especially when compared to snow loads that the subject building was subjected to during previous winters during the life of the structure, and it is not likely that this load caused any new damage to the trusses during the specified winter.

SUMMARY OF CONCLUSIONS

Based on the investigation and structural analyses the following conclusions were made:

- The structural analyses revealed significant calculated overstresses in the bottom chord members of the as-originally-built trusses (without consideration of the existing repairs) under dead load without snow loads. When snow loads are considered, the bottom chords are overstressed to an even greater degree and the top chords are also overstressed. Additional members are also overstressed in each truss under the unbalanced snow load case.
- The tensile failure of the truss bottom chords is consistent with distress due to accumulated damage and the gradual weakening of these members due to a sustained high dead load throughout the life of the structure, and an unknown number of excursions above that level when snow loads occurred on the roof. This damage appeared to be the primary reason for the installation of the majority of the previous repairs.
- The observed truss damage was determined to have occurred prior to the specified winter.
- None of the previously installed repairs addressed the risk of failure of the truss bottom chords in tension perpendicular to grain. Therefore, it was believed that this damage may have manifested at some time after the installation of the existing repairs. This type of damage is not related to snow loading and, therefore, could not have been caused by snow loads during the specified winter.
- Snow loads experienced during the specified winter were relatively light and not likely to have caused new damage to the trusses.

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Application of Performance-Based Fire Engineering to Existing Structures and Forensic Investigations

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ABSTRACT

Performance-based fire engineering (PBFE) has gained attention in recent years as a modern alternative to the conventional prescriptive methods for fire protection design. Acknowledged in the 2016 edition of ASCE-7 code, PBFE provides structural engineers with great flexibility to achieve more rational and cost-effective designs against fire hazards. In addition to applications in design optimization and performance evaluation of new structures under fire, PBFE can be an efficient tool for the assessment of existing structures, including renovation and fire protection, fire risk assessment, post-fire forensic investigation, and post-fire structural assessment. This paper outlines the key steps of the PBFE process to perform fire analysis for both new and existing structures, including simulation of fire scenarios with computational fluid dynamics (CFD) and finite element (FE) analysis of the subsequent thermal and structural effects. An example of a tall building façade subject to fire hazard will serve as a benchmark case to demonstrate how structural forensic investigations can benefit from each phase of the PBFE process. For example, it will be illustrated how fire simulation, complemented with traditional investigational data (e.g. photos, witness statements, etc.), can be used to reconstruct a fire event, or how thermal analyses can be utilized to determine the extent of fire-induced damage.

INTRODUCTION

With the increasing complexity of the built environment, design methods able to provide a structure with an expected performance under predetermined levels of hazard become a necessity. Performance based fire engineering (PBFE) provides such flexibility when designing for fire hazards.

Prescriptive design does not address many aspects that should instead be considered when designing for large and complex structures(BS 7974:2001, 2001). For example, whilst design load combinations account for extreme load events, the considered scenarios are not specific for the particular project under analysis. Prescriptive approaches prevent the designer from identifying potential capacity reserves for the designed members and cannot provide guidance to assess the structural behavior once the demand prescribed by code is exceeded. More importantly, being based on a member-by-member analysis, prescriptive design cannot lead the designer to conclude whether the structure could have the same, or even a better, performance, if other solutions are taken into account.

Prescriptive design remains the preferred approach for the vast majority of structural design projects. Its popularity is mainly due to the fact that prescriptive design procedures are standardized and easy to apply. The ease of application stems from the necessary simplifications the code must consider in order to make its applicability as general as possible. However, prescriptive design pitfalls become evident when considering design under hazardous conditions. For example, when designing for fire conditions, prescriptive design assigns a particular fire rating to each structural component. This approach fails to clarify the actual behavior of the structure in case of occurrence of a fire event. In order to achieve this, realistic fire scenarios and their effects on the overall structural integrity should be considered. This is the approach at the core of Performance Based Fire Engineering (PBFE). The PBFE approach develops into three phases: hazard analysis, thermal/structural analysis and decision making. During the first phase, realistic, project-specific fire scenarios are selected and the required performance of the structure under said scenarios is established by the project's stakeholders. The fire event can then be simulated using advanced numerical methods or simply modeled as a temperature input obtained from the solution of first principle thermal equations (Marx et al., 2018; Imani et al., 2017). The effects of the selected event are analyzed on numerical models of the identified critical parts of the structures. The structural behavior is then compared to the predetermined performance objectives. The design process is complete when a solution is found meeting the predefined design performance. In the United States, established codes and guidelines have recently started to formally acknowledge PBFE as a viable alternative to prescriptive design for fire protection. For example, Appendix E of the last edition of ASCE-7 discusses 'Performance-Based Design Procedures for Fire Effect on Structures' (ASCE 7-16, 2016), while Appendix 4 of the fifteenth edition of AISC 360 explicitly mentions design to achieve the 'specific performance objective' of life safety as an available approach to design for fire conditions (AISC-360, 2017).

When an investigation is conducted after a fire, different tasks may be required depending on the objectives of the investigation. For example, it is often of interest to identify the source of the fire. The forensic engineer is also frequently required to recommend the best repair options for the structure damaged by the fire. Irrespective of the goal of the investigation, availability of circumstantial evidence, such as reliable witness statements and physical evidence, plays an important role in defining the modalities of the event. Weather conditions at the time of the event are also an important aspect to consider, as they may change the outcome of a fire event (Barowy et al., 2012). Gathering as much information as possible on the thermal properties of the materials collected on the scene is extremely important, in order to be able to reconstruct the event and determine the best rehabilitation options. The tools used for PBFE and the PBFE approach itself can be used within the context of a fire investigation to provide further insights on the development of the fire and of the thermal conditions of the system.

In order to illustrate how forensic engineering can benefit from performance based fire engineering, the case of a fire occurring in front of a building façade is considered in this paper. After a description of the details of the PBFE application for design of new constructions, the paper proceeds in describing the possible use of the PBFE tools thorough a case study mock up of a fire occurring in front of the façade of a tall building. In presenting the case study, it is assumed that the objective of the investigation is that of identifying a rehabilitation plan for the damaged façade. The paper shows how the evidence collected on site can serve as validation for the simulated fire scenario, and how finite element analysis can then be exploited to refine the understanding of the structural conditions.

PERFORMANCE BASED FIRE ENGINEERING (PBFE)

Fire scenario selection: The first step of the PBFE exercise is the selection of the fire scenario and associated performance objectives. The accuracy of the results of the PBFE approach is intimately related to the selection of an adequate suite of fire scenarios. Reference (BS 7974:2001, 2001) offers some guidelines to identify the set of fire scenarios to consider for the design. Gravity and lateral load resisting system layouts, uses and contents of the different areas of the building are some of the factors that must guide the designer in defining the possible fire scenarios. Fire location and mechanism, available fuel to start and propagate the fire, and ventilation conditions are also some important factors to consider when defining the design fire loads. The selection approach depends on whether the PBFE assignment requires a risk or a hazard assessment. In a risk assessment, several fire scenarios with different combinations of the aforementioned parameters are considered, each scenario weighted by its likelihood of occurrence, and the system is designed to perform according to criteria, which are based on acceptable consequences for given levels of event likelihood. In a hazard assessment, a limited pool of fire scenarios is selected, and the system is required to meet the performance criteria set at the beginning of the design under each selected fire conditions.

Analyses: Once a fire scenario has been selected, an analysis method must be selected to simulate it. The performance-based approach is well suited for the analysis of the fire performance of systems of different complexities. For example, it can be of interest to determine whether a single structural component can withstand the effects of a fire scenario without the need of fireproofing the member. If the member is located in an area with low fuel loading, it can be assumed that a fire event occurring next to the member under analysis will affect only that member, with negligible effects to the surrounding components. This would be the case, for example, of columns in a structure with long spans and minimal load redistribution between columns. In this instance, simplified heat transfer models, mainly addressing heat transfer by radiation, can be adopted to assess the temperature and incident heat fluxes affecting the structural member. Where the complexity of the system warrants it, more advanced methods of heat transfer analysis, combining radiative, convective and conductive heat transfer analyses might be necessary. Fire events occurring in systems with compartmentalized geometries are well represented by zone-models (Peacock 2016), while open space fire may require the use of computational fluid dynamics (CFD) models constructed with appropriate software such as FDS (McGrattan, 2017).

Once the temperature exposure of the structure has been evaluated, it is necessary to conduct a heat transfer analysis to determine the temperature distribution within the structural members of interest. Depending on the level of detail required by the project, the outcomes of the thermal analysis may suffice to conclude whether the performance of the structural components meets the predefined acceptability criteria. In those instances where the impact of the structural component must be studied in combination with the surrounding elements, the outcomes of the thermal analysis constitute the initial conditions for a subsequent structural analysis. The latter must be able to capture transient effects, nonlinearities, and instabilities.

Performance criteria: A fundamental difference between the prescriptive and performance based design approach is that the latter explicitly includes the analysis of the consequences of each loading scenario into the design process. Number of occupants, building's type of occupancy, egress and access conditions are examples of factors contributing to the definition of performance criteria (SFPE, 2012). In a hazard assessment, the evaluation of the fire event consequences is qualitative and drives the selection of the fire scenarios. As mentioned at the beginning of this section, in a hazard-based PBD approach, the structure must be able to withstand all selected fire scenarios. Such scenarios are usually the most likely scenarios expected to occur in the lifetime of the system. It is then expected that the structure will be able to withstand such loadings without harming the occupants until the evacuation of the building is complete. From a structural point of view, this requirement is usually met by designing a system that is able to sustain the fire loading for a predetermined amount of time, such as 2 hours, without losing structural stability. In a risk assessment, the evaluation of the consequences is quantitative and is used to define the risk of a given fire condition. In case the risk associated to a given fire condition exceeds a threshold value defined at the beginning of the PBFE process, the design of the structure must be improved to meet the desired level of safety.

APPLICATION OF PBFE TO FIRE INVESTIGATIONS

Identifying the origin, cause and responsibility of a fire are possible objectives of a fire investigation. The outcomes of such an analysis can be used for litigation support, rehabilitation recommendations or prevention purposes. The NFPA 921 Guide for Fire and Explosion Investigation (NFPA, 2017) recommends applying the scientific method to a fire investigation. The method starts with acknowledging the occurrence of the fire event and setting the objective of determining its cause, listing the findings in order to prevent similar occurrences in the future. In order for the forensic engineer to complete the cause analysis, circumstantial evidence should be collected on the scene and a review of similar incidents, if possible, should be conducted. The factual evidence is then analyzed to form the basis to produce a hypothesis on the fire incident cause. The analyst should then test the hypothesis to ascertain its robustness. Such a test can be set forth by conducting experiments, but can also be performed analytically, employing accepted scientific principles. Once all available hypotheses have been tested, the one consistent with all the empirical data and scientific principles is selected as the most plausible explanation of the incident.

In the remainder of this paper, we will discuss how the steps employed in PBFE can be used as a complement to the circumstantial evidence collected during a fire investigation to complete the investigation assignment. To support the discussion, the analysis of a fire incident occurring in front of a glass façade is considered. The structure is assumed to be a residential tall building with a setback at mid-height, used for recreational purposes. The fire is assumed to have originated close to one of the dining tables located on said setback. It is assumed that the purpose of the investigation is to identify the extent of damage to recommend a rehabilitation plan. The study here is performed with the goal of showing the methodology and capabilities of PBFE in a generic setting and hence, does not focus on specific values regarding the fire or material behavior that could vary significantly depending on the specifics of a project.

Fire scenario selection: The same factors leading the designer to select the fire scenarios in design should also be considered when trying to reconstruct a fire event to determine the cause of the incident. Within a fire investigation, the objective of fire simulation is that of approximating the actual fire event in order to assess the level of damage incurred to the structure. Once a reasonable reproduction of the actual event is available, it is also possible to vary some of the factors defining the fire event to assess whether the fire development could have changed, had the conditions been different. This mode of analysis is of interest when the fire investigation is conducted to identify the responsibility of the incident or for prevention purposes. In the first phase of the fire investigation, the objective of the analysis must be clearly agreed upon. In the case study under analysis, it is assumed that the objective is to recommend a rehabilitation strategy for the damaged façade.

Analyses: In the mock-up assessment considered in this work, the fire starts as a flaming fire on one of the tables located in front of a corner of the building (arbitrarily designated as southwest corner for this study), on the building setback. The Fire Dynamics Simulator (FDS) software by NIST (McGrattan et al., 2017) was used to simulate the fire event. FDS is a Computational Fluid Dynamics (CFD) model of fire-driven fluid flow. The simulation portrays a 15-minute duration event, which is approximately three times the average end-to-end response time for structural fires (4.867 minutes) according to FDNY vital statistics for the 2016 calendar year (Fire Department, City of New York, 2016).

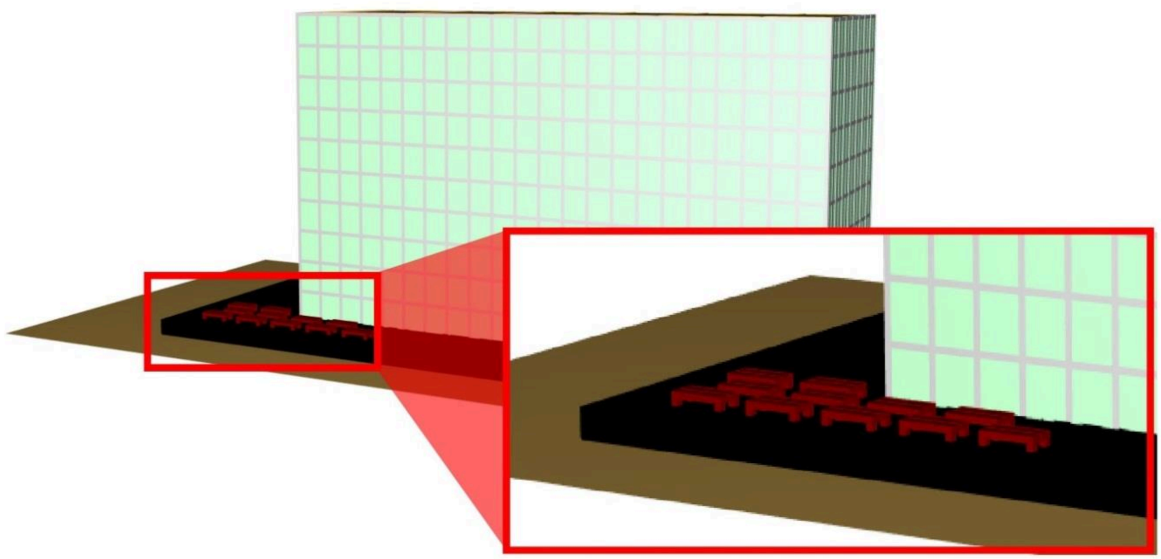

Figure 1. CFD model geometry used for fire event simulation.

Figure 1 shows an isometric view of the model used in FDS to simulate the fire scenario. The model represents only the 22 m high part of the building above the setback, assumed placed at an elevation of 25 m. The façade is modeled as a series of 2 x 2 m laminated glass panels, framed on aluminum mullions. The setback is covered by waterproofing material (Ethylene Propylene Diene Monomer – EPDM). The dining tables, visible in the close-up view of Figure 1, are assumed to be made of softwood. In the simulation, both tables and waterproofing membrane contribute to the fuel load. In setting up a CFD simulation, it is critical to assign plausible thermophysical properties to the model materials. This is particularly crucial when attempting a reasonable reproduction of an actual fire event. Construction data sheets could aid this task, but it is often necessary to conduct extensive research to retrieve such values. For the analysis in this paper, several different references were used to retrieve thermophysical and heat release rate properties of the materials. In particular, references (Hwan et al., 2013) and (Nodehi, 2016) were used to define the properties of laminated glass; reference (Tang et al., 2013) for the EPDM heat release rate (HRR) curve characteristics; reference (Barowy et al., 2012) for the softwood thermophysical and HRR curve properties. The parameters input into the model must be calibrated in order for the simulation to reproduce at a reasonable level of detail the circumstantial evidence observed at the fire scene. The aim of this exercise is not that of reproducing exactly the fire event, but that of having a model able to mimic the most critical events occurred during the fire. For this reason, FDS offers several features enabling the user to include such events when predefined times/temperatures thresholds are reached.

When producing recommendations for façade rehabilitation, one of the most difficult tasks is that of determining the extent of the façade to be replaced. After a fire event, the project's stakeholders are called to select such an area and the factors driving their decision are often empirical evidence (visible damage) combined with expert judgement. In this regard, it is noteworthy that certain materials can start degrading before showing signs of damage. For this reason, it could be reasonable to replace a larger portion of façade than that visibly damaged by fire. For the purpose of this study, we will use an arbitrary temperature threshold of 200 ˚C: façade elements believed to have exceeded such a value are replaced. Moreover, the cluster of replaced panels is selected to cover a rectangular area, as modern curtain walls could be set up in modules that are not easy to replace individually. In general, material testing can be an important part of the investigation to determine the extent of damage and the scope of what needs to be replaced. Even when testing is performed, the results of thermal analysis can be used to guide the testing process to establish the location, frequency, and nature of material testing. Laboratory tests performed on the panels outside the selected replacement area can confirm the adequacy of the area selected for removal. Supporting such a decision with the results obtained from a fire simulation enables all decision-makers to take a more educated selection, hence leading to a more cost-effective solution.

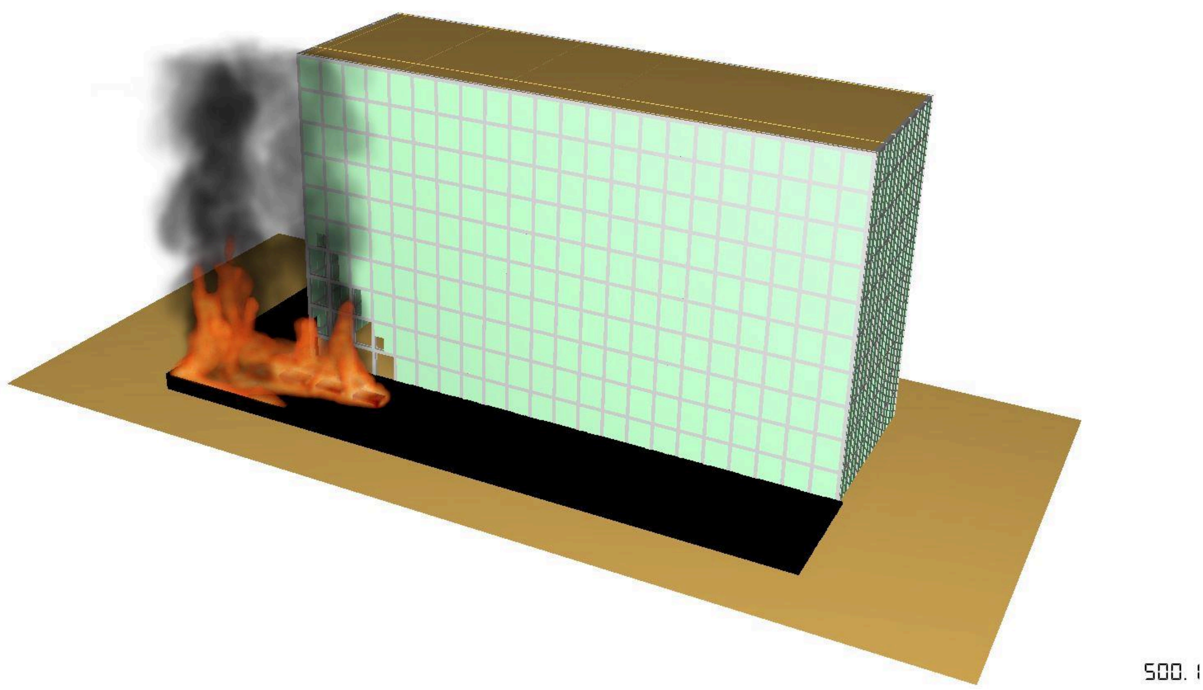

Figure 2. Rendering of the fire event at 500.1 seconds of simulation

Figure 2 shows a frame of the simulation depicting the peak of the fire event. Figure 3 shows the simulation results in terms of temperatures reached by the exterior parts of the façade's elements at the end of CFD model analysis. In Figure 3, the irregular black line appearing at the façade's bottom left corner encloses the area exceeding 200 ˚C. In order to simulate glass breakage induced by thermal shock, the model is calibrated so to remove glass elements when they reach 450 °C; the missing glass elements at the bottom left corner of the façade are a result of such setting (see Figures 2 and 3). The behavior of glass could significantly vary for specific projects depending of the type of glass used. Based on the 200 °C performance criterion, the rectangular area delimited by the red line of Figure 3 could be tentatively selected as the portion of façade to be replaced.

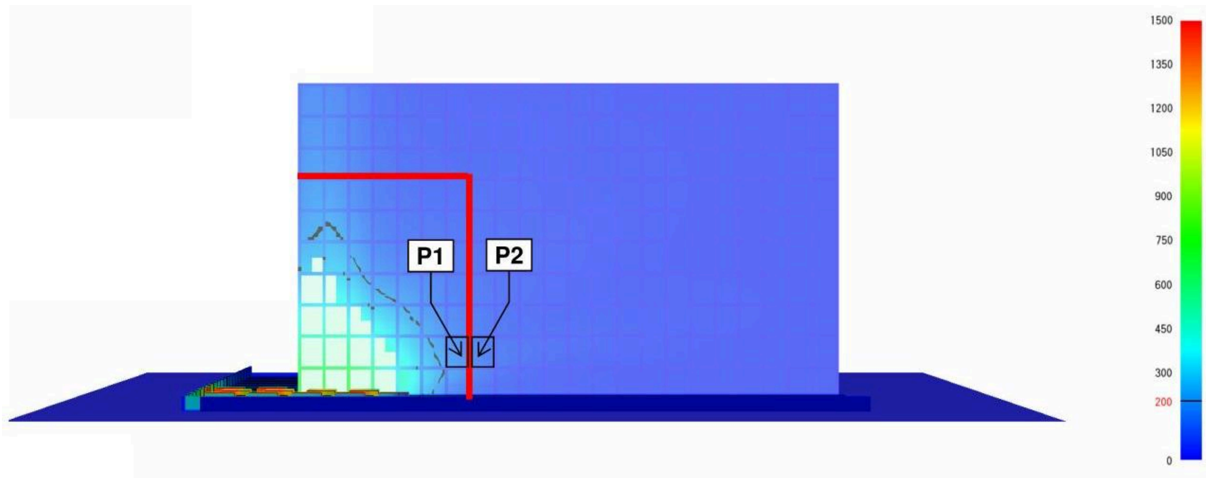

Figure 3. South façade temperature contours (in °C) at the end of the fire simulation.

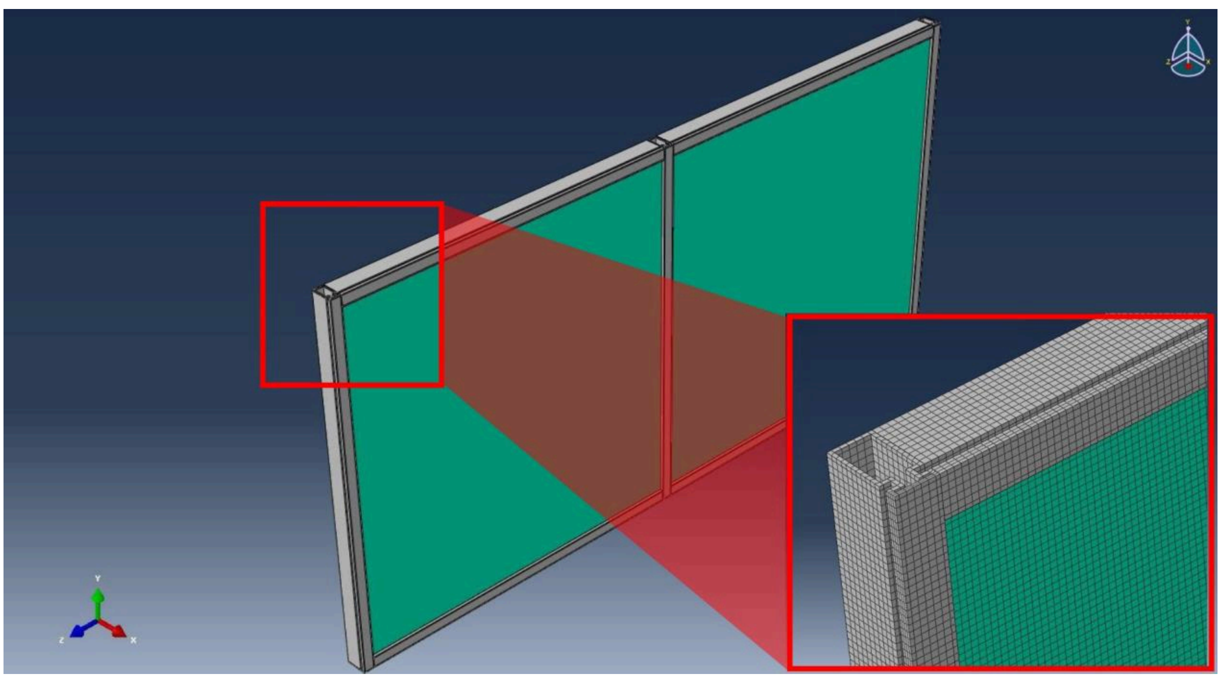

Figure 4. Geometry of the Finite Element Model used for thermal analysis of panels P1 and P2.

In order to confirm the selection, a more thorough thermal analysis was performed to assess the temperature of the elements on the interior side of the building. A finite element analysis was performed using the software Abaqus v6.11 (ABAQUS) employing heat transfer solid elements of type DC3D8 to perform the heat transfer transient calculations. Figure 4 displays the geometry of the model.

Figures 5.a and 5.b show the Adiabatic Surface Temperature time histories used as inputs for the thermal analysis.

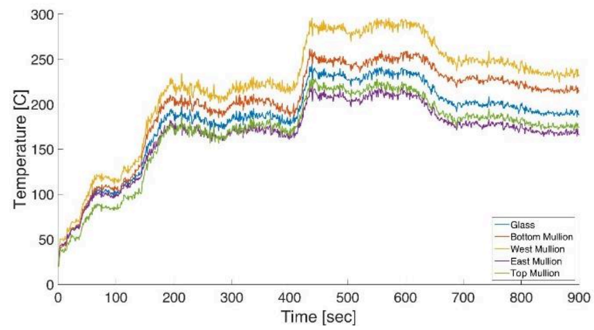

Figure 5.a. Gas temperature time histories for different elements of panel 1.

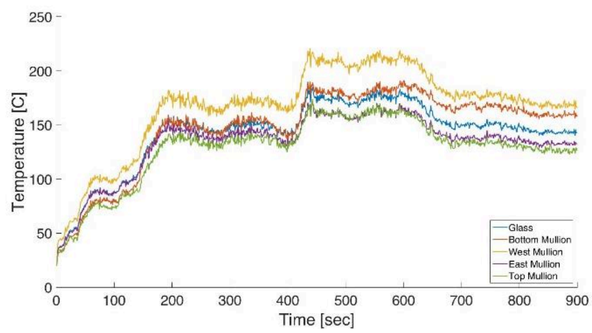

Figure 5.b. Gas temperature time histories for different elements of panel 2.

Figure 6 shows the results of the finite element thermal analysis in terms of temperatures reached by the glass and mullion elements of panels ‘P1’ and ‘P2’ during the simulated fire event. It is noted that while most of the elements of Panel 1 reach a maximum temperature close to 300 ˚C during the fire event, this is not the case for the elements of panel 2. This confirms the adequacy of the width of the selected replacement area. Performing a similar analysis of the panels at the top of the replacement area could confirm the accuracy of its selected height.

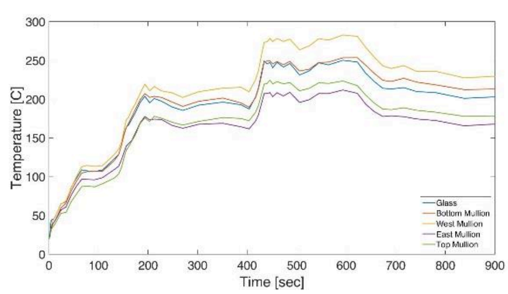

Figure 6.a. Temperatures on mullions and glass of exterior of panel 1.

Performance criterion: Cost-benefit considerations combined with safety needs are the driving criteria for selecting repair options after a fire incident. In the example displayed in this paper, the performance of the façade is deemed unacceptable for the elements exceeding a temperature of 200°C. The results of the fire and thermal analysis combined with visual observations and any testing that might be done can be used to determine the extent of façade replacement or repair. By providing additional information, the use of the PBFE tools allows the decision makers to estimate the damaged area of the system more accurately, hence leading to a more cost-effective solution.

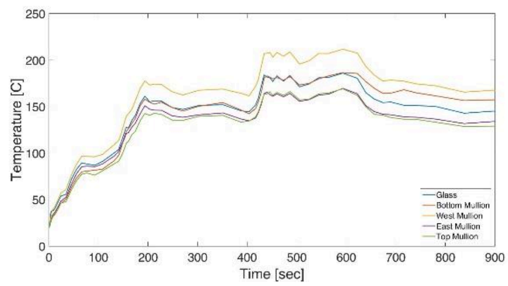

Figure 6.b. Temperatures on mullions and glass of exterior of panel 2.

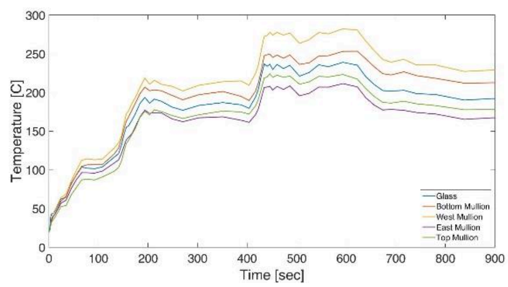

Figure 6.c. Temperatures on mullions and glass of interior of panel 1.

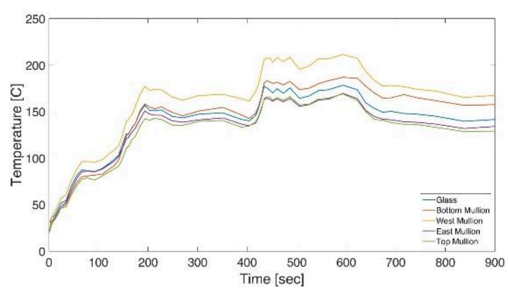

Figure 6.d. Temperatures on mullions and glass of interior of panel 2.

CONCLUSIONS

Performance Based Fire Engineering is an alternative to prescriptive approaches for the design of complex and unique structures under fire hazards. This paper demonstrates how the PBFE methods and tools can be applied to fire investigations as a complement to the traditional approaches based primarily on factual evidence and experience. Through a case study mock up, it is highlighted how fire simulations through CFD models can aid the forensic engineer in confirming the hypothesis of the fire incident cause, using the evidence collected on site as a mean of validation of the model accuracy. It is further demonstrated how finite element analysis can be exploited to refine the understanding of the conditions experienced by the structural elements during the fire event. It is finally argued that by complementing the traditional means of fire investigations with the tools of PBFE, decision makers could attain more accurate and cost-effective repair solutions.