Performance-Based Fire Safety Assessment of UNESCO Heritage Structures: CFD Simulation of Gothic Timber Carpentry in Our-Lady Cathedral of Tournai, Belgium

Abstract:

- **Purpose** – This paper focuses on assessing fire safety level of a patrimonial structure by combining a fire outbreak scenario with various protection measures.

- **Design/methodology/approach** – Heritage buildings often fail to meet modern fire safety standards due to multiple concerns, including the presence of highly flammable aged materials, outdated electrical systems and insufficient contemporary firefighting systems. Furthermore, preserving these structures requires careful consideration, as their historical and cultural significance must be maintained. Any alteration must be strongly justified in accordance with the Venice Charter [1]. To evaluate the fire safety of such a structure, a performance-based approach using Fire Dynamics Simulator (FDS) is applied. A model case study of the Gothic carpentry of Our Lady Cathedral at Tournai was built to simulate different fire protection scenarios and analyse the fire behaviour. The study aims to address safety research questions related to fire propagation and prevention strategies.

- **Findings** – For the studied structure layout, the results indicate that (1) an electrical fire outbreak in the isolated Gothic carpentry would lead to widespread flashover of the structure; (2) natural ventilation through windows can help mitigate the flashover by allowing heat dissipation; (3) compartmenting the electrical cabinet proves to be more effective in limiting fire and smoke propagation compared to relying solely on natural ventilation.

- **Originality** – This case study provides some recommendations for enhancing fire safety strategies tailored to the Gothic carpentry while preserving its structural integrity and patrimonial value. The proposed fire protection measures can be adapted to similar heritage structures.

Keywords: Fire safety, Patrimonial structure, Fire protection measures, FDS

1. Introduction

Several centuries ago, numerous high-rise religious edifices were constructed in Europe to symbolically consolidate the Christian presence during the medieval period. Many of these structures are now recognized as National landmarks and UNESCO World Heritage sites due to their significant historical, architectural, and cultural values. However, these patrimonial buildings face various threats, among which fire remains one of the most critical risks. Fires not only endanger lives and property but also have profound socio-economic consequences, particularly when they result in the destruction of heritage sites of global importance. The loss of such historical structures significantly impacts cultural heritage and directly influences the national/international economy by diminishing tourism income and increasing restoration costs. According to the Observatory of Religious Heritage in France, in 2023, 27 religious properties were affected by fires [1]. Similar incidents have been reported in other countries worldwide [2] [3] [4]. More than 450 World Heritage buildings have been listed worldwide between 1970 and 2023 [5]. Consequently, fire safety measures for patrimonial buildings have garnered substantial attention in recent years, with engineers emphasizing the need for advanced fire prevention strategies in such buildings.

Heritage buildings present several unique challenges that are not typically encountered in modern or newly constructed structures. One of the primary difficulties lies in the need to preserve the patrimonial integrity of these buildings, which significantly restricts the implementation of contemporary fire safety standards. Fire protection upgrades must be carefully designed to avoid compromising historical authenticity, thereby limiting the use of modern fireproofing materials and certain active fire suppression systems. Additionally, historic buildings often exhibit specific structural vulnerabilities that affect their fire resistance and evacuation strategies. Many of these buildings were constructed centuries ago using traditional materials such as wood, stone, or plaster, which may have deteriorated over time. Unlike modern buildings, which are designed with fire-resistant materials, historical structures often contain highly combustible elements, such as wooden beams and aged insulation. These aged materials not only increase the fire load but can also contribute to rapid fire spread, making suppression efforts more complex.

Fire risk management in heritage buildings is a growing global concern, particularly in Belgium, where appropriate measures must be taken to prevent and control potential fire hazards, reduce casualties and economic losses, and ensure compliance with fire safety regulations. Given the historical and cultural significance of these structures, effective fire risk management is essential to mitigate damage while preserving their authenticity. Identifying and understanding the potential causes of fires is crucial for site managers to implement effective fire safety measures while maintaining the historical integrity of heritage buildings. Recent data indicate that more than 450 fires have been recorded in heritage buildings across multiple countries [5]. Among these incidents, electrical faults in isolated areas, such as attics, have been identified as one of the most prevalent causes of fire worldwide [5] [6]. Fires in heritage buildings have also been attributed to various other factors, including natural lightning events (Aubigne Church, 2022), restoration activities (Our-Lady Cathedral of Paris, 2019), arson (Nantes Cathedral, 2020; Serbian Orthodox Cathedral, 2016), and negligence-related incidents such as smoking or fireworks [7]. These cases serve as a stark reminder of the necessity to enhance fire prevention measures, improve emergency preparedness, and conduct regular safety inspections in such buildings. Given the extensive damage caused by such fires, addressing fire risks is imperative, as the destruction of heritage buildings leads to the irreversible loss of invaluable architectural and cultural works.

Therefore, this study framed as an engineering-based fire-safety assessment intended to support architectural conservation decision-making, rather than as a purely regulatory compliance study. The case study focuses on the fire safety assessment of the Our-Lady (OL) Cathedral of Tournai (Belgium), specifically in its Gothic choir carpentry, which contains an electrical panel unlike the other carpentries of the cathedral. This investigation follows the devastating fire that occurred in 2019 at the carpentry of the OL Cathedral of Paris [8], raising concerns about similar risks. Key questions explored in this study include: Does the existing carpentry provide sufficient fire safety? Could natural ventilation through windows have a beneficial effect on fire mitigation? What fire safety strategies, compliant with heritage preservation guidelines, can be implemented to enhance fire protection? Addressing these questions is complex, requiring a performance-based approach. We employed fire simulation tools, specifically PYROSIM, which interfaces with FDS (Fire Dynamics Simulator), to analyse the fire behaviour inside the chosen premise and evaluate potential fire safety improvements.

2. Fire regulations for heritage buildings and methodological implications

Fire safety in heritage buildings raises a complex regulatory and methodological challenge, as it requires the reconciliation of two objectives that may appear partially conflicting: the protection of human life and property against fire, and the preservation of architectural, historical, and cultural significance. In conventional buildings, fire safety is generally governed by prescriptive regulations, which establish predefined technical requirements related to compartmentation, structural fire resistance, evacuation routes, detection and alarm systems, suppression systems, access for firefighters, and smoke control. These provisions provide a standardized framework for achieving an accepted level of safety. However, when applied to historic buildings, such requirements may become difficult to implement without compromising the material authenticity, spatial configuration, decorative elements, and construction techniques that constitute the heritage value of the building.

The limitations of a purely prescriptive approach become particularly evident in the case of protected heritage monuments [9]. In Belgium, fire safety regulations are mainly structured according to parameters such as building height, date of construction, occupancy, function, and urban-planning conditions. This framework is appropriate for new buildings, where fire-safety measures can be incorporated from the design stage. Nevertheless, its direct application to older heritage buildings, particularly UNESCO-listed religious monuments, remains problematic. These buildings were not conceived according to contemporary fire-safety assumptions, and their protected status may restrict interventions such as the subdivision of spaces, or alteration of original materials. Consequently, the regulatory issue is not limited to determining whether a building complies with current standards, but rather to assessing how an equivalent level of safety can be achieved while preserving the cultural significance of the monument. Therefore, it is essential to balance fire safety objectives with the constraints of preserving the building's historical integrity, ensuring both protection of life and cultural heritage [10].

A comparison with international heritage conservation principles further clarifies this tension. The Venice Charter [11] and related conservation doctrines emphasize authenticity, minimum intervention, reversibility, and respect for the historic fabric. From this perspective, fire-safety measures must be evaluated not only in terms of technical effectiveness, but also in relation to their impact on the heritage values of the building. Conversely, fire regulations prioritize life safety, limitation of fire spread, and support for emergency intervention. These two frameworks are therefore based on different but complementary logics: fire regulations seek to reduce risk through technical control measures, whereas heritage conservation principles seek to prevent the loss or alteration of cultural significance. The challenge lies in developing a strategy that does not subordinate one objective to the other but instead integrates both within a coherent risk-management process.

Performance-based fire safety approaches provide an appropriate response to this challenge [12]. Unlike prescriptive regulations, which specify predetermined solutions, performance-based approaches define safety objectives, performance criteria, design fire scenarios, and acceptable levels of risk. It is a tailor-made approach, offering a more flexible alternative to traditional prescriptive methods for heritage site where standard measures may be technically infeasible, visually intrusive, or incompatible with conservation requirements [5] [13]. Standards such as NFPA 914 and ISO 23932-1 [14] are particularly relevant in this context because they support the development of fire-safety strategies adapted to the specific characteristics of historic buildings. There are no strict fire regulations for this kind of building (old and sensitive), hence the need to carry out a fire audit specific to each of them, since the fire protection measures may differ from one heritage building to another due to their uniqueness [15].

This comparative regulatory analysis directly informed the methodological framework adopted in the present study. Since the case study concerns the carpentry and roof structure of the Our Lady Cathedral of Tournai, a UNESCO-listed monument, the research could not rely exclusively on prescriptive compliance. The timber roof structure represents both a significant heritage component and a critical fire-risk zone, as many major fires in historic monuments originate or propagate through attic and roof spaces. The methodology was therefore designed to evaluate fire propagation in chosen scenario such as the introduction of compartmentation strategies, smoke management. These scenarios are compatible with both safety objectives and conservation constraints.

The methodological integration between FRAME and FDS is therefore central to the study. FRAME is used to establish the overall fire-risk profile of the cathedral and to identify critical scenarios, while FDS is used to examine the physical consequences of chosen scenarios in greater detail. This sequential combination allows the research to move from a broad risk assessment to a scenario-based performance evaluation. The results of the FDS simulations then provide a scientific basis for assessing possible design decisions.

Hence, in this paper, a Tailor-made approach between preservation and modern safety requirements is adopted for the carpentry of the OL Cathedral of Tournai. Specific scenarios of natural ventilation and electrical cabinet compartmentalization are analysed to protect the building and its occupants while respecting its heritage value. An understanding of the fire risk modelling at the cathedral is essential to propose solutions to mitigate it. The cathedral's carpentry is the main heart of this fire analysis as many fires in patrimonial buildings broke out in its attic or roof. This analysis is necessary to evaluate if the OL Cathedral of Tournai is protected against a potential risk of fire outbreak.

3. Materials and methods

This research aims to contribute to understanding the behaviour of heritage structures in the event of a fire. Studying fire behaviour in such an environment requires exposing the structure to an irreversible hazard to obtain extrapolated empirical data. However, such an approach is both unsafe for individuals and potentially destructive to the building itself. Therefore, computer simulation serves as a valuable alternative, providing crucial information for evaluating safety levels [16].

3.1. FRAME method

The Fire Risk Assessment Method for Engineering (FRAME), developed by Erik De Smet [17], is the chosen method applied here to quantify the risk of fire inside the study case. The FRAME approach is an empirical, systematic method specifically designed for engineering applications to evaluate new or existing buildings in terms of fire risk, considering both severity and probability [18]. Based on the Gretener method, it analyses and classifies the fire risk by calculating three parameters (potential risk, acceptable risk, and detection degree) to have the total risk of each premise for property, occupants, and activities of the studied building.

3.2. Pyrosim & FDS

PYROSIM (version 2023.1 employed) is a Graphical User Interface (GUI), used to represent the characteristics of the study building and specifications of the fire. PyroSim enables the creation of building drawings and fire models for input into the Fire Dynamic Simulator (FDS) engine. The software enables users to create 3D fire scenario models and simulate fire spread by considering various variables, such as the type of fuel burned, the material composition, the material density. This enables users to simulate realistic fire design scenarios and take preventive measures to improve the safety of buildings, people, and their activities.

Then, FDS (version 6.7.9 used) is a powerful software developed by the National Institute of Standards and Technology (NIST). It calculates the dynamics of smoke and fire propagation by solving numerically a form of Navier-Stokes equations in a large eddy simulation for low-speed thermally driven flow. It analyses Computational Fluid Dynamics (CFD) flow around or through solids and investigates heat exchange, mixing, and turbulence inside the flow [19]. It provides time-based results simulation that can be visualized on the graphical post-processor Smokeview.

4. Numerical simulation

4.1. Brief description of the building

The Tournai OL Cathedral is a prestigious and important construction in Belgium, and the only Belgian Cathedral entirely classified as a UNESCO World Heritage site since 2000 [20], which combines Gothic and Roman architectural styles [21]. It is divided into four large parts erected at different times (Figure 1). At the entrance, we welcome the narthex (recent restoration). Then, the Roman nave (the oldest part of the four) is arranged on two floors and spreads out 48 m in length, 25 m in width, and 26 m in height. Then we approach the next part, which is the Roman transept (14 m x 67 m x 50 m), built at the same time as the nave but underwent renovations. It supports 5 towers, one of which is central. Next comes the Gothic choir, one of the vulnerable parts of the cathedral, where the framework of this study is located. This is the most impressive part of the whole building, with its stained-glass windows, its multiple chapels, its mural painting, and its access to the treasure (pictures, decorations, etc).

In the 2025 version of the gothic carpentry, various electrical devices, including an electrical cabinet and electrical lighting, are installed in the roof. The old carpentry is characterized by a network of dry oak timber beams (with average cross-sectional dimensions of 225 mm x 225 mm), a dusty environment. Inside, there are about twenty smoke detector devices, and several fire doors are present. The whole cathedral is not modelled because the Gothic carpentry is compartmentalized from the rest of the cathedral. There is only a small grid connection (1000 mm x 300 mm) linking the Gothic carpentry with the carpentry of the main tower. Thus, we modelled the carpentry (50 m x 12 m x 17 m) and a volume extension to roughly represent the carpentry area of the main tower (in order to know the temperature of flue gases entering this premise). The size of the window is 1600 mm x 600 mm, which is about 3000 mm high from the ground. The modelled carpentry is relatively consistent with reality (location of electrical cabinet, oak beam dimensions, windows positioning, indoor geometry, and volume) but is somewhat simplified (geometry layout and some unknown attic details). The whole roof has been modelled considering the beam shapes available in literature and confirmed by a visit of the site. The 3D model of the Gothic carpenter's interior is shown in Figure 2.

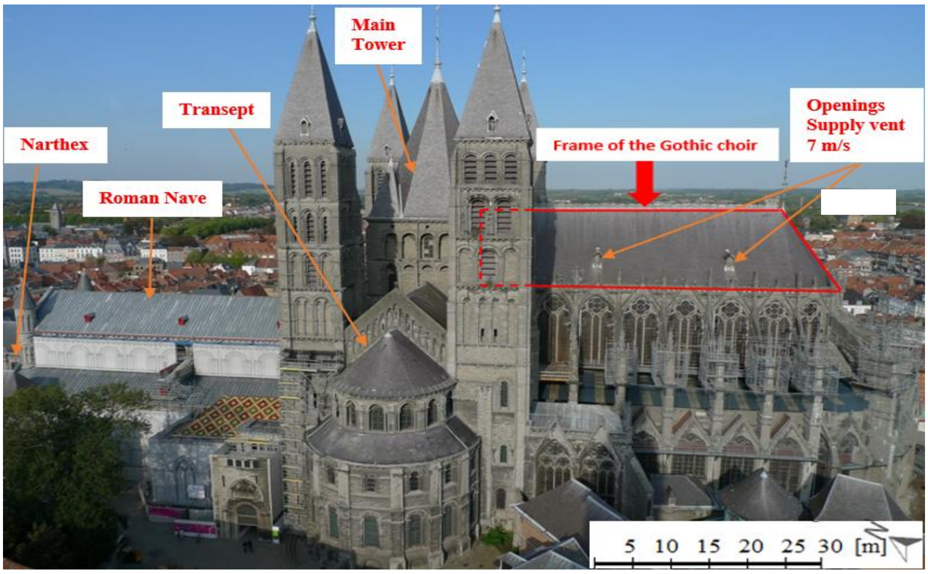


Figure 1: Side view of the Gothic carpentry case study and the rest of the Our-Lady Tournai cathedral

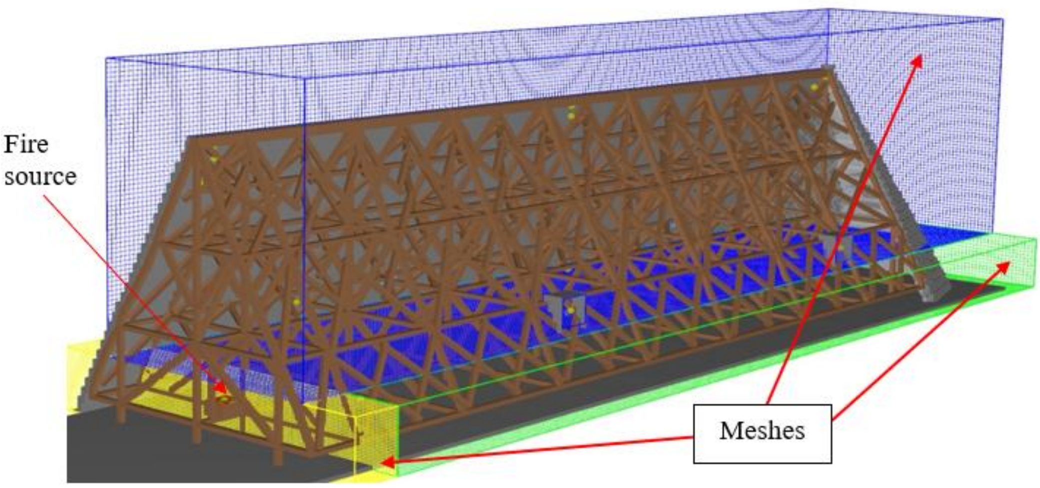


Figure 2: Isometric indoor of the oak timber structure of the gothic carpentry

4.2. Fire specification and designed simulation

The fire fuel source is the electrical cabinet present inside the studied premise, mainly comprised of PVC, PMMA, and PE. Its average chemical composition is $CH_{1.65}O_{0.1}$, and the PMMA properties input are assumed (see Table 1) [22]. Located at 1.5 m from the ground, the fire burner source area is a square section of 1 m² to represent a realistic fire outbreak of an electric panel, given its dimensions (medium enclosure with a volume less than 1 m^3). During the simulation, the peak HRR (Heat Release Rate) value of 1300 kW is used to represent the fire source from an electrical cabinet (fast fire) in a huge oak wood-based carpentry [22] **[23] [8]**. The lead element above the roof has been neglected. Moreover, the considered radiative fraction is 0.35.

In reality, the fire needs some time to obtain the peak HRR, depending on the fire growth coefficient α following a quadratic fire growth (HRR= αt^2). However, since we wanted to compare the fire behaviour at its fully developed critical state, i.e. its peak HRR, 1300 kW was directly reached (i.e. one second after the fire ignition), considering an instantaneous fire. This peak HRR remained constant during the simulation period of 1200 seconds. According to existing data, the average response time of the fire brigade, including departure, travel, and setup in the event of a fire is approximately 12 minutes in Belgium [24]. For the simulations, an additional margin of 8 minutes is considered to account for potential delays, ensuring a more comprehensive assessment of fire dynamics and risks after the performed simulation.

Before running the simulation, the optimal mesh configuration is chosen by a compromise between efficiency and time consumption. It depends on the structure geometry dimensions (the computational domain), the fire model parameter (HRR), and the ambient air properties **[25]**. The dynamic pressure of 750 Pa is calculated from Eurocode 1, EN 1991-1-4. The mesh grid comprises cubes of 10 cm side near the fire (yellow mesh in Figure 2) and cubes of 20 cm side far away from the fire (blue and green meshes in Figure 2). It corresponds to a "medium" criterion, leading to a total mesh of 1,480,820 cells in the model.

Table 1: Oak wood beam and electrical cabinet input properties

Material	Oak timber **[26]** Carpentry structure	PMMA + PVC + PE Electrical cabinet [22]	Calcium Silicate Fireproof panel
Chemical formula encoded	$CH_{1.7}O_{0.72}N_{0.001}$	$CH_{1.65}O_{0.1}$	$CaSiO_4$
Density [kg/m^3]	540	1200	720
Thermal conductivity [$W/(m.K)$]	0.17	0.2	0.12
Heat capacity [$J/(Kg.K)$]	2400	1260	1.25 – 1.55
Emissivity	0.9	0.9	0.83
Calorific combustion heat [kJ/kg]	17900	27400	/
Longitudinal section size m^2	0.225*0.225	1*1	1*1
CO yield (kg/kg)	/	0.01	/
Soot yield (kg/kg)	/	0.022	/

4.3. Studied scenarios

In heritage buildings, fire growth must be prevented with compliance to architectural preservation. In general, fire growth can be controlled through three primary methods: compartmentalization, smoke extraction management, and active fire suppression [12]. Active fire suppression includes sprinkler system, but it has not been studied in this work as when activated, it may cause water damage and affects the carpentry preservation. That is why only two scenarios that involve the use of the two first methods separately are analysed in order to identify which non-invasive fire prevention design could be suitable to deal with a potential fire outbreak. Therefore, in this work, we analyse the fire behaviour in: (1) the carpentry with closed windows (scenario 1) for investigating the current configuration; (2) the naturally ventilated carpentry allowing fresh air entering the roof through windows (scenario 2) for investigating the ventilation contribution, and (3) the compartmented electrical panel with a CaSiO4 fireproof cabinet of 1200 mm x 1000 mm x 2000 mm dimensions (scenario 3) for investigating the effect of compartmentalization. Using the Kawagoe law [27], the theoretical mass flow rate of fresh air (T=20°C) entering the windows (1.6 m x 0.6 m) in the ventilated scenario is 0.63 kg/s.

5. Results and discussion

5.1. FRAME method

The results of the FRAME method applied to the Gothic carpentry of the O-L Cathedral of Tournai are illustrated in Figure 3. For a premise to be adequately protected, the risk values should not exceed the threshold of 1. However, the figure reveals that estimated risk values for activities, occupants such as workers present during control periods, and the building's contents exceed this threshold. This can be attributed to the patrimonial and historical significance of the structure, which is classified as a UNESCO heritage site. Inflammable dry wood carpentry, electrical installation, and dust are considered as the main fire risk factors. The calculated values represent a scenario in which a fire destroys the building and its contents, causing casualties.

FRAME values were assessed based on visits of the Cathedral, observations made and information collected from discussions with two architects of the Cathedral. All calculations of the FRAME process [17] were encoded in an Excel file that allow to compute intermediate values of potential risks, acceptable risks and protection degree, and the final values of risks for goods, occupants and activities. These computed risks were particularly high principally because of the big volume of the premise without inside compartmentalization, the huge flammable wood quantity inside with an important calorific weigh, and the difficult access for fire brigade (very narrow hallway and a tall building). The FRAME method results for Gothic carpentry indeed reveal that the safety of the building, its activities, and its occupants is insufficiently guaranteed. Then, find relevant fire protection is necessary. To address this, fire scenarios within the Gothic choir are thoroughly examined using numerical simulations whose results are presented in following sections.

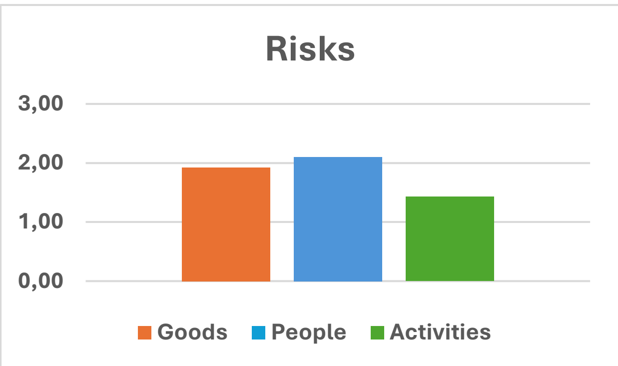
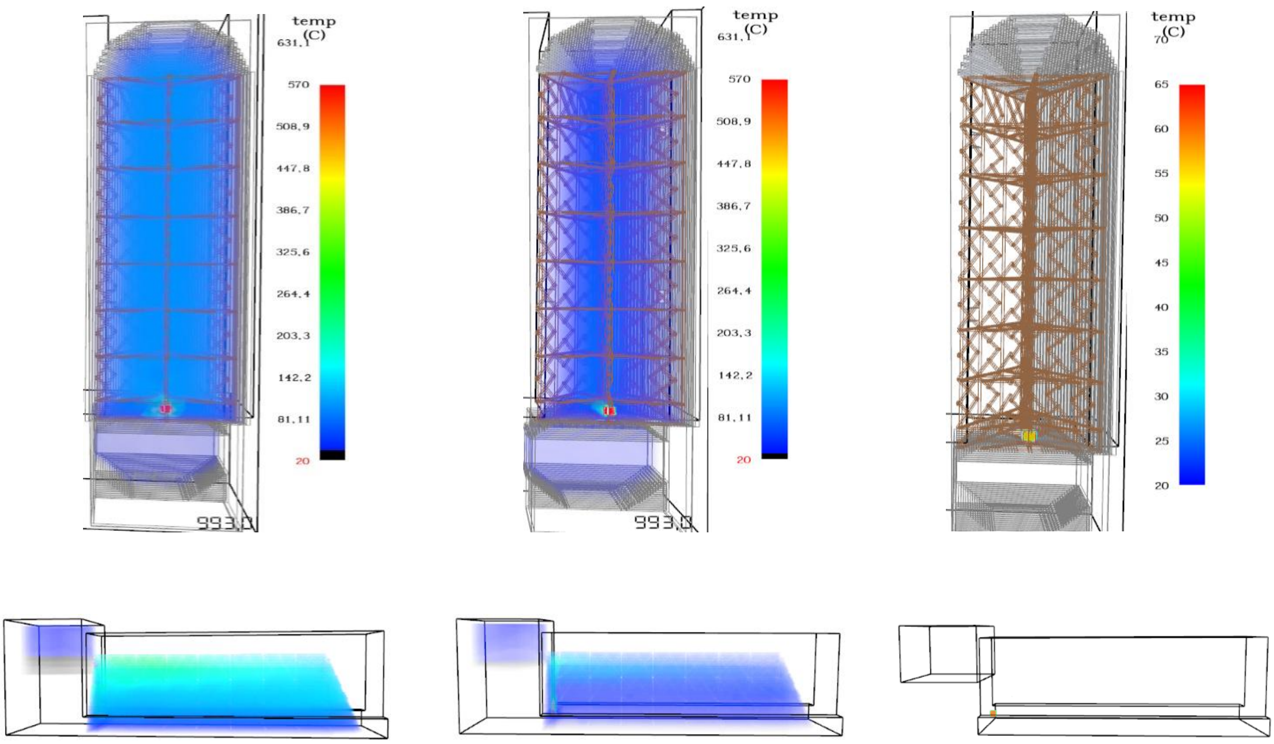


Figure 3: Fire Risk calculation for the Carpentry of the OL Cathedral of Tournai

5.2. Temperature distribution results

Figures 4 and 5 respectively illustrate the bottom view of the smoke temperature and the wall temperature distribution fields at 993 seconds for the three scenarios. During all the 1200 seconds in scenario 2, the amount of hot smoke and heat decreases compared to scenario 1. In scenario 3, the heat does not spread outside the fireproof cabinet throughout the entire simulation. Indeed, the fire remained fully contained within the fireproof enclosure throughout the entire simulation.

The maximal 98% percentile of the wall temperature reached 570°C in scenario 1, 270°C in scenario 2, and 119.5°C in scenario 3. Some research ([8], [28], [29]) indicates that the auto-ignition temperature of the oak wood is about 380°C, depending on the external heat flux and wood dimensions. This highlights that the isolated carpentry will continue enriching the fire, faster than the ventilated carpentry, which could lead to a flashover after additional simulation time [30]. This isolated structure cannot withstand a fire originating from the electrical cabinet until firefighters arrive and deploy equipment within 20 minutes. After 1200 s, sufficient oxygen remains in the frames to sustain the flames. This could explain why ventilation in scenario 2 does not significantly increase the flame temperature compared to scenario 1, as the latter is not oxygen-starved and already has sufficient oxygen to sustain combustion.



Scenario 1 **Scenario 2** **Scenario 3**

Figure 4: Spatial smoke temperature in the carpentry at t = 993 s for the three scenarios

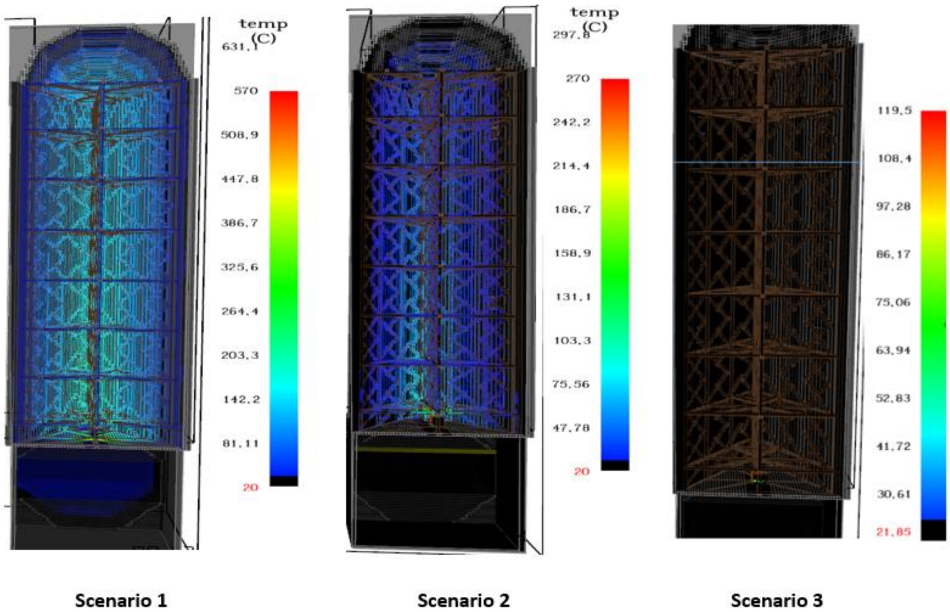


Figure 5: Wall temperature distribution at 993 s for the three scenarios

5.3. Temperature profiles results

The temperatures of the smoke layer and the wall have been calculated for the three scenarios at different strategic locations by positioning several thermocouples inside the carpentry (see Figure 6): around the fire source, at the grid connection between the gothic carpentry and the main tower carpentry, at the ceiling, at some random positions and at the windows vent for the ventilated scenario. In this section, we examine some of these profiles in more detail to compare the three scenarios. Figure 7 represents the temperature rises above the fire source, at 1 m up the fire source, at the ceiling up the fire source, at the middle ceiling, at man's height, and at the grid connection between the carpentry and the main tower.

From these profiles, it can be observed that, at certain points, the temperature in scenario 2 initially exceeds that in scenario 1. However, by the end of the 1200-second period, the temperature in scenario 1 surpasses that in scenarios 2 and 3. Overall, temperatures in scenario 2 reach a relatively steady state, whereas in scenario 1, they continue to rise. This suggests that the ventilated scenario allows for a more controlled fire compared to the non-ventilated scenario. The increasing temperature in the confined carpentry (scenario 1) indicates that sufficient oxygen is present to sustain and enhance the fire. In scenario 3, the temperature inside the compartment rapidly reaches its peak before progressively decreasing over time, likely due to oxygen depletion. Additionally, the temperature outside the compartment remains at 20°C, indicating that the heat is effectively encapsulated within the fireproof panel.

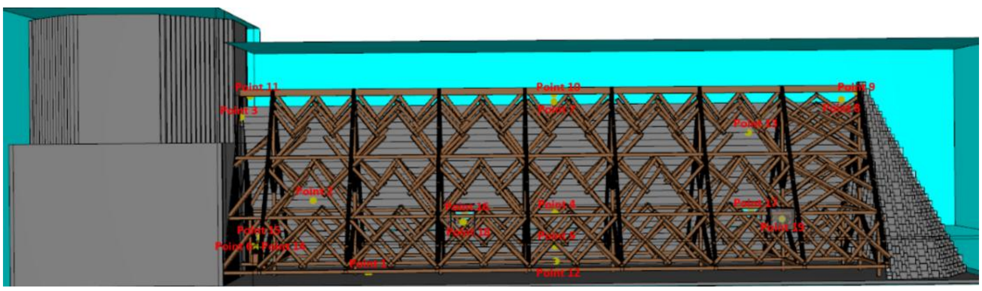
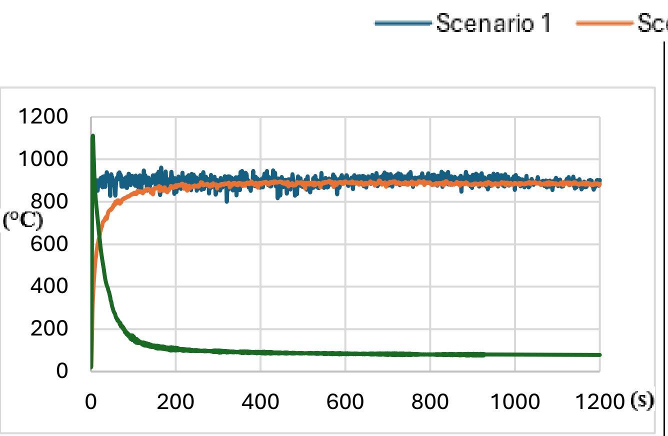
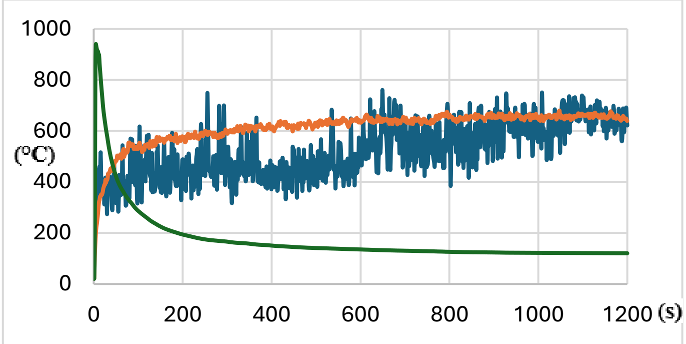


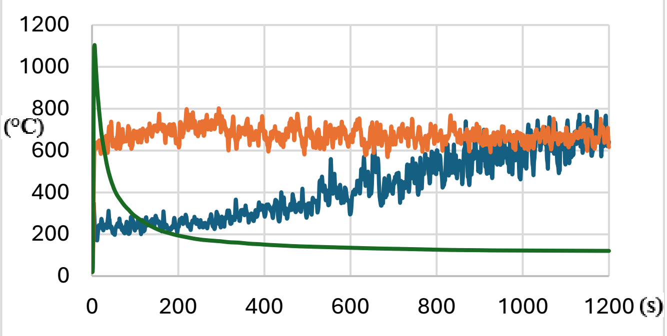
Figure 6: Positioning of thermal devices and thermocouple points



Temperature just above the fire source
[Point 6]



Smoke temperature around the fire source
[Point 14]



Temperature at 1m up the fire source
[Point 1964
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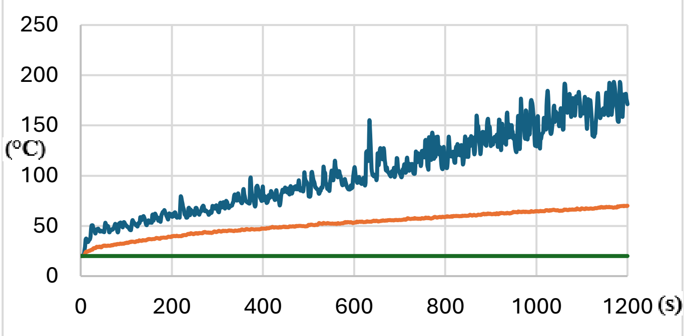
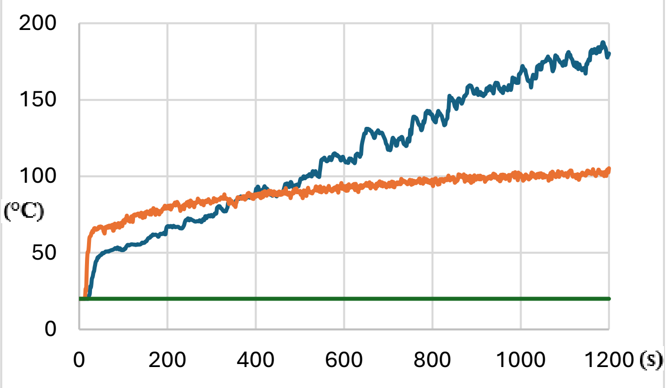
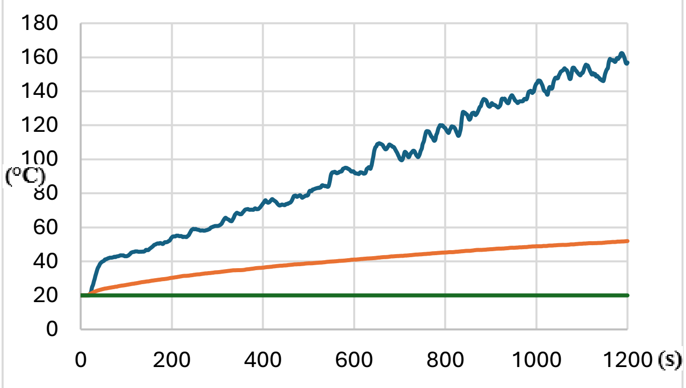


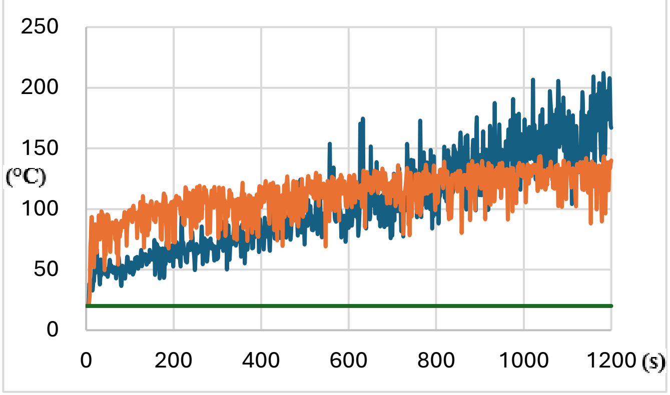
Wall temperature at the ceiling up the fire source
[Point 11]



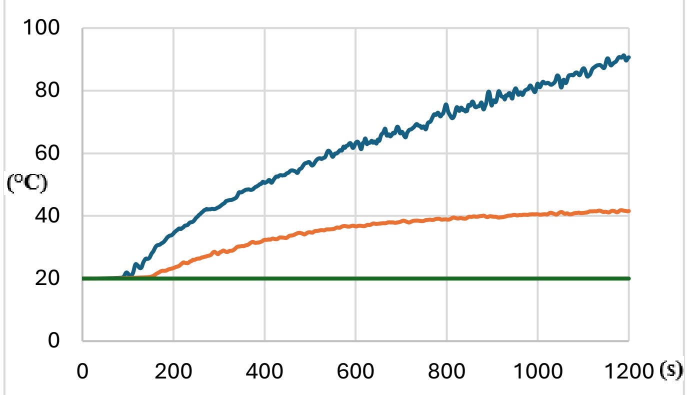
Smoke temperature at the middle ceiling
[Point 7]



Timber wall temperature at the middle ceiling
[Point 10]



Smoke temperature entering the carpentry of the tower [Point 3]



Temperature at man's height (1.8 m from the ground) [Point 5]

Figure 7: Temperature evolution at different locations in the Gothic carpentry

5.4. Discussions

The numerical results should be interpreted not only as temperature-field comparisons, but also as guidance for fire safety design. Scenario 1, representing the current isolated configuration, shows a continuous increase in smoke and wall temperatures, indicating that the existing carpentry does not provide sufficient passive control of a fire originating from the electrical cabinet. The predicted thermal exposure of the timber elements suggests a risk of ignition, charring, and rapid fire spread if no additional protection measures are implemented.

Scenario 2 indicates that natural ventilation through the windows reduces hot gas accumulation and lowers wall and smoke temperatures compared with the isolated configuration. This strategy is relatively non-invasive and therefore compatible with heritage conservation principles. However, its effectiveness depends on opening size, airflow conditions, wind effects, and activation timing. Thus, natural ventilation should be considered a complementary smoke and heat management strategy rather than a standalone fire safety measure.

Scenario 3, involving compartmentation of the electrical cabinet, provides the most effective reduction of fire spread. By confining the fire source within a fire-resistant enclosure (minimum intervention), the thermal impact on the surrounding timber structure and smoke propagation into the carpentry are strongly limited. This approach is particularly relevant for heritage conservation because it targets the hazardous element locally, without requiring extensive modification of the historic timber.

Overall, the results support a conservation sensitive fire safety strategy based on localized, reversible, and minimally invasive interventions. Priority should be given to reducing ignition probability through maintenance and monitoring of electrical systems, isolating or relocating hazardous technical equipment, and integrating smoke management measures, compatible with the heritage value of the building. The FDS results therefore provide a performance-based basis for selecting fire safety measures that are technically effective, and respectful of the cultural significance of the Gothic carpentry.

6. General discussion

Detecting a fire quickly is both fundamental and essential; while extinguishing it is decisive to ensure safety. Thierry Burger said in his conference (2020) [31] that fire prevention systems in religious heritage must be strengthened. That is why this paper investigates target protection strategies: the natural ventilation and the compartmentation to enhance fire safety level of the Gothic choir. One key finding of this study is the cooling effect of natural ventilation, as evidenced by the lower temperatures observed in Scenario 2 after some time compared to Scenario 1. The introduction of fresh air through the windows reduced both the wall temperature and the concentration of hot gases in the carpentry. Consequently, by lowering the temperature of the smoke emitted from the burning structure, the risks associated with intoxication and heated surfaces are mitigated, allowing for extended evacuation time and improved visibility. Kumar et al. [32] also supported this affirmation by showing the great contribution of smoke extractors in heritage temples. The temperature of the flame is comparable throughout the simulation time in both scenarios 1 and 2. The entered fresh air in scenario 2 seems not to further enrich the fire due to the indoor cooling and the outflow of hot flue gases through openings. The fire within this scenario is therefore controlled by the combustible instead of the comburant.

Fire safety in the carpentry could be reinforced by compartmentalizing the electrical cabinet. Rather than encasing it within a fireproof panel, relocating the cabinet to a more open area could be a better alternative. Venegas Vásconez et al. (2021) [7] summarized a range of fundamental fire safety measures from the literature aimed at protecting heritage buildings. The preservation of these sites necessitates continuous maintenance, as stated in Article 4 of the Venice Charter (1964), to ensure their structural integrity. In buildings such as the Cathedral, routine inspections and maintenance of essential equipment, including electrical systems and fire detectors, are crucial in identifying potential risks. Additionally, selecting an appropriate fire extinguishing system based on the building materials, conducting in-depth investigations in accordance with established guidelines, and implementing effective management policies are among the recommended preventive actions to mitigate fire-related damages. In parallel, integrating safety equipment that ensures a reasonable level of fire protection is vital. Many heritage sites, including Saint Patrick’s Cathedral (New York City, USA), Bristol Old Vic (Bristol, UK), and Teylers Museum (Haarlem, The Netherlands), have implemented water mist extinguishing systems. Furthermore, a smoke extraction system could be beneficial in regulating smoke levels. This can be achieved by installing an automatic window-opening system, that activates when at least one smoke detector is triggered.

Although the numerical model provides a detailed representation of fire and smoke development within the studied space, several modelling assumptions must be acknowledged when interpreting the simulation results. These assumptions were introduced to reduce computational complexity and to focus the analysis on the most relevant fire-safety indicators, including temperature distribution, smoke propagation, visibility conditions, and the potential exposure of the timber roof structure. However, they may influence the predicted evolution of the fire scenario and therefore require critical discussion.

First, the initial growth phase was not explicitly modelled. Instead, the fire was introduced according to a predefined heat release rate or design-fire condition. This assumption allows the simulation to focus on the fully developed, the critical phase of fire, which is generally the most relevant stage for evaluating smoke movement, thermal exposure, and potential fire spread. Nevertheless, neglecting the incipient growth phase may affect the predicted timeline of hazardous conditions. In particular, the time required for smoke accumulation, temperature increase, and visibility reduction may be shortened compared with a real fire that develops gradually from ignition. As a consequence, the simulation should not be interpreted as an exact reconstruction of ignition-to-growth behaviour, but rather as a conservative assessment of the consequences once a significant fire has developed.

Second, the geometry of the building was simplified in order to obtain a computationally manageable model. Minor architectural details, small decorative elements, local irregularities, and some secondary structural components were not represented explicitly. Such simplifications may influence local airflow patterns, smoke stratification, and heat transfer in specific areas. However, the main spatial configuration, roof volume, openings, and principal structural elements were retained because they govern the global behaviour of smoke and heat propagation. Therefore, while the model may not reproduce all local phenomena with complete precision, it remains suitable for assessing the overall fire dynamics and identifying critical zones within the studied volume.

Finally, it is important to note that, in all three scenarios, the porosity of the carpentry was not considered. However, during the site visit, natural porosity in the slate roof was observed. Since the objective of this study was to compare the impact of two fire protection strategies, the influence of porosity was excluded from the analysis. The results obtained are based on computer simulations.

7. Conclusion

This study investigated fire-protection strategies for the Gothic carpentry of the Our Lady Cathedral of Tournai, a UNESCO-listed heritage structure in Belgium. The research was positioned at the intersection of fire-safety engineering and architectural conservation, using performance-based numerical simulation to support conservation-compatible design decisions. The objectives were to analyse the development of a fire originating from the electrical cabinet, assess the influence of natural ventilation on fire behaviour, and evaluate mitigation strategies that could improve fire safety while preserving the patrimonial value of the structure.

The results show that the current isolated configuration of the carpentry is not sufficient to control a fire outbreak from the electrical cabinet until the arrival and deployment of the fire brigade. Natural ventilation through the windows can reduce heat and smoke accumulation, but its effectiveness depends on airflow conditions, opening configuration, and ambient parameters. Compartmentation of the electrical cabinet using calcium-silicate fireproof panels provides a more effective and localized means of limiting fire and smoke propagation. This solution is particularly relevant for the case study because it targets the ignition source without requiring extensive alteration of the historic timber structure.

The main scientific contribution of this study is the demonstration of how CFD-based fire simulation can be used as a decision-support tool for heritage fire-safety design. Rather than applying prescriptive fire regulations mechanically, the proposed approach allows different protection scenarios to be compared according to both their technical performance and their compatibility with conservation principles. This is especially important for historic timber roof structures, where fire risk is high, but interventions must remain limited, reversible, and visually discreet.

Beyond the specific case of the Our Lady Cathedral of Tournai, the findings suggest broader design principles for heritage buildings. Fire-safety strategies should first reduce ignition probability through inspection, maintenance, and monitoring of electrical installations. Hazardous technical equipment should then be relocated, isolated, or compartmentalized whenever possible. Smoke and heat management systems may provide additional protection, provided that they can be integrated without compromising the historic fabric. More generally, each intervention should be evaluated according to proportionality, reversibility, visual impact, and compatibility with the architectural and cultural significance of the building.

The study also has limitations. The simulations are based on selected design-fire scenarios, simplified geometry, and specific ventilation conditions. Consequently, the results should not be interpreted as an exact prediction of all possible fire events, but rather as a comparative assessment of the relative effectiveness of different mitigation strategies. Future work should examine the sensitivity of the results to seasonal ventilation conditions, roof porosity, and alternative fire scenarios. Further research should also investigate evacuation conditions for technical staff in case of fire outbreak.

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