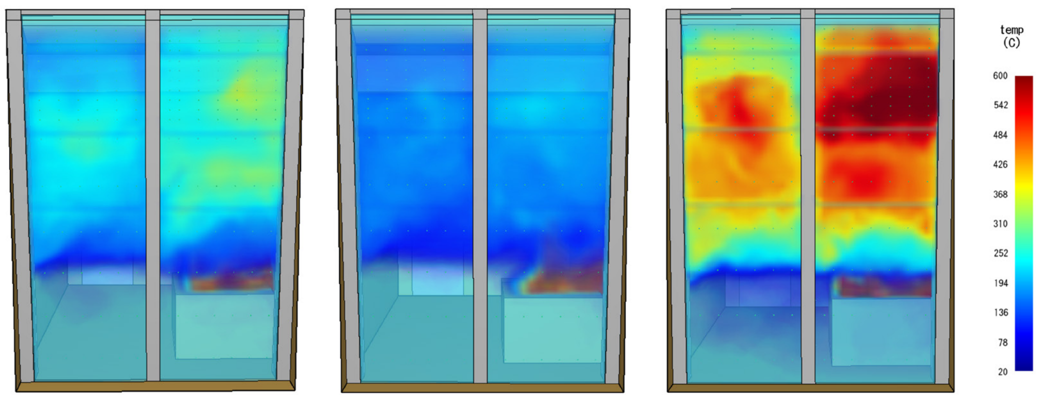

FIG. 18 Temperature distribution on façades for scenario SN1 (on the left), SN2 (in the centre), and SN3 (on the right)

For SN2, temperatures do not exceed 250°C, and for SN1 they reach the highest value of 280°C (Fig. 19 and Fig. 20). Meanwhile, the third case shows an uncontrolled fire (i.e. sprinkler system failure) and flashover (namely the sudden involvement of a room or an area in flames from floor to ceiling caused by thermal radiation feedback) occurrence, reaching temperatures of 600°C (Fig. 21).

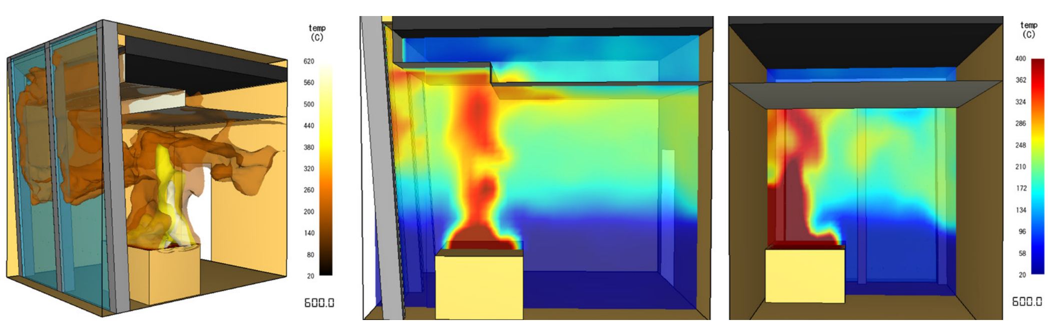

FIG. 19 SN1 - Isosurface at 200-400-600°C (on the left) and temperature of two vertical planes at stationary conditions after 600 seconds (in the centre and on the right)

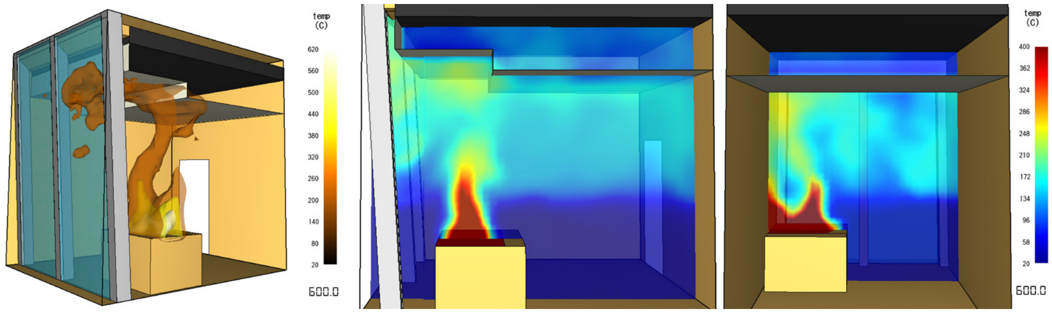

FIG. 20 SN2 - Isosurface at 200-400-600°C (on the left) and temperature of two vertical planes at stationary conditions after 600 seconds (in the centre and on the right)

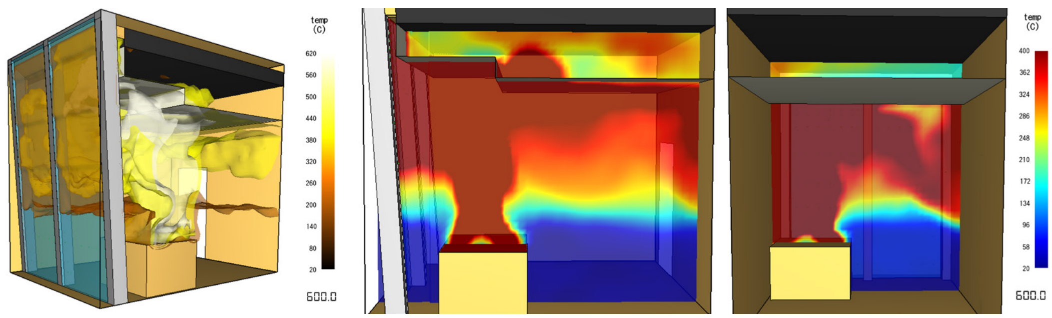

FIG. 21 SN3 - Isosurface at 200-400-600°C (on the left) and temperature of two vertical planes at stationary conditions after 600 seconds (in the centre and on the right)

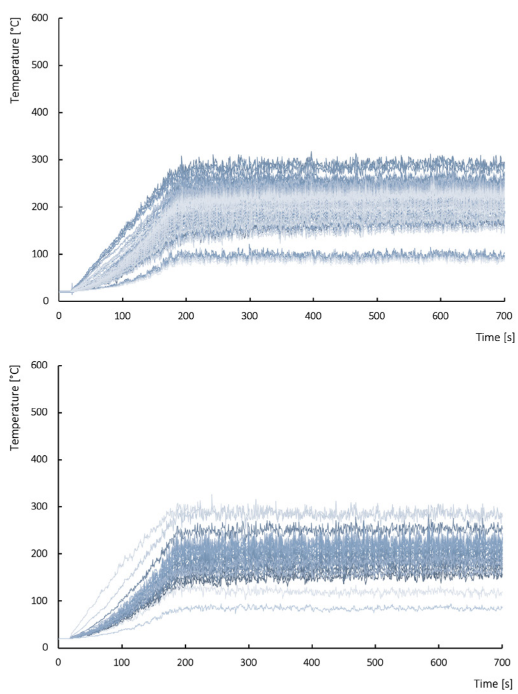

FIG. 22 SN1 – Glazing no. 1 (top) and Mullion no. 1 (bottom) time-temperature chart (data from AST sensors). The temperatures, after a first growth phase, stabilise when the stationary conditions (sprinkler system activation, after about 200 s of simulation) are reached

The temperatures obtained in the CFD analysis along the façade elements by AST sensors are summarised in time-temperature charts (see Fig. 22 for SN1): the temperatures, after a first growth phase, stabilise when the stationary conditions (sprinkler system activation, after about 200 seconds of simulation) are reached. The temperatures recorded on the mullions and the glazing reach a maximum of about 300 °C. The highest temperatures reached are for mullion no. 1 and glazing no. 1 (as identified in Fig. 16), which are the closest to the fire source. The CFD analysis results highlighted that the sprinkler scenario SN1 and the uncontrolled fire SN3 are the most relevant, as they have the higher recorded temperatures.

The CFD results and the temperature distribution have been used as inputs for TTA to estimate and determine the temperatures reached in the whole mullion section, their variation over time and the possibility of a structural failure. In this regard, a study of each façade component has been performed to evaluate the temperature effect from a structural stability point of view (see Fig. 23 and Table 2). For this analysis, some material properties are needed (e.g. specific heat, mass density, etc.) in order to take into account the contribution of their thermal inertia.

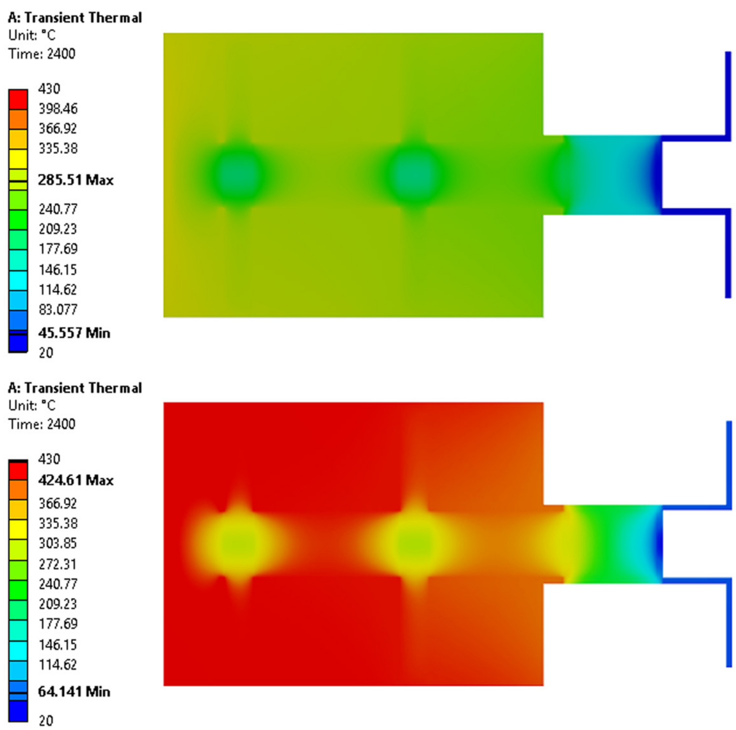

FIG. 23 SN1 (top) and SN3 (bottom) TTA mullion temperatures

As a thermal break, a polyamide 6.6 is used, which offers good insulating properties and excellent mechanical performance. According to the producer technical data sheet, its melting point is between 250°C – 265°C, while the flash point is at 490°C and the ignition temperature is 530°C. In the SN1, the thermal break highest temperature reached is 214°C, therefore melting, heat problems, and ignition phenomena are negligible. Although considering that the service temperature of the polyamide is between 120°C-150°C, a softening phase of the material is expected with a loss of mechanical properties. In the SN3, a temperature of 288 °C is reached, and this could cause the thermal break to melt. The gaskets are made of EPDM, which has a self-ignition temperature of 279 °C at a standard room percentage of oxygen of 21% (Steinberg, Newton, & Beeson, 2000). Considering SN3, the temperature reached its highest value, higher than the auto-ignition of EPDM, and so the gaskets fail. Since, for the structural calculation of aluminium profiles, the EPDM elements are not taken into account, the softening of the gaskets can be considered irrelevant. Regarding the structural silicone thermal properties, the temperature reached within the mullion in all the scenarios leads to its mechanical failure. To secure the glazing, an aluminium bead was considered (Fig. 17).

TABLE 2 Summary of transient thermal analysis (TTA) mullion temperatures

FIRE SCENARIO	ALUMINIUM	EPDM	POLYAMIDE 6.6
SN1	256 °C	242 °C	214 °C
SN2	226 °C	216 °C	190 °C
SN3	425 °C	415 °C	288 °C

The loads on the structural elements were assumed from the structural report provided by the builder. The mullion numerical verifications (according to EN 1999-1-2: Eurocode 9, Design of aluminium structures, Part 1-2: Structural fire design, 2007) consider only the aluminium section, neglecting the contribution of other materials such as silicones, EPDM, and polyamide. The results show that all the metallic elements on the façade that reach temperatures below 400°C are not affected by a significant mechanical strength reduction and are verified in case of SN1 and SN2 scenarios (see Table 2). For the SN3 scenario, the temperature is above 400°C and a significant mechanical resistance loss occurs, putting the glazing in a potentially dangerous situation.

The triple glazing was modelled in Window software (provided by Lawrence Berkeley National Laboratory) as a triple pane system (internal 13 mm clear float glass pane, 18 mm argon filled cavity, 6 mm middle glass pane,18 mm argon filled cavity, external 17 mm glazing pane made of heat strengthened glass with PVB interlayer). This model was then exported to THERM software (provided by Lawrence Berkeley National Laboratory) to analyse the temperatures on each glazing pane surface. According to the National Research Council of Canada (Babrauskas, 1998) the range of gradient temperature from exposed to unexposed surfaces that causes cracks on float glass goes from 25°C to 75°C. For the heat strengthened glass, the gradient temperature from inside to outside surfaces should be at least 100°C. Considering SN1 and SN3 scenarios, the minimum gradient temperature from the exposed surface to the unexposed has been calculated as 26 °C. With this value, a failing condition in the inner pane can be considered. Thus, another analysis is required to evaluate the behaviour of the middle heat strengthened pane after the failure of the inner pane. This second analysis has been performed considering the glazing as a double pane configuration. The maximum gradient temperature from the exposed surface to the unexposed one was calculated as 45 °C. From these results, it can be concluded that the middle pane does not break in the different fire scenarios (De la Fuente, 2019).

3.3 LABORATORY TEST AND MODEL VALIDATION

A fire resistance test was carried out on a façade mock-up (Fig. 24) at the Istituto Giordano's Fire Resistance Laboratory (Italy). Even if the façade is not subjected to specific fire requirements, except for the horizontal fire stop at slab level (it does not include any fire resisting glazing or fire resisting spandrel panel), the test was performed following the general provision given by the standard EN 1364-3 (Fire resistance tests for non-loadbearing elements - Part 3: Curtain walling - Full configuration - complete assembly, 2014), with a modification of the temperature profile in accordance with the fire analysis carried out. In fact, the temperature curves follow the software simulation with an exposure of 320°C for 60 minutes, and slowly increase for the last 15 minutes to a temperature of 450°C. The increased temperature was imposed to verify the ultimate resistance state of the façade exposed to a fire event. The test duration was evaluated in relation to the evacuation time for the given building and occupancy.

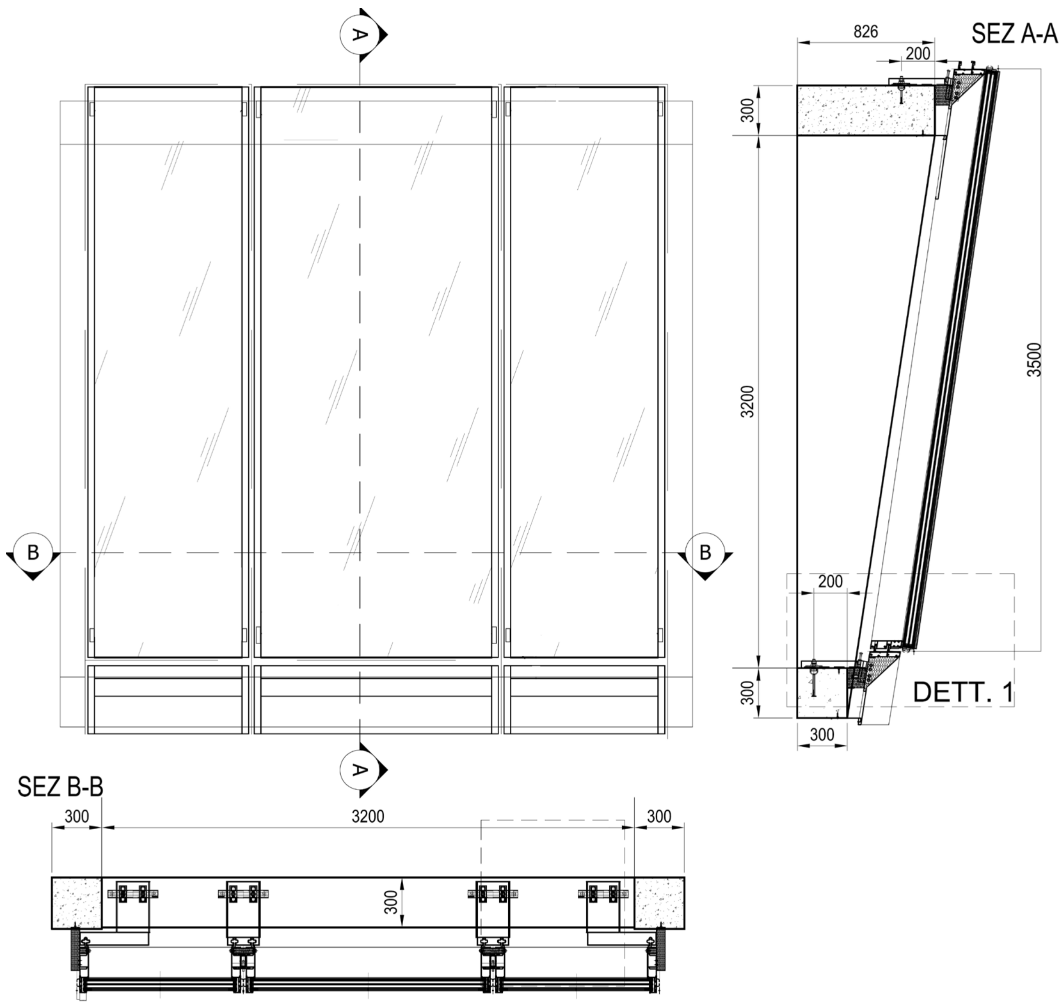

FIG. 24 Laboratory set up configuration of the façade mock-up in accordance with EN 1364-3 standard

The tested sample has shown no damage, except for the deterioration of the PVB layer in the strengthened glass pane. To carry out the test, an experimental oven (internal height of 3200 mm, width of 3200 mm, and depth of 1200 mm), fitted with 8 oil-fired double flame burners, evenly distributed on the vertical side walls, and two fireplaces placed separately, with output section electronically controlled variation valves, was used. The pressure detection system included two pressure detectors connected both to an automatic and a manual pressure reading system.

The temperature detection system included control units located on the vertical sides of the oven (to measure the inside temperatures), "K" type wire thermocouples (Nickel-Chromium/Alumel) connected to a mobile unit, in turn connected to a reader to translate the thermocouples potential difference into temperature values, laser deformation detection system, data acquisition system connected to an electronic computer with a management software. 75 thermocouples and 14 points for the deformation measurement through the laser detection system were placed at the unexposed side of the sample (Fig. 25).

FIG. 25 Façade mock-up after the laboratory test (on the left). Façade mock-up with thermocouples test equipment (on the right)

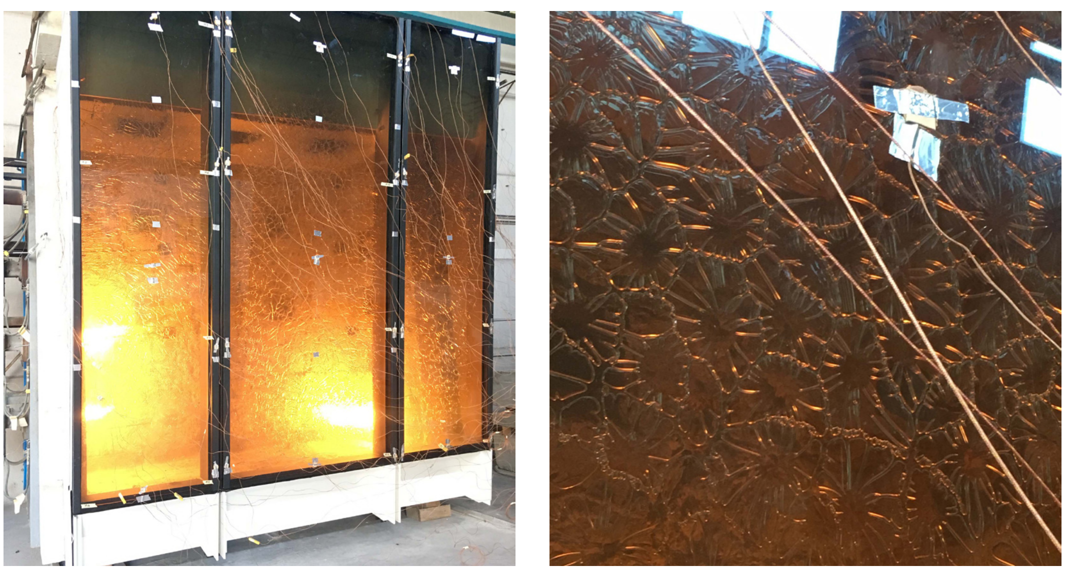

FIG. 26 Façade mock-up under fire exposure (on the left). Glass interlayer appearance after the laboratory test (on the right)

The test was successful, as the façade element maintained the thermal insulation and integrity for the entire test duration (70 minutes) evaluating the SN1 scenario. The mock-up and the glazing panels did not collapse during the test. Throughout the 70-minute test, there were no significant effects other than a change in colour of the PVB layer, which started 16 minutes after the beginning of the test (Fig. 26).

4 DISCUSSION

Different analyses were performed to assess the real behaviour of the façade in case of fire. To evaluate the accuracy of the model and the experimental test, a comparison pertaining to the mullion was done, taking as a base point the experimental test results by the Istituto Giordano laboratory, considering the experimental test conditions after 40 minutes of fire exposure and the scenario SN1, which is the one performed in all the analyses carried out. The thermocouples output of the six mullions are summarised in Fig. 27, which correlates to the experimental test and ANSYS simulation time-temperature charts; for Straus7 TTA, only the final temperatures of the sensors are considered. To avoid peak temperatures and follow the trend behaviour, the time-temperature chart of the laboratory test was traced considering the median values.

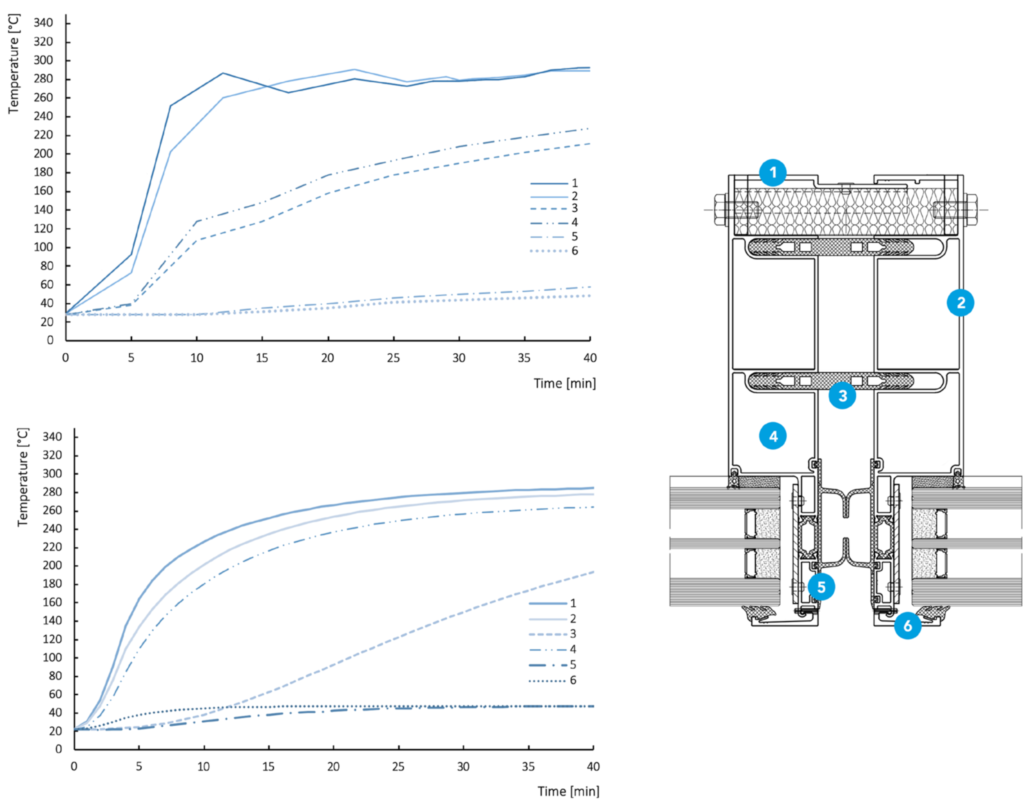

FIG. 27 Experimental test thermocouples time-temperature chart (on the top left), ANSYS sensors time-temperature (on the bottom left) and thermocouples analysed in the mullion comparison test (on the right)

TABLE 3 Summary of sensors' temperatures at 40 minutes of fire exposure

SENSOR	FIRE TEST	STRAUS7	ERROR [%]	ANSYS	ERROR [%]
1	292 °C	256 °C	12.32	284 °C	2.73
2	288 °C	242 °C	15.97	278 °C	3.47
3	211 °C	217 °C	2.84	193 °C	8.53
4	228 °C	201 °C	11.84	264 °C	15.78
5	58 °C	36 °C	37.93	47 °C	18.96
6	48 °C	36 °C	25.00	48 °C	0

The final assessment between the software and the fire test results (see Table 3) is useful to estimate the differences between them. In this regard, the overall difference with a median average is 17.65% for Straus 7 and 8.24% for ANSYS. Both simulations have a satisfactory result and are a good pre-design tool to simulate the behaviour of the mullion. ANSYS seems to give results that are closer to the real value measured during the laboratory test but, as a general remark, both software outcomes seem to be very close to the measured temperature values with an acceptable error. Once the reliability of the ANSYS model is confirmed, in case of an uncontrolled fire scenario, the time-temperature curve gives an overview of what could happen if this catastrophic case occurs.

In general terms, it is very important to set out the correct fire scenario, which clearly drives any possible consideration regarding this methodology of simulation and its potential extension to other cases. Reference fire scenarios can be found in national and international standards, but they need to be adapted to the specific design situations, involving a detailed knowledge of adopted fire prevention measures (in the case study, a sprinkler system) and architectural consideration of the building and façade details.

Façade construction details are relevant with regard to assembly and installation procedures, making a clear distinction between unitised curtain walling systems and stick construction systems. FEA analysis shows that, in terms of critical temperatures, stick systems are better performing due to a general higher thermal resistance of discrete framing (mullion and transom sections), when compared to typical coupled unitised mullions sections. In the case of unitised curtain walling systems, the presence of water and air control barriers (elastomeric EPDM gaskets, as components highlighted with number 3 in Fig. 27) represent a discontinuity in regard to temperature distribution in the framing section (see Fig. 23). On the contrary, in regard to Fig. 23, it is also very clear the importance of the thermal break made of polyamide strips, which highly reduce the heat transfer in the critical area of the curtain walling system, thus improving the mechanical glass retention (see sensors placed in 5 and 6 positions in Fig. 27). A specific consideration needs to be given in regard to the structural silicon bonding between glazing and aluminium framing. Experimental and FEA results show temperature values that are theoretically not compatible with the mechanical resistance of the bonding silicone, but no glass bonding failure occurred during the fire test. This could be explained by the local difference of temperature not recorded by the sensors (sensor no. 4 was placed inside the aluminium profile cavity and not in contact with the glass to sealant adhesion surface). In this case, a lower surface temperature could justify a residual mechanical resistance of the bonding. For sure, this specific topic requires a more detailed FEA analysis and it could be part of further investigations.

5 CONCLUSIONS AND FUTURE WORKS

The current tendency is to design high-rise buildings or skyscrapers with glazed façades, that involve a multidisciplinary design practice to ensure a high level of performance in terms of resistance to environmental actions (such as wind, rain, and earthquake) and to meet advanced standards of fire safety. FSE is part of the building design, but seldom is it properly considered in detail. Relevant considerations, as well as decisions, must be taken in regard to which kind of analysis is most suited to a particular project, which fire scenarios should be chosen to assess a real situation, the most appropriate safety devices to select, etc. Moreover, simulation software nowadays represents a cost-time efficient tool at a preliminary design stage, so that laboratory tests can be performed only later to validate the simulation results.

The case study presented here helps to understand how these new buildings with complex shapes can be analysed and assessed. All the studies and simulations performed (CFD, FEA, TTA) have been concluded with a valuable comparison between two different approaches, both with satisfactory results. Regarding the glazed façade, it should be considered that the SN3 represents a catastrophic scenario which is not likely to occur. It was studied to evaluate what could happen in case of a sprinkler system failure, which would also cause a general failure of the façade components. Here lies the importance of FSE, which ensures the possibility of evaluating multiple fire scenarios in a reasonable time and with good reliability, in order to give occupants and/or fire brigades the opportunity to understand how to act, thus reducing property damage, including structure, equipment, and building components.

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