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# Notre-Dame de Paris as a validation case to improve fire safety modelling in historic buildings

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ABSTRACT

The analysis of the thermal damages in Notre-Dame de Paris is necessary to estimate the impact of the dramatic 2019 fire on the remaining structure prior to reconstruction. In doing so, the large amount of data being generated creates a benchmark environment to test the relevance of numerical fire models in the unconventional configuration of a medieval roof. While being an uncontrolled and complex configuration, it can provide insights regarding the relevance of numerical tools for fire risk assessment in historic buildings. Analysing the thermal degradation of the Lutetian limestone in a vault of the choir, experimental techniques are developed to track the in-depth maximum temperature profile reached during the fire. Numerical simulations of the fire development in the roof space then aim at replicating the observations through the evaluation of the heat flux impinging the vaults during the fire. These simulations are carried out using Fire Dynamic Simulator, which requires a large range of assumptions prior to any simulation regarding materials, geometry, meshing and scale. These assumptions are described and pave the way to a future sensitivity analysis to confront the upcoming outcomes of the simulations with the experimental observations.


## 1. Introduction

Numerical simulations play an increasingly important role in the assessment of fire safety in modern constructions. With an emphasis on life safety, simulations aimed at evaluating smoke progression [32] or structural integrity [27] in a fire situation inform building designers of the need for relevant protective elements, detection systems and intervention strategies. In modern construction, these simulations are primarily used in pioneering buildings which depart from the standard architectural and engineering practice. Simulations are costly but allow any innovative building to deviate from the prescriptive framework of codes and standards [15,18].

Quite astonishingly, landmark buildings which predate practice codes rarely receive the same attention. Yet, in addition to their non-standard material and geometries, such constructions feature unique fire safety needs since, second to life safety, the protection of specific materials and artefacts held withing that carry cultural, historical or religious value is considered a priority [3]. Their cultural significance is such that unknown potential consequences cannot be tolerated in case of an accident, and prevention has to take into account the worst-case scenarios. Practice codes, however, are ignorant of the specifics of historic buildings, which may lead to fire engineers and curators implementing incomplete, if not completely irrelevant, fire safety solutions [28,31]. Numerical simulation tools, if correctly manipulated, can provide additional insights to assist specialists in their safety designs.

Numerical tools, however, have inherent flaws due to our limited understanding of fire and solid combustion mechanisms, still being investigated at an academic level. While theories can be developed and validated in certain configurations, the universality and scalability of the associated conclusions must be questioned [20]. For instance, zone models, which assume that a burning room can be divided in an upper layer of heated combustible products and a lower layer of cooler fresh reactants, have been successfully established to understand the development of a fire in a compartment through the vertical segregation of specific heat and mass transfer equations [4]. Such models are suitable to understand fire hazard in compartmented buildings, however their relevance is dubious in open-floor areas. With a more holistic approach and

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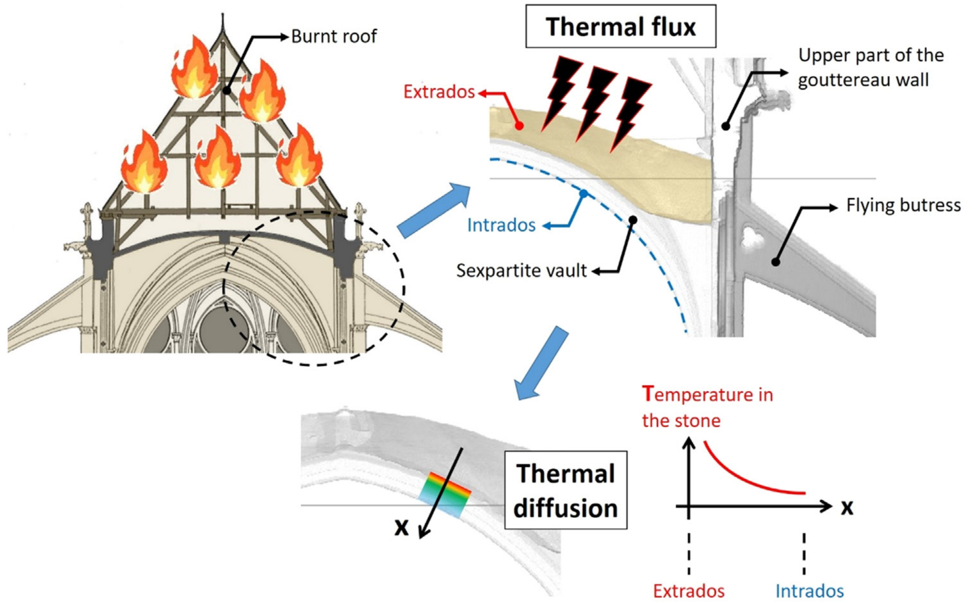



**Fig. 1.** Schematic representation of the objectives of the study: estimation of the thermal flux induced by the fire onto the Choir vaults extrados, based on the prior estimation of the temperature field reached into the stones due to thermal diffusion. In the following, intrados and extrados refer to the inner and outer curve of the vault, respectively.

inspired by the successes of Computational Fluid Dynamics (CFD), numerical solvers like Fire Dynamic Simulator (FDS) [21] or OpenFoam [17] have focussed on the resolution of the equations for compressible, multi-specie and multi-phase systems, with additional modelling for combustion and chemistry effects. Considering local conservation equations, they can be easily scaled up to large configurations of various geometries through the definition of adapted meshing, volume elements, and boundary conditions.

Yet, in the absence of validation on scenarios of relevant scale and configuration, their impact is limited as the associated conclusions are hard to interpret. Ideally, validation is carried out through the design of tailored experiments, featuring a well-documented configuration of controlled complexity and equipped with the adequate diagnostics to compare experimental results with numerical predictions [10]. In the absence of such experiments, the analysis of past fires may provide insights into the capabilities of existing models. In that context, the 2019 fire of Notre-Dame de Paris that torched the roof, the spire and part of the North tower is a tragic but unique situation to improve fire modelling in historic buildings and prevent future disasters. This uncontrolled fire is not an ideal test case, yet an unusual broad range of information is accessible regarding the initial configuration, the fire development and the consequences of the blaze. Surveys had been carried out in the buildings [8] and laser measurements accurately mapped some areas of the historic timber frame. The large number of videos shot by firefighters and pedestrians during the event makes a set of partial but still exploitable evidence to understand the development of the blaze, and the intense scientific analysis that has followed provides in-depth measurements on the impact of the fire.

As questions remain regarding the condition and structural stability of the standing vaults, there is an opportunity to contrast the on-site evaluation of thermal degradation of the Lutetian limestone with predicted damages from numerical simulations. A good correlation could provide confidence in the ability of numerical modelling to capture other crucial aspects of the fire development in medieval timber roofs, which could help design adequate fire protection in similar buildings. So far, simulations have been performed to evaluate the possible location and size of an incipient fire [12], to analyse the effect of the lead-covered roof on the fire growth rate, and to evaluate the water flow required for the fire brigade to successfully quench the flames as they arrived on site [1]. The associated conclusions will be valuable once the degree of confidence in the simulations has been assessed.

The following sections describe the experimental and numerical work being presently carried out. Insight is provided into the methodology being implemented to assess the validity of numerical modelling through the evaluation of thermal damage in a vault of the choir of Notre Dame de Paris, while early experimental measurements are presented. Initial results demonstrating the potential of the methodology are shared. Additional in-depth results are expected to be contrasted in upcoming publications.

## 2. Research aim

The main objective of this study is to bridge the gap between available outputs from numerical simulations of the fire in the gas phase and post-fire temperature assessment in the vaults (Fig. 1). Both are related through the modelling of the evolution of temperature in the Lutetian limestone, which can be simply carried out by coupling a description of the configuration and material properties of a given vault with a heat flux evaluation from the fire.

The study focuses in particular on one of the vaults of the Choir, referenced CH15–18 on the system set up by the architects in charge of the Cathedral's restoration (Fig. 2).

This thin vault (12 to 15 cm web thickness) is a point of particular interest because it was not directly impacted by the fall of flaming elements of the spire or of the wooden beams of the roof structure. In addition, firefighters could hardly access this area, so it can be hypothesized that the fire burnt freely. Locally, the fire development can be decomposed in two sequences: the fire develops on the standing structure first, and then, after the failure of the charred oak trusses, the fire burns the collapsed structural elements scattered over the vault. Considering the heat received by the vaults, these two phases are fundamentally different. As the fire burns intensely in the attic, heat is mostly transferred through radiation. However, when the burning timber elements lay on the vaults, diffusion becomes a major heat transfer mode.

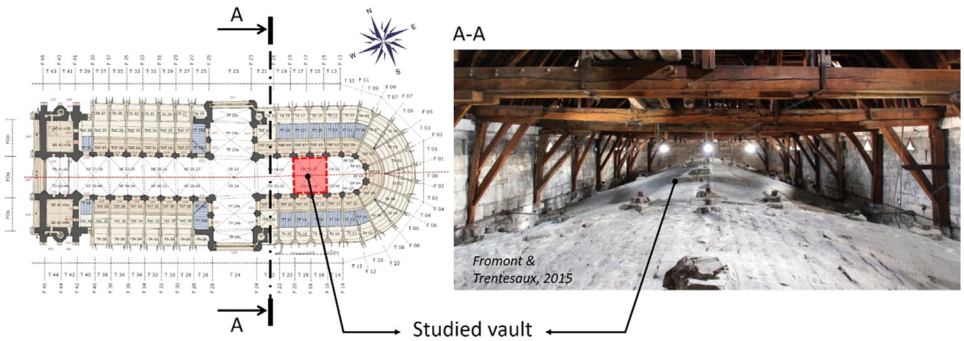



**Fig. 2.** On the left, plan view of the Cathedral with the studied Choir vault in red [30]. On the right, picture of the Choir vaults seen from above (extrados) before the fire, according to [9].

Following the fire, the question of the preservation of the vaults naturally arises and requires a precise structural diagnosis. This vault presents alterations on the extrados (spalling and cracks in the stone, [30]) and degraded areas on the intrados. In addition, the comparison (carried out by the BESTREMA engineering office) of point clouds taken before and after the fire shows significant deformations (deflection of 4 cm and uplift of 2 cm in different parts of the vault), which may indicate a modification of the overall equilibrium condition of the vault. Finally, a ground-penetrating radar monitoring from the extrados seems to indicate zones of discontinuity (cracks, delamination).

In addition to assessing the validity of numerical tools, it is essential to estimate the impact of the fire on the vault at two scales of observation for the restoration of the Cathedral:

- At the material level: it is necessary to know the residual state of the stones, as this will determine whether they can be preserved as they are, or whether repair or replacement solutions can be considered.
- At the structural level: the fire has impacted the mechanical behaviour of the vaults for three reasons: (i) during the fire, a nonlinear differential thermal expansion across the thickness of the vaults is observed (the extrados, which is warmer, expands more than the intrados, which is cooler), which can lead to thermomechanical damage around the extrados; (ii) the geometrical distortions observed after the fire indicate a new state of equilibrium has been reached as a result of thermally and impact- induced displacements of the stones in the vault; and (iii) a deterioration of the mechanical properties (stiffness and resistance) following the diffusion of heat in the thickness of the vault. These aspects need to be taken into account in studies that aim to calculate the load-bearing capacity of vaults after fire. A study by a consortium of research teams is underway at the time of writing [23].

## 3. Material and methods

### 3.1. Experimental material and methods

The methodology developed is based on the study of the physiochemical transformations in limestone that are induced by temperature. The main transformations and the associated temperature levels are described. before the experimental techniques envisaged in connection with these transformations are presented. The section concludes with results from the materials studied, focusing on the use of colorimetric analysis.

#### 3.1.1. Effects of heating on limestone

The methodology is based on existing works that focus on post-fire observation of limestone rocks, either after exposure to real fires or to laboratory heating [7,13,14,24,26,29]. Limestone rocks present a rather distinct and reproducible behaviour under temperature increase, due to mechanical and chemical transformations. The following phenomena are highlighted:

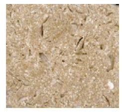
- Transformation of iron oxides (if present) in temperatures varying between 250 and 300 °C. Goethite is then transformed into haematite, according to the reaction 2 $FeO(OH) \rightarrow Fe_2O_3 + H_2O$. This reaction leads to rubefaction of the stone, i.e. a coloration tending to pink/red tones.
- Transformation of quartz (if present). At precisely 573 °C, the quartz-$\alpha$ is transformed into quartz-$\beta$. This transformation is reversible with temperature and is accompanied by a sudden swelling of the crystal.
- Decarbonation of calcite according to the reaction $CaCO_3 \rightarrow CaO + CO_2$, occurring depending on the type of limestone for temperatures generally above 600 °C.
- After sufficient heating to trigger decarbonation, the possible transformation of lime into portlandite according to the reaction $CaO + H_2O \rightarrow Ca(OH)_2$. This reaction implies the presence of water in the immediate environment of the rock, which was probable in the case of the cathedral stones.

These transformations are mostly irreversible and their occurrence can be observed by various analytical techniques. Therefore, they can serve as benchmarks for estimating the temperature reached by the material. A set of evaluation principles to distinguish between the above mechanical and chemical transformation and to link them with temperature levels has been developed by Montier [22] on the basis of an experimental campaign carried out on laboratory-heated limestone samples.

#### 3.1.2. Laboratory-tested materials

The preliminary laboratory study was carried out on two limestone sources. First, limestone samples from the Saint-Maximin quarry (Northern France), supplied by “Rocamat” company, were studied. According to a comparative study commissioned by the French Laboratory for Research of Historical Monuments (LRMH), this limestone has mechanical and petrographic characteristics similar to the Notre Dame stones. For this preliminary study, 3 types of limestone were selected, namely “liais”, “franche construction” and “franche fine”. Some properties of these stones are given in Table 1. Prismatic samples of dimensions 5 × 5 × 2 cm were studied. Secondly, limestone samples taken from the Cathedral, provided by the LRMH, were tested. These samples came from one of the vaults of the North Transept and were found on the ground, having fallen, probably due to the impact of the collapsed roof on the vault. It is assumed that these samples were not heated during the fire (the samples were taken from the intrados of the voussoirs). Some properties of the samples coming from the same

**Table 1**
Some estimated properties of the limestone samples analysed during the preliminary study. Data coming from Rocamat company and [5,29] **1**: Some estimated properties of the limestone samples analysed during the preliminary study. Data coming from Rocamat company and [5,29].

| Laboratory-tested materials | | | Bulk density ($kg.m^{-3}$) | Porosity (%) | Compressive strength ($MPa$) | Ultrasonic wave speed (m/s) |
|---|---|---|---|---|---|---|
| **Saint-Maximin "ROCAMAT" quarry (France)** | **"Liais"** |  | 2100 - 2300 | 15 - 25 | 30 - 60 | *No measurement* |
| | **"Franche construction"** |  | 1900 - 2100 | 25 - 35 | 10 - 20 | 3671 ± 133 |
| | **"Franche fine"** |  | 1700 - 2000 | 25 - 35 | 9 - 12 | 2971 ± 124 |
| **Cathedral (North Transept)** | |  | 1500 - 1960 | 26 - 43 | 4.5 - 19.3 | 2040 - 3290 |

Cathedral area were measured by LRMH [5], and complemented by in-situ ultrasonic measurements. These properties are given in Table 1. Cylindrical samples with a diameter of about 3 cm and a thickness of about 1 cm were studied.

The samples were subjected to a controlled heating in a laboratory furnace, to temperatures up to 20, 100, 200, 250, 300, 400, 500, 600 and 700 °C, at a rate of 5 °C/min. The temperature of 250 °C was chosen in order to study the rubefaction of the stone. The heating rate is deliberately low compared to the kinetics of a real fire, in order to limit the thermomechanical damage of samples. After a stabilization period of 3 h, the samples are cooled naturally in the furnace.

### *3.1.3. Experimental techniques*

Different experimental techniques have been used to observe the physiochemical transformations described in Section 3.1.1.

- Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DCS): these combined techniques make it possible to identify the physiochemical transformations that have a strong impact on the mass loss and the heat release (exothermic) or absorbtion (endothermic). This technique proved to be particularly interesting for detecting the decarbonation of samples, and then estimating whether they had been heated up to 600 °C or not. In addition, this technique allowed to identify the decomposition of portlandite in samples previously heated to more than 600 °C, and cooled in ambient temperature through several days.
- Scanning Electron Microscope (SEM): the observation of the microstructure of limestone subjected to different levels of heating made it possible to identify the temperature level at which micro-cracks appear. These appeared primarily after heating to 600 °C and were probably caused by the swelling of the quartz grains.
- RAMAN technique: this technique made it possible to identify the transformation of iron oxides (goethite => haematite) on samples heated up to 300 °C.
- Measurement of thermal properties: this technique showed a linear decrease of the thermal diffusivity of the studied limestone with increasing temperature (20% loss at 800 °C).

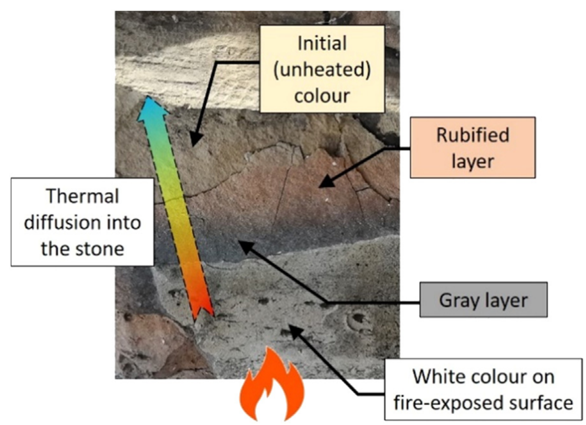



**Fig. 3.** Colour changes in a stone of the cathedral that has been strongly exposed to fire. As the stone has spalled under the effect of fire, the colour change of the limestone though its depth (i.e. parallel to the direction of the heat diffusion) can be observed.

- Colorimetry: this technique is based on the fact that the physiochemical transformations described above modify the colorimetric properties of the material. This behaviour is particularly interesting since these colour changes are irreversible with temperature. This is illustrated in *Fig. 3*, which shows the gradient of colour within a fired stone in Notre-Dame: the limestone keeps its initial colour in non-heated zone, turns to red/pink colour when the temperature is around 250 to 300 °C, turns to grey around 400 to 500 °C then finally turns to white when limestone starts decarbonating (temperature higher than 600 to 700 °C).

Colorimetry proved to be the simplest of the experimental methods. It does not require complex measuring equipment and has shown good repeatability of results. Unlike the study of thermal properties, it does not require calibrated sample geometries. Moreover, its field of application covers a particularly interesting temperature range (100–600 °C) compared to the probable level reached in the vault stones. Other techniques, in particular TGA,

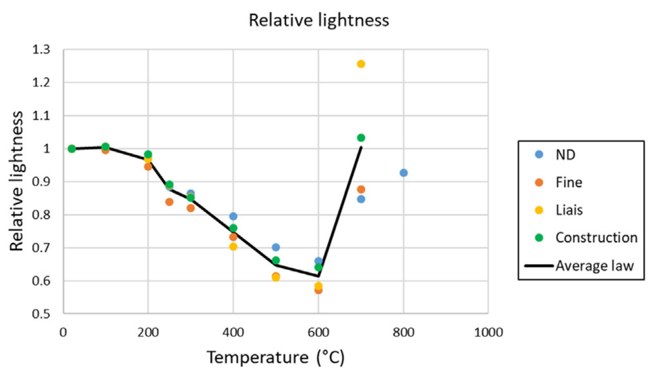



**Fig. 4.** Temperature evolution of the relative lightness for the four studied limestones.

SEM and RAMAN, can locally confirm the temperature reached in the stones.

*3.1.4. Focus on the colorimetric analysis*

In order to quantify the effect of temperature on the colorimetric properties of the limestone, high-resolution scans of the samples were studied by *ImageJ*, an image analysis software [25]. From the colorimetric data obtained in the RGB domain, several parameters calculated in other colorimetric domains were calculated, and their evolution with temperature was analysed. From this study, it appears that the "lightness" parameter is the one whose evolution with temperature is the most linear and monotonic. Lightness, or L*, is a coordinate of the "CIELAB" space that evaluates the perception of the luminous aspect of a studied colour [2]. The lightness is a real value, ranging from 0 (black) to 100 (white). An internal tool in the software converts the scan into CIELAB space and calculates the lightness value of each pixel of an area of interest. This area of interest is defined by the user in such a way as to be free from edge effects of the scan, and large enough to collect the maximum amount of information. The average lightness of the area of interest is then calculated and related to the temperature reached by the sample. Three samples for each type of limestone were tested.

In order to avoid potential lighting variation between scans, the effect of the temperature on the colorimetric properties is studied in a relative way. Thus, we define the relative lightness as the ratio between the lightness obtained at a given temperature level and the one obtained on the unheated sample. Fig. 4 shows on the same graph the variation of the relative lightness with temperature for the four types of limestone. The relative lightness is calculated from the average luminosities (3 samples for each type of limestone). Three phases can be identified on the graphs: (i) No variation of the colorimetric properties between 20 and 100 °C; (ii) a linear decrease up to 600 °C indicating a darkening of the colours (with an acceleration around 250 °C, attributable to the rubefaction of the limestone); and (iii) a new increase in lightness after 600 °C linked to the bleaching of the stone (decarbonation, formation of lime).

In order to estimate the temperature field reached in the Cathedral stones, a monotonic evolution of the relative lightness as a function of temperature is necessary. Thus, we reduce the curve presented in Fig. 4 to the temperature interval 100 - 600 °C, defining the application range of the methodology. Fig. 5 shows the evolution of the average relative lightness of the 4 types of limestone, taking as a reference the lightness obtained for temperatures below 100 °C. In other words, a luminosity of 1 is equivalent to a temperature between 20 and 100 °C. A linear regression is performed on the interval 100 - 600 °C in order to define the relative lightness/temperature law that will be applied on samples coming from the Cathedral's vault.

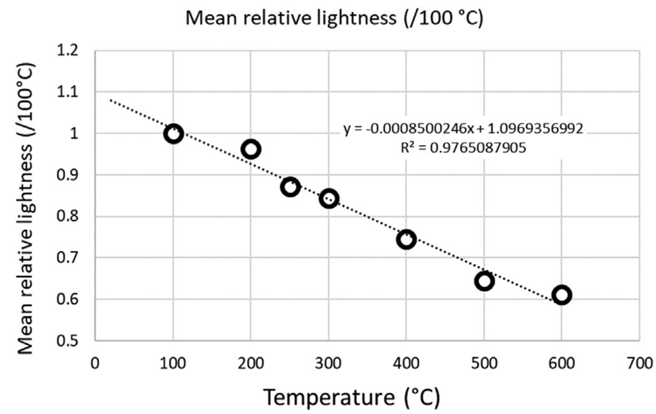



**Fig. 5.** Evolution of the average relative lightness as a function of temperature for the four types of limestone. For the calculation of the relative lightness, the reference value is that obtained at 100 °C.

*3.2. Numerical methods*

In the course of the fire, the extrados of the vaults are exposed to a net heat flux $\dot{q}''_{net}$ which drives the thermal diffusion in the stone. At present, two methods allow a quantitative assessment of this flux: (I) starting from the experimentally reconstructed temperatures within the vault, a backward method is devised to find candidate profiles of time-dependant heat fluxes which could lead to the reported degradation; and (ii) using the available numerical data about the roof structure prior to the fire, a forward CFD model can be built to extract the boundary conditions regarding heat flux at the extrados.

This evaluation of $\dot{q}''_{net}$ is critical to support the development of credible fire scenarios in timber roof structure, as described in Fig. 6.

This prospective article will pave the way to further in-depth developments carrying out an estimation of the net heat flux through the assessment of the mean thermal exposure, defined as the heat flux at the vault surface integrated through the duration of the fire. As numerical simulations have not reached completion at the time of publication, the use of integrated quantities circumvents the issue of comparing two time-dependant heat fluxes computed from systems with inherently different timelines.

*3.2.1. Heat flux based on temperature profiles*

First, the heat flux can be estimated by focusing on the solid phase. Using the experimental assessment of temperatures in the stone, a value of the mean thermal exposure can be prescribed as a boundary condition in a problem of uniaxial thermal diffusion to retrieve a reasonable incoming heat flux which could result in the observed temperature evolution.

Thermal simulations are performed on the finite element code Cast3M (http://www-cast3m.cea.fr/), based on a simplified 2D geometry of the thickness of a vault. The thermal properties of the tested stone, and their respective evolution with temperature, were measured by a hot plane method. For the simulations, as the properties of "franche fine" stone were used, as this stone has a porosity and density very close to that found in the vaults of the Cathedral. The same thermal properties are applied to each drilled core (see Section 4.1) in this first approach.

For a given location, a time-varying net heat flux is then applied on the extrados and a random 1000 draws of the parameters governing the heat flow history are performed. At the end of the random draws, the data set that best approximates the temperature profile estimated by colorimetry is selected. On the intrados, a mixed convection and radiation boundary condition is applied,

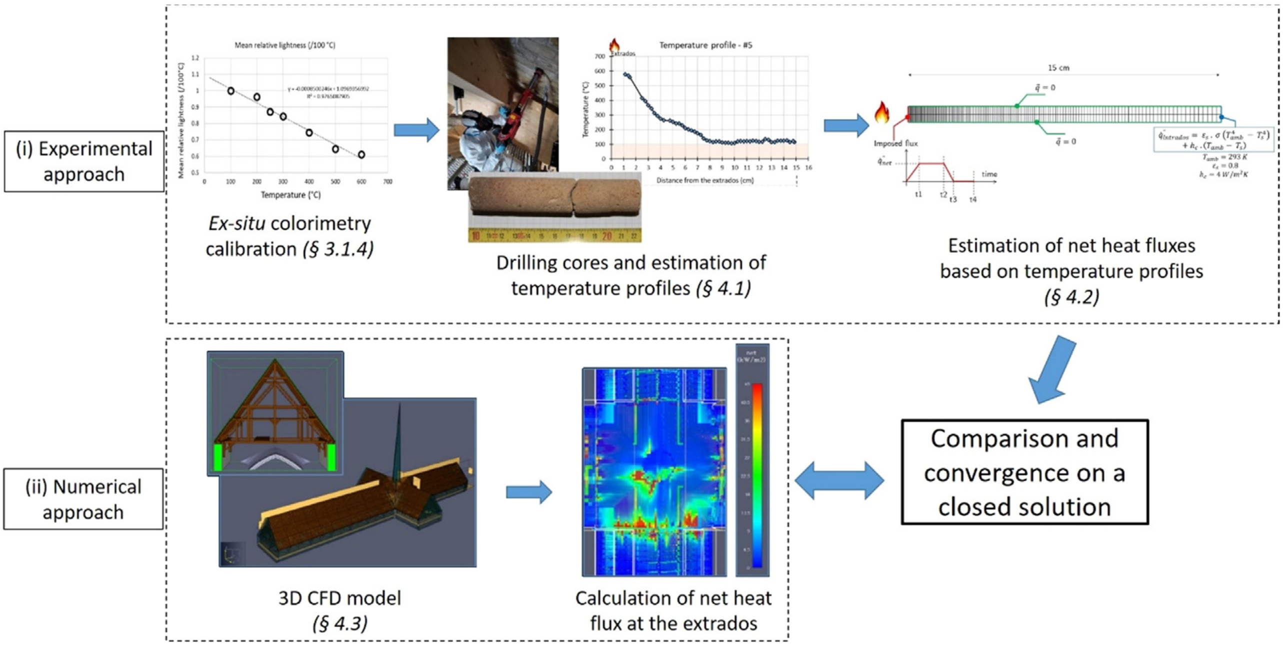



**Fig. 6.** Relation between experimental and numerical approaches based on the estimation of the net heat flux at the extrados.

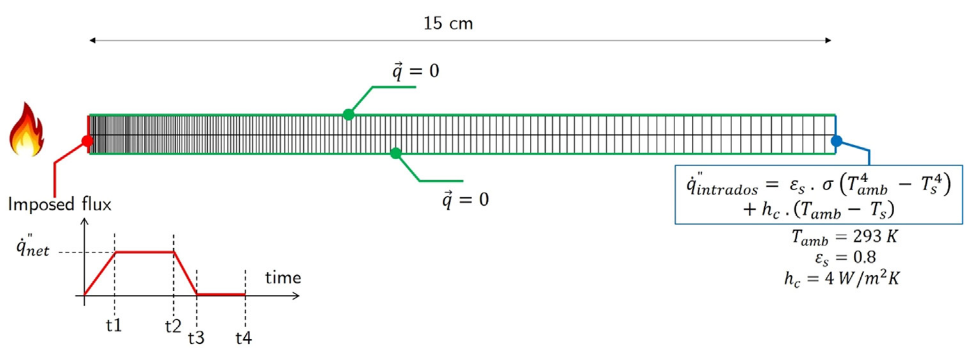



**Fig. 7.** 2D finite element mesh for estimating the net heat flux q ̇net^". 1000 random set of imposed flux parameters are tested (t1 = 20 min ± 10 min; t2 - t1 = 3 *h* ± 2 h; t3 - t2 = 2 *h* ± 1.5 h; t4 – t3 = 1 h; q ̇net^" = 10 kW/m² ± 8 kW/m²).

considering the temperature in the Cathedral enclosure as constant and equal to 20 °C. The mesh used and the boundary conditions are summarized in Fig. 7.

*3.2.2. Heat flux based on the fire model*

Second, the same net heat flux at the surface of the vaults can also be expressed from the gas phase properties as follows:

$$\dot{q}''_{net} = \epsilon_s \left(\dot{q}''_{rad} - \sigma\ T_s^4\right) + h(T_{gas} - T_s) \quad (1)$$

Where $\dot{q}''_{net}$ is the sum of the radiative and convective heat flux, where $\epsilon_s$ is the surface emissivity, $\dot{q}''_{rad}$ the incident radiative heat flux obtained at the boundary of the domain, $T_s$ the surface temperature of the vaults, $h$ the associated coefficient and $T_{gas}$ the gas temperature in the vicinity of the surface.

$\dot{q}''_{rad}$ and $T_{gas}$ can be extracted from fire simulations in the gas phase and $T_s$ is initially assumed to be constant and equal to an ambient temperature of 297 K in the initial heat flux estimation.

$T_s$ and $\dot{q}''_{net}$ are is then iteratively corrected from the resulting temperature profile (Section 4.1) and estimation of the heat fluxes in the vault (Section 4.2) to converge on a closed solution. Numerical simulations are then designed to evaluate the evolution of $\dot{q}''_{rad}$ and $T_{gas}$ with time through the fire.

Simulations have been developed using FDS, which resolves low-speed Navier-Stokes equations adapted to thermally driven flow with an emphasis on smoke and heat transport from fires. FDS solves transport and chemistry equations at each timestep in the gas phase and treats the decomposition of solid fuels as a uni-directional heat transfer problem. The heat feedback to the solid surface sustains the production of reactive species as a boundary condition in the gas phase. Given the dimensions of Notre-Dame, large eddy simulation (LES) is implemented to resolve the flow field over the large-scales and model the smaller scale mechanisms to reduce computational time.

FDS does not solve mechanical constraints in the solid phase and as such ignores the possible collapse of the roof. As a consequence, two distinct scenarios must be developed in the context of heat flux measurement.

The radiation transport equation is solved using a finite volume method for a grey gas, where the local absorption coefficients for Mie scattering are retrieved from the RadCal narrow band model [11]. The overall radiative fraction is prescribed from experimental measurements to limit the errors arising from the LES approximation [19]. This optically thick approach captures at a first order the preheating of the roof under the influence of the hot smoke, consistent with observations by the firefighters.

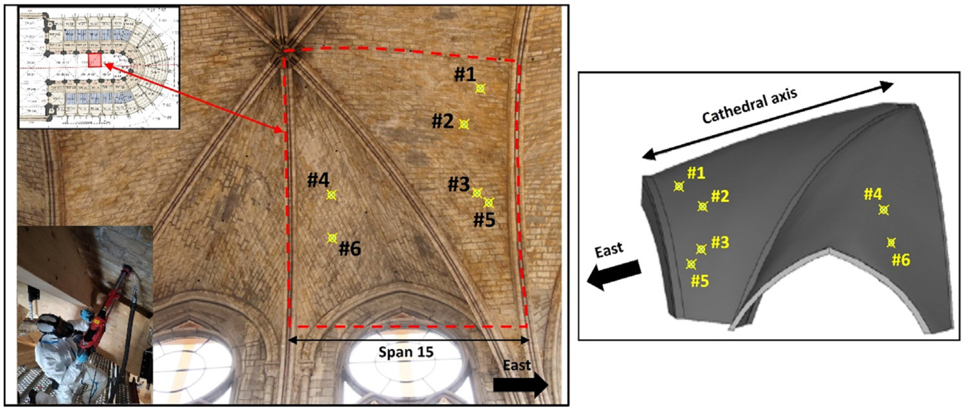



**Fig. 8.** On the left, view from below (intrados) of the localization of the samples drilled in the ‘CH15’ Choir vault. On the right, 3D view from above (only a quarter of the vault’s extrados is modelled here) of the localization of the drilled cores.

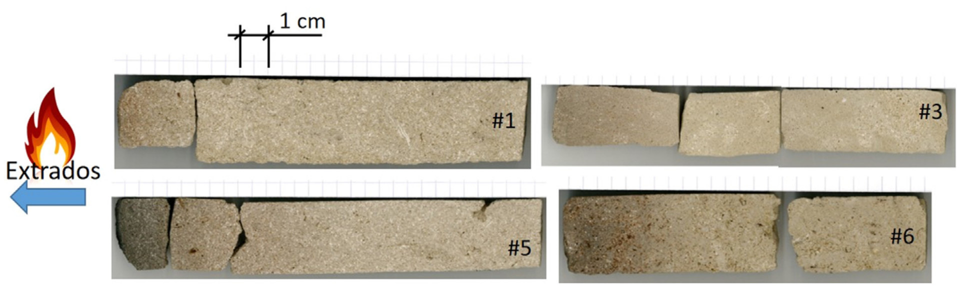



**Fig. 9.** Pictures of the drilled cores after cutting.

## 4. Results

### *4.1. Estimation of temperature in the Choir vault*

Four cores were taken from the ’CH 15′ span of one of the Choir vaults, as shown in *Fig. 8*. The samples were taken by core sampling (under water) from the intrados of the vault on 22 July 2021. Cores of around 30 mm in diameter were obtained.

In order to obtain flat surfaces for the scans required for colour analysis, the four cores were cut lengthwise with a diamond saw (under water). Fig. 9 shows the resulting core surfaces. As expected, a colour gradient is observed in the direction parallel to the thermal diffusion.

Each core surface was then scanned and analysed in the same way as in the preliminary study (Section 3.1.4), allowing the temperature profile reached in each core to be estimated. Fig. 10 shows the mean temperature profile obtained for cores #3 and #5. For each core, a statistical analysis of the colorimetry data has then been carried out in order to estimate a range of reached temperature.

In their heated part (temperatures higher than 100 °C), the temperature profiles are consistent with "physical" temperature profiles induced by thermal diffusion, tending to validate the methodology developed. The temperature range reached in the heated part of the stones is sufficient to cause irreversible degradation of the mechanical properties of the stone [29].

The temperature levels estimated by colorimetry are confirmed by additional punctual analyses. In particular, the transformation of iron oxides (estimated around 250 - 300 °C), the possible presence of portlandite in the zones heated to more than 600 °C (decomposition of portlandite around 450 °C) and the presence of microcracking (around 600 °C) are analysed respectively by RAMAN, TGA and SEM techniques.

### *4.2. Expected thermal exposure from stone temperature fields*

Fig. 11 shows the net heat fluxes inputs used in the thermal simulations that provide temperature distributions in line with the experimental temperature profiles estimated by colorimetry, based on a high and low profile for each drilled core. Except for the high estimated profile of core 6, the heat fluxes are in the range of 3 to 6 kW/m$^2$, with a full power phase lasting between one and two hours. The higher estimation for core 6 required a higher heat flux (of the order of 10 kW/m$^2$), over a shorter time.

The mean thermal exposure of the vaults is estimated from the results presented in Fig. 11, by integrating the area under the time-evolution curves of the net heat fluxes. It is found that the mean exposure is 40 MJ/m$^2$, with a standard deviation of 10 MJ/m$^2$. This value should be compared to the heat flux estimated from numerical analyses.

### *4.3. Numerical model of the vault*

The numerical model developed of the studied vault to estimate the mean thermal exposure requires inputs in terms of geometry, material properties, chemistry, boundary conditions, meshing and initial conditions.

The geometry of the model is extracted from a numerical database developed by the ‘Numerical Data’ working group of the French CNRS/Ministry of Culture *Chantier Scientifique Notre Dame de Paris*. The numerical model focuses on the roof space and the spire, where the fire primarily developed, and ignores the lower part of the cathedral as well as the towers. Hence, properties of the complex timber frame, the roof, and the upper part of the vaults as a boundary condition must be captured.

Combining surveys and laser measurements, a model of the timber frame designed by the Numerical Data working group is

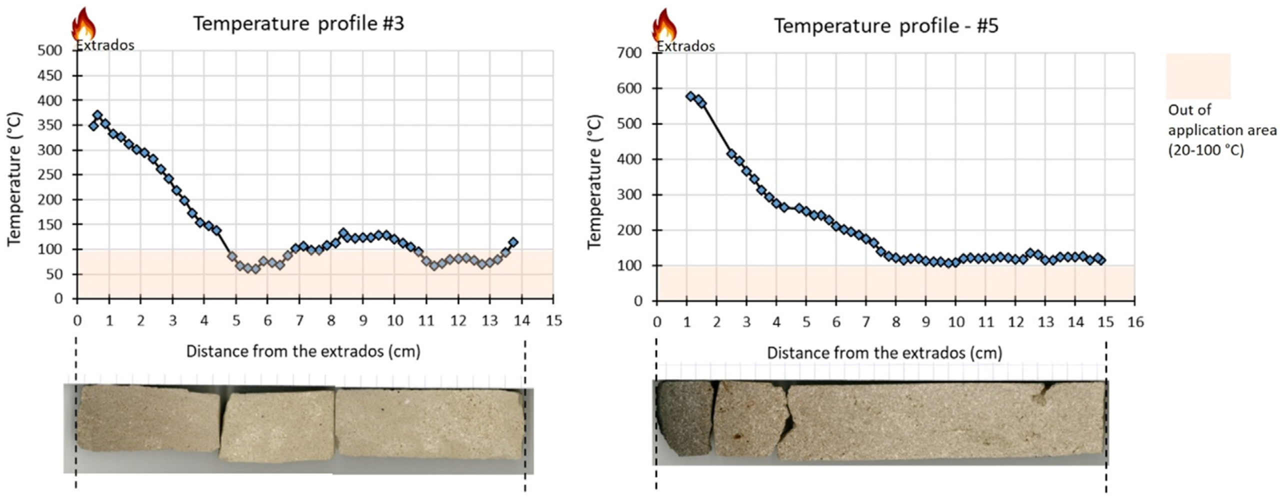



**Fig. 10.** Temperature profiles obtained in #3 and #5 cores.

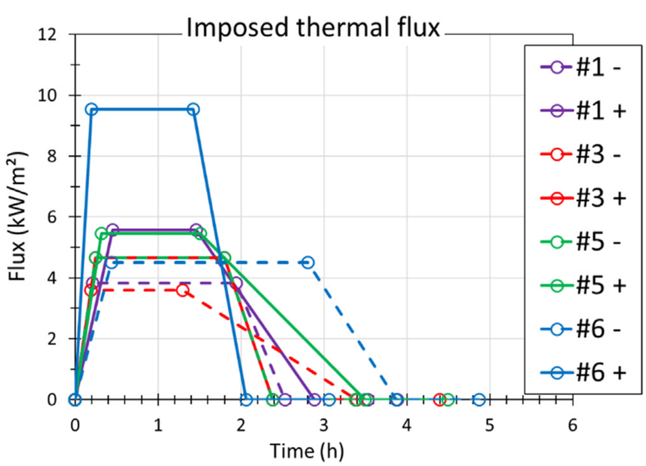



**Fig. 11.** Net heat fluxes estimated based on temperature profiles. For each drilled core (#), a high (+) and low range (-) are calculated.

**Table 2**
Key material properties used in the simulations.

| | Timber | Lead |
|---|---|---|
| Density (kg/m$^3$) | 570 | 1130 |
| Specific heat (kJ/kg/K) | 1.3 | 0.13 |
| Conductivity (W/m/K) | 0.2 | 35 |
| Pyrolysis enthalpy (kJ/kg) | 430 | 23 |
| Heat of combustion (MJ/kg) | 14.5 | – |

imported in a 3D modelling software. The roof is then added, approximated by a 30 mm thick layer of battens [6] topped by 5 mm thick lead tiles, while the surface of the vaults exposed to the fire is approached by spherical caps laid over point clouds collected from the numerical database, as illustrated in Fig. 12. Material properties are recalled in Table 2.

To simplify the chemistry, timber is first assumed to decompose into a product of stoichiometry $CH_{1.7}O_{0.74}N_{0.002}$ [16], which reacts with oxygen from the atmosphere to produce a majority of carbon dioxide, water vapour and nitrogen, with a fraction of soot and carbon monoxide. FDS does not inherently support the fusion of lead. To bypass this issue and still capture the opening of the roof, the fusion of lead. is approximated by a one-step endothermic reaction, taking place at a temperature of 600 K and characterised by the associated latent heat of fusion.

A key boundary condition in this configuration, the vaults are assumed to make up an inert isothermal surface at a set temperature. In the course of the fire, the temperature increases and so do radiative losses from the surface, hence the net heat flux to the surface is overestimated in the first iteration. As the surface temperature is iteratively updated, this method successfully allows decoupling of the solid and gas phase problems.

Simulating the evolution of the fire over the whole roof of the cathedral would be extremely costly from a computational perspective. In the present context, the simulation can focus on a section of the choir where the fire actively participates in the heat transfer to the vault of interest. A 10m-long section centred over the investigated vault is chosen, with a width of 14 m corresponding to that of the roof and a height of 20 m to avoid constraining the flames escaping through the melted roof, as illustrated in Fig. 9.

32 cores are used for parallel computing to optimize computational time, using Open MPI to manage the architecture on. To prevent the development of instabilities in the evaluation of the strongly buoyant flow, a 10 cm uniform rectilinear grid is used. Each core is then handling about 90,000 cells, which allows hours-long simulations to be performed in a matter of weeks.

To initiate the fire, an 1MW ignitor is prescribed under the roof, near the boundary of the studied volume. This ignitor is kept on through the simulation to mimic the effect of the burning roof in the vicinity of the control domain.

The simulation of the fire burning on the collapsed roof requires modification of the geometry of the problem. The distribution of the collapsed trusses can be extrapolated from photogrammetry measurements performed the day after the fire. Featuring limited flame height, the fire burning over the collapsed geometry can be investigated over a reduced volume, but the evaluation of the diffusive heat flux at the surface of the vaults requires a finer meshing, which needs to be carefully monitored.

At each step of the creation of this model, assumptions are made that affect the final heat transfer output. Looking at the configuration, a layer of plaster of unknown variable thickness covered the vaults as evidenced by video footages and sampling [9]. Assumptions will have to be made regarding the properties of this layer to model its impact on heat transfer. The numerical simulation also integrates a range of approximations to resolve sub-grid

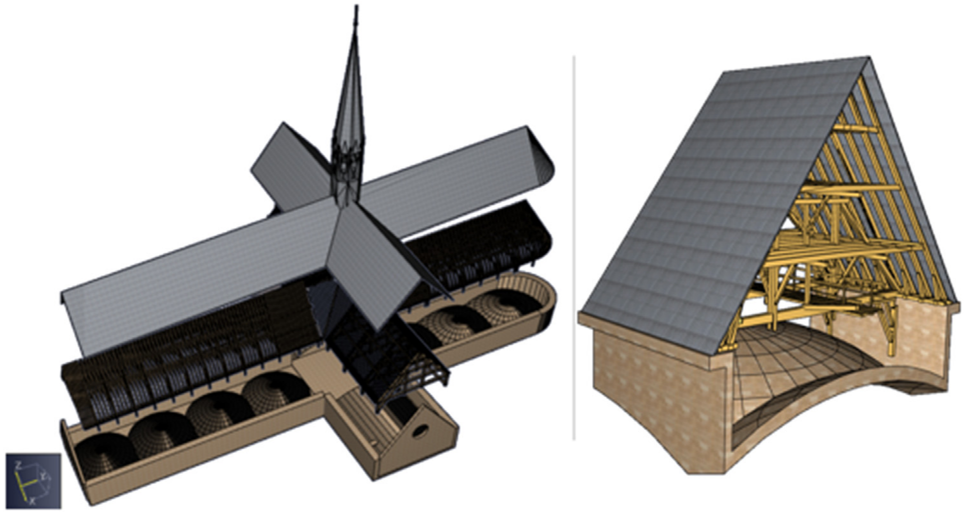


**Fig. 12.** Numerical model of the section of interest. The heat flux is expressed as a boundary condition on the vaults.

mechanisms absorbed by the LES low-pass filter, which incorporate constants usually extrapolated from small-scale experiments. For instance, if has been noticed that in large scale fires comparable to the situation of Notre Dame, the integrated radiative coefficient used for regularization of the local radiative losses should be increased. The outcome of this validation scenario will consequently have to be carefully weighed against the associated uncertainties through a systematic evaluation of the major hypotheses.

### *4.4. Expected thermal exposure from CFD*

In this prospective paper, hand calculations only are performed to evaluate the mean thermal exposure from the scale of the expected fire.

First, the total volume of combustible elements $V_c$ is estimated as the sum of the volume of the timber structure, which can be extracted from the digital model of the Numerical Data working group, and of the volume of the continuous layer of battens over the pitched roof. The pitched roof is approximated as a cross structure combining a 100 m long nave with a width of 14 m, and a 48 m long transept with a width of 16 m, both with an overall pitch angle of 55°. This leads to a volume of battens of about $100m^3$, to be added to the $585m^3$ of structural timber. Since dry oak is the dominant wood, a density $d$ of 0.75 and a heat of combustion $\Delta H_c$ of 15 MJ/kg are adopted. Two factors lower the overall heat released: (i) in this open configuration with significant heat losses, the efficiency of the combustion processes is limited; and (ii) part of the structure did not fully burn, as charred elements littered the vaults the day after the fire. Accounting for both, an efficiency $\epsilon$ of 0.5 is adopted. This results in an overall energy release $E = V_c \times d \times \ \Delta H_c \times \epsilon = 3900GJ$ which is then dissipated through convection, conduction and radiation. As long as the structure stands, which corresponds to the moment where the fire intensity peaked, it can be assumed that heat was mostly conveyed to the vaults far beneath the flames through radiation. Given that the zone of interest was not directly impacted by falling burning debris, the second phase of the fire should have had a limited impact on the unidirectional heat transfer in the stone. In this context, radiations account for approximatively 30% of the total heat release, and considering isotropic radiative heat release, a maximum view factor of 0.2 for a source term at the centre and mid-height of the roof space is adopted. This results in a total thermal exposure of the roof of 234GJ, and a mean thermal exposure of 120 $MJ/m^2$.

### *4.5. Comparison*

The 120 $MJ/m^2$ prediction from the CFD model is three times as large as the 40 $MJ/m^2$ mean thermal exposure extracted from the solid sample model. Finding similar orders of magnitude motivates additional modelling efforts to obtain refined CFD calculations and contrast not only the integrated results but also the time-dependant heat fluxes. It is worth noticing that the probable presence of the plaster layer over the vaults at the beginning of the fire will partially shield the stone vaults from the heat [9]. This means that the CFD model is expected to deliver a higher heat flux on the extrados that the solid model takes in.

Feeding further reflexion, if some of the underlying assumptions for the CFD model such as the amount of timber and the heat of combustion are straightforward inputs, others like the total radiant fraction and view factor will be analysed as outputs of the simulations to identify where the difference between these mean thermal exposures comes from and restrict the expected shielding effect of the plaster layer.

## 5. Conclusion

Despite the complex geometry and the broad uncertainties, the fire of Notre-Dame de Paris must be considered to improve the present state of fire protection in historic buildings. To that end, this article describes a combined experimental and numerical methodology to assess the relevance of simulation tools to assist fire engineers and curators. This initial analysis focuses on the thermal degradation recorded in a vault over the choir which has not been deeply affected by the collapse of the spire or by the actions of the firefighters. The in-depth temperature profile can be estimated experimentally through selected crossed-experiments and numerically through the evaluation of the heat flux from the fire. Beyond the quantification of the fire damage in the cathedral, contrasting the profiles and assessing the associated uncertainties helps understand the relevance of fire modelling in heritage sites.

In the field of heritage building preservation, the proposed methodology can be adapted to other cases of fire in masonry structures provided that (i) a good assessment of the in-situ material is done and (ii) the geometry of the structure is precisely known to be meshed in a CFD/fire model. The first point may be low-cost if one uses, amongst other techniques, the colorimetry method: all is needed is access to virgin material (taken in non-heated zones of the structure), and to heat it in laboratory conditions. The image analysis for temperature profiles estimation and the numerical estimation of the net heat fluxes can be done by using open-source software. It is worth noting that depending on the type of stone, colorimetry should be completed by other observations (RAMAN, TGA or SEM for instance). Developing the associated CFD simulation can be of higher cost because it relies on a precise scanning of the structure in order to build the more accurate numerical "twin" of the structure. Nevertheless, it is expected that more and more 3D scanning of major buildings will be available in coming years. This study underlines a concrete use of the data generated in the process, and future sensitivity studies will highlight what level of precision should be implemented. The developed method is applicable to historic buildings in general, even before the occurrence of a fire. Based on estimated heat fluxes, fires occurring in historic buildings can be simulated by CFD models, and prevention measures (sprinkler, water mist, thermal protection…) can then be optimized.

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