MiCHe project
Final report Uniroma1 unit

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Summary

Fire hazard

Introduction

Fire hazard analysis (FHA) is aimed at the definition reliable fire scenarios and fire intensity measures (IMs), and their probability of occurring during a reference time span (e.g. one year or the life-cycle of a considered structure).

Since fire hazard is directly related to the presence of flammable material, as already introduced for earthquakes, it turns out to be influenced by exposure, i.e. intended uses, in that the reference building assumed as target drives the choice of the analysis approach and assumptions on the characteristic fire considered.

As a general consideration, it is important to highlights (also at the hazard analysis step) that, although often the main focus is towards to the direct consequences of fire, the indirect consequences of a fire are even more important. Direct consequences include structural damage and even structural collapse, while indirect consequences are those due to oxygen consumption by the fire that may lead to the asphyxiation of the nearby people (since fire consumes the oxygen in the air, thereby increasing the concentration of deadly carbon monoxide in the atmosphere). In this view, the FHA should be intended to focus on quantify the hazards and risk of fire and its indirect effects on people (Buchannan 2017).

Then, the correct quantification of the fire hazard require a very good understanding of the fire phenomenon. One important aspect is the understanding of the interactions between building, fire and human dynamics, and their role in the fire severity and intensity (Grosshandler 2007). For example, due to onset of suffocation symptoms, people can be forced of opening windows in a close room under fire attack, this can generate a surge in fire intensity due to the additional oxygen entering the room from opened windows. On the other side, humans can react rapidly to fire (Lougheed and Hadjisophocleous 2011) and generate alarms which are able to starts mitigation measures (e.g. manual splinkers' activation) which are able to decrease the fire intensity. All these human-hazard interactions (schematized in Figure 1) are not present in other hazard (e.g. earthquakes).

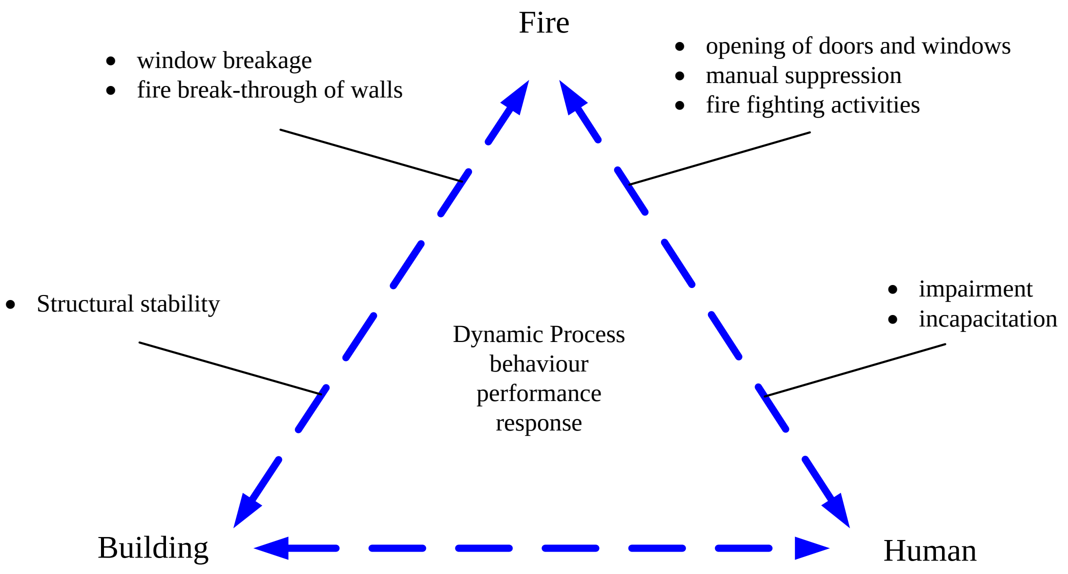


Figure 1: Conceptual view of interaction of dynamic processes (adapted from Grosshandler 2007).

In order to understand basic phenomena involved in fire developments for structural engineering purposes, the general development of the room temperature in a compartment under fire can be described by the Temperature-time (T-t) idealized curve shown in Figure 2.

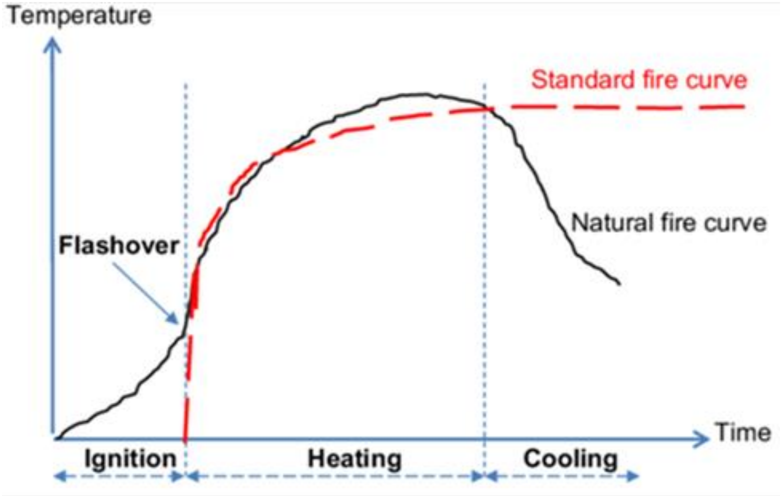


Figure 2: Standard Vs Natural fire curves (adapted from Behnam and Ronagh 2013)

The idealized curve shows that the fire begins with ignition, it is then in the growth phase, where the heat-release rate increases until the fire is fully developed, after sometimes necessary for burning main combustible available, the temperature in the environment starts decreasing (cooling phase) due to the lack of combustible. In a compartment fire (contained environment), the transition from the growth stage to the fully developed stage involves a particular transition stage called flashover. In flashover, surfaces exposed to thermal radiation from fire gases in excess of 600°C reach ignition temperature more or less simultaneously. Fire spreads very rapidly through the compartment, with burning from floor to ceiling. Without an intervention before the flashover point, the fire is rarely (almost impossibly) to be extinguished by firefighters or splinkers. Before the flashover occurs, the fire is called “ventilation-controlled” since it is assumed to be developed in a compartment with sufficient combustible to develop the flashover, and its growing is temporally governed by the availability of oxygen in the department (if oxygen is not sufficient fire decays). From flashover on, fire becomes “fuel-controlled”, meaning that the amount of oxygen needed to sustain the heat-generating chemical reaction with all the combustible material in the compartment. In such cases, the peak temperature and peak heat-release rate is limited by the amount of available combustible material, and the decay stage is typically related to the reduced amount of fuel available for burning. In the same Figure 2, the ISO fire design curve (ISO 1999a,b , EN 1990) is shown; this is the standard T-t curve used in structural design for fire, where pre-flashover and cooling phases are neglected since they are not relevant for the evaluation of the maximum structural resistance to fire action.

In order to better understand the above-mentioned human-fire interaction, we can focus on the time history of a ventilation limited fire (Figure 3). Fire development is taken from NIST (2018, https://www.nist.gov/%3Cfront%3E/fire-dynamics): "*in this case the fire starts in a compartment with doors and windows closed. Early in the fire growth stage there is adequate oxygen to mix with the heated gases, which results in flaming combustion. As the oxygen level within the structure is depleted, the fire decays, the heat release from the fire decreases and as a result the temperature decreases. When a vent is opened, such as when the fire department enters a door, oxygen is introduced. The oxygen mixes with the heated gases in the structure and the energy level begins to increase. This change in ventilation can result in a rapid increase in fire growth potentially leading to a flashover (fully developed compartment fire) condition*".

By relying on the T-t representation, it is natural to identify the peak compartment temperature T_{max} as the suitable IM and the opening factor (also called Ventilation fartor "V") of the compartment (ratio between opening and wall surfaces in the compartment), which leads oxygen enter the room and increasing fire intensity, as an important parameter for IM characterization. Of course other IMs can be chosen (Lange et al. 2014), like fire duration, or rate of increase in the temperature in the compartment). FHA can then focused at the characterization of this IM.

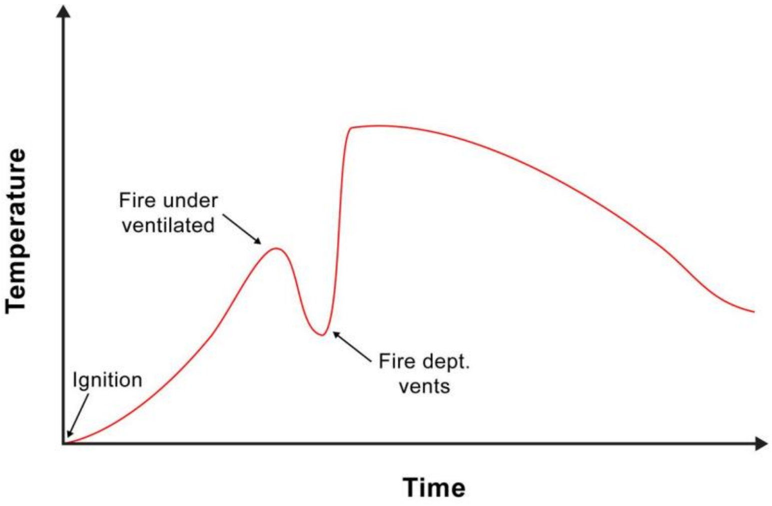


Figure 3. Idealized time-temperature trend for a typical ventilation-controlled fire. After NIST(2018)

As well as the IM of a specific site in a seismic hazard analysis (e.g. the PGA) can be disaggregated in its different sources (identified by the epicentre distance R and the magnitude M), the fire air temperature, assumed as fire hazard IM, can be associated/disaggregated to different combinations of fire combustible loads “q” (expressed in MJ/m^2, and ventilation factor “V”. Is then consequential that the duration of the fire is proportional to q and inversely proportional to V, while fire-induced peak air temperatures (peak of the IM) are proportional to both q and V. Another suitable IM, with characteristics similar to the air temperature, is the Heat Release Rate (HRR), which is expressed in kW and represents the time trend of the thermal energy which is effectively released by the burning combustible during the fire event. As well as the air temperature, the HRR can be effectively disaggregated in different combinations of fire combustible loads “q”, and ventilation factor “V”.

Different approaches to FHA and LPHC events

Different approaches can be followed in fire hazard characterization: deterministic, heuristic/semi-probabilistic (scenario-based), and (not-yet completely developed in literature) fully probabilistic.

Traditionally, the fire design of structures can be conducted in **deterministic** terms, meaning that a single worst-case fire is considered and selected in FHA for each fire compartment in the considered environment, and it is defined on the basis of “expert” judgement.

Real attention to modern this approach for FHA (aiming at establishing some like hood or “occurrence” of different fire severities) started come up on ’90, where the definition of fire “scenario” started to be used in structural design, including room/compartment dimensions, contents, arrangement of room in the structure/building, source of combustion air (windows, doors, etc.), building/structure’s users location. Then a more detailed FHA can be conducted by an **heuristic approach**, meaning that a set of “fire scenarios” are defined by the designer on the basis of the specific features of the problem and a like hood is someway assigned to the scenarios. The following key aspects need to be addressed in heuristic FHA:

- identification of a comprehensive set of possible fire scenarios;
- estimation of probability of occurrence of the scenario;

two above points imply the ranking of fire scenarios by severity and probability, the inquiry of operational constraints and a list of recommended actions to eliminate or control the hazard. The advantage of this approach is that an inventory of possible fire scenarios can be easily generated. On the downside, some scenarios can be missed, thus it is not easy to have an insight into overall risk associated with the system. A method of group examination to identify hazards and their consequences is the so-called Hazard and operability study (HAZOP), where comprehensive number of possible fire initiative hazards is given (SFPE 2005), and include:

- cigarettes or other smoking materials (e.g., lighters, matches);
- torch, hot work, or other open flame devices;
- heating, refrigeration, and air conditioning equipment;
- cooking equipment;
- tools and appliances;
- process or service equipment, including separate motors or internal combustion engines;
- electrical distribution equipment (e.g., wiring, switches, outlets, cords and plugs, light fixtures, transformers);
- hot objects, most of which also fall into one of the above categories, such as a light bulb or the heating surface of heating equipment;
- vulnerability to lightning or static electricity;
- chemicals capable of spontaneous heating;
- wildfire or other exterior exposure fire.

The above are direct hazards, in the sense that constitute heat sources themselves. Other events, natural or not, may constitute as well (indirect) fire initiating fires, since they have the potential to create a heat sources (e.g. lighting, earthquake, floods, impacts), alone or in combination with the specific conditions (e.g. the presence of pipe work carrying flammable liquids or gases). The choice of important fire scenarios for the case studied is focused on three areas that, after an initial evaluation, seem to produce the most adverse fire scenarios.

The identified most severe areas for the fire ignition and their features in terms of ventilation, presence of combustible material and fire ignition factors (listed above), give birth to a number of scenarios. When the fire risk prone areas are identified, an event tree (NFPA 2017, Haines 1998) representing the evolution of the triggering event has to be developed for each scenario (Figure 4). Here three areas are assumed for a generic building facility for illustration purposes: the central zone of the building (Area A), a secondary zone of the building (Area B), he outer zone (Area C). The event tree is further divided to take account for more than one initial situations. The one presented here, is relevant to a condition where the doors of the facility are closed, yet there are employees inside. In the generic event tree of Figure 4 (as already said, it is shown here for illustration purposes), the consequences of an initiative event are followed in a series of possible paths.

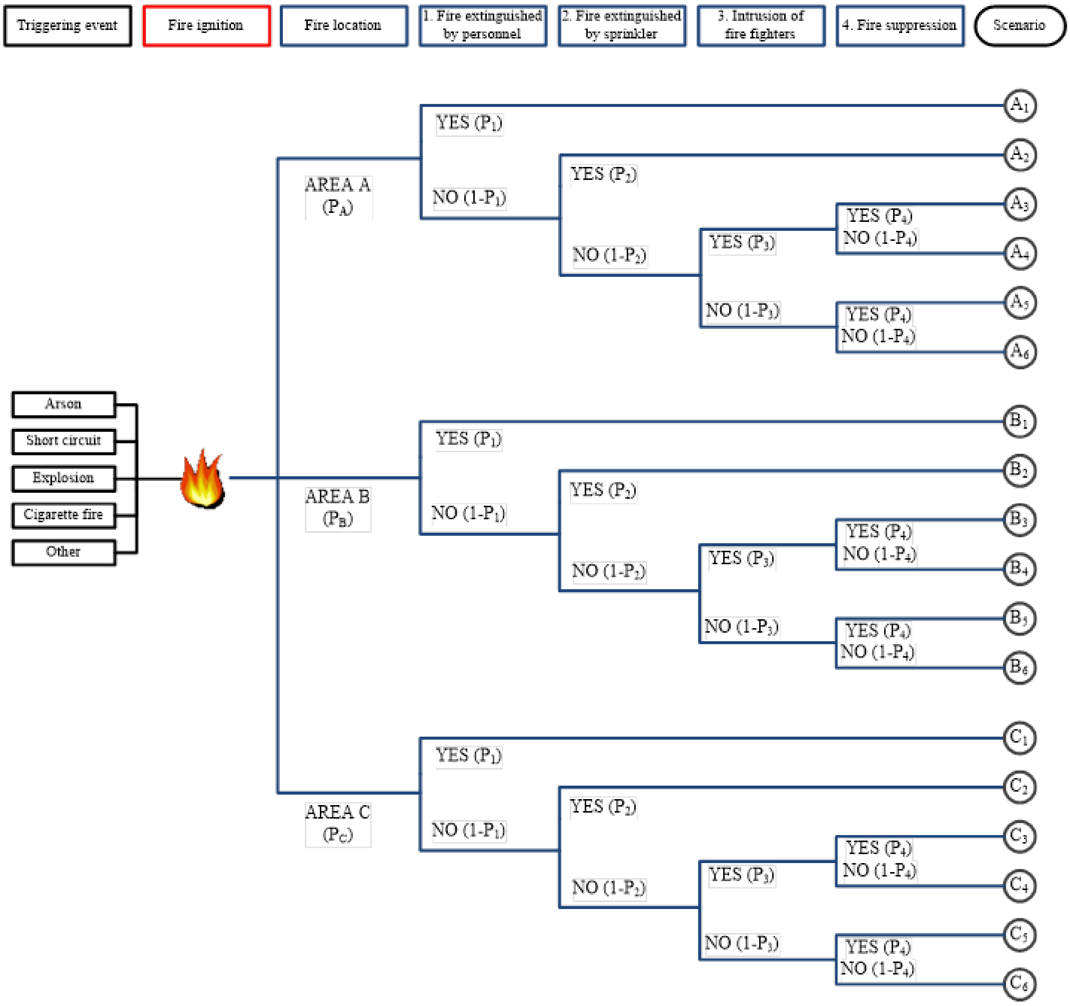


Figure 4: Cause-consequence (“event”) diagram for fire ignition in an industrial facility.

The analysis can be quantified by assigning numerical values to the probabilities as shown for example in Table 1, in the case of a triggering event in area B.

Table 1: Probabilities for the occurrence of different scenarios.

SCENARIO	PROBABILITY
B_1	P_B*P_1
B_2	$P_B*(1-P_1)*P_2$
B_3	$P_B*(1-P_1)*(1-P_2)*P_3*P_4$
B_4	$P_B*(1-P_1)*(1-P_2)*P_3*(1-P_4)$
B_5	$P_B*(1-P_1)*(1-P_2)*(1-P_3)*P_4$
B_6	$P_B*(1-P_1)*(1-P_2)*(1-P_3)*(1-P_4)$

The shown probabilities are intended as in function of time, that is, P = P (t). In this sense, P_4 may not the same after condition 3 (intrusion of the fire fighters), since the expansion of the fire is different for the two cases. For the same reason, probabilities of the various branches are different for the 3 different areas (e.g. the probability P_2 of the fire being extinguished by the sprinklers, is different for each one of the Areas, since the sprinkler arrangement is different in each area).

Finally, regarding **fully probabilistic models** (Stewart and Melchers 1997), it must be said that, at the contrary of Earthquake Engineering, at the present date for FHA they are not yet completely developed in literature. This is due to two main reasons, still hiring the use of fully probabilistic analysis in fire engineering:

- first of all (Lange et al. 2014), there are relevant differences between the two hazards (earthquake and fire). In fact for earthquake engineering as opposed to fire engineering, a number of independent records of earthquake events exists different regions, something that is facilitated by the independence of the earthquake and the corresponding ground motion from the structure – the variables which are of interest in determining the ground motion intensity may be limited to only the distance from the fault line of the facility and the soil/ground conditions at the site. Conversely, the evolution of a fire in a structure is (as already said) strictly dependent upon the features of the compartment;

- second issue related to the application of fully probabilistic approaches in fire engineering is more relevant than the previous one. In cases (like fires on structures) where the hazard is not natural but, on the contrary, it is connected with human activity, and where the consequences can be extreme (e.g. collapses, loss of life), the analysis and management of the problem is matter for the so-called “complex system theory” (Randall 2011, Bier 1997). Beside the structural one, others component of the overall problem complexity arising in structural performances evaluation under fire are given by: i) the difficulties arising in characterizing the fire IM from a probabilistic point of view (see above); ii) the needs of exploring extreme structural behaviours (e.g. progressive collapses or extremely damaged configurations or sudden changes of structural configuration). The two components listed above are typical of those events that, due to both the possible induced structural collapse and their low occurrence, are called “Low Probability and High Consequence (LPHC)” events (Perrow 1984, Ellingwood, 2009, Starrosek 2009). These situations arise for a lot of different and multifaceted reasons, being possibly followed by catastrophic consequences and it’s almost impossible to frame them inside any well-recognized probabilistic format. Opposite to the LPHC events, there are the ordinary hazard scenarios (e.g. low intensity earthquakes or winds) which are called “High Probability and Low Consequence (HPLC)” events. Of course, problem complexity increases passing from HPLC to LPHC events. This appears clear when one thinks that, by definition, HPLC events are frequently observed (and then statistically describable), being LPHC events only rarely experienced and, above all, more variable in nature. As shown in Figure 5, one can adopt two different frameworks to solve the problem: i) a deterministic approach; ii) a stochastic approach. It means that with the first approach one fixes all the aspects of the problem in a definite way, while with the second approach one allows some stochastics to enter in the description. Now, one recognizes essentially three regions: a) the first one is a region connected with low complexity, i.e. evolutive designs or HPLC events, where even direct qualitative analysis finds place; usually, here, true deterministic analysis are conducted; b) the second region is found where the complexity of the problem has grown and aspects of the problem can be usefully considered adding stochastics in the formulation; c) finally, it appears that as the complexity of the problem has reached some critical size, the only way to face and to solve the problem is turning back to some ad-hoc deterministic approach; it means that, with an act of force, the problem is posed and solved by the so-called heuristic way of thinking.

Then at the present stage, the more reliable approach to FHA is the semi-probabilistic scenario-based one described above.

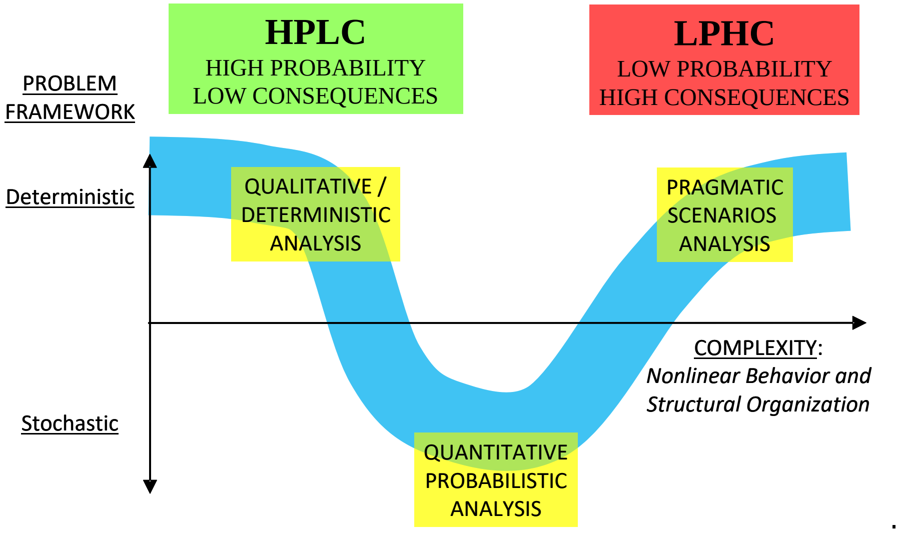


Figure 4 – HPLC vs. LPHC situations and corresponding analysis strategies.

Multi-Hazard and multi-scale aspects in FHA

It is worth noting that Fire Hazard has two peculiar characteristics which are relevant for the MiCHe project, focusing on multi-hazard, multi-scale problems.

First, there is a strict relationship and correlation between fire and other hazards like earthquake and blast. In fact it is not rare that fire is triggered as “cascade” hazard by a previous earthquake or explosion, in this sense the fire hazard is probably the most important between the considered ones. In this cases (fire triggered by earthquake or blast) the full probabilistic characterization of the fire intensity is even more complicate and not investigated in literature, then also in this case the scenario-based heuristic approach for FHA is the most reliable tool.

Second, the multi-scale approach is not easily and coherently applicable for fire hazard at the present state, in fact when switching from the facility-scale (single structure) to upper scales (site- or urban- scale), then the fire phenomenology and dynamics changes. For example at the site scale, only accidents in nearby special facilities (e.g. accidental fire in gas pipeline station) can affect other facilities in the same site, and this kind of fires have different developments and spread from the compartment fire generated in the single structure (especially cultural heritages or heritage structures/building) previously introduced. The same hold for the urban/regional scale, where only wildfires (e.g. in forests) become of interests in terms of impact on the area.

Site scale

In case of fire hazard, investigations aims at the definition of possible fire sources in the neighbouring of the considered heritage facility (focus of the analysis), and that can affect the heritage facility in direct (e.g. fire spread) or indirect (e.g. damage to other facilities which are structurally connected with the heritage facility) ways. In this sense, two main cases are of interest:

- presence in the neighbouring of a special facility which is particular relevant as hazard source: fireworks factory, gas/oil station, refuelling station, etc. In this case, accidental events on one of these facilities can involve the heritage structure of interest. Spreads should be considered both for fires (primary) that for smokes (secondary), causing hazards for structural or non-structural (cultural values) damages respectively;
- belonging of the focused heritage facility to buildings aggregates where other fire hazard sources are present. Our heritage facility can be part of a structural aggregate (very common in historical cities) together with other facilities/buildings (named here

“aggregate facility”) which have some internal fire hazard source. As well-known, building aggregates are very complex from the structural point of view, and structural damages in a unit of the aggregate can affect the structural integrity of other units. Then, if the fire hazard and fire-induced damages affect the aggregate facility, with a consequent loss of structural integrity or global stiffness for the aggregate facility, the considered heritage facility can be also affected.

In both of the above mentioned cases, conducting a heuristic or a probabilistic analysis is almost impossible due to lack of info about the sites and due to the low probability assigned to such evets. Then at the site scale the hazard analysis can be conducted by deterministic approaches: expert judgement has to be involved in defining a reduced number of worst-case scenarios (no occurrence is assigned) that has to be used in design. For the first of the above mentioned case (neighbour facility accident) the data which are needed for defining these design scenarios are:

- location of the hazardous material/combustible inside the neighbour facility;
- maximum temperature that can be reached by a fire in the neighbour facility;
- maximum indoor fire duration in the neighbour facility;
- fire security systems of the neighbour facility (e.g. splinkers)
- possible presence of fired-missiles/debris in the neighbour facility;
- resistance of neighbour-to--heritage barriers (side walls and roof covering of the neighbour facility) to blast of impact;
- distance of the neighbour facility from the focused heritage;
- proximity of firefighters to the neighbour facility;

In the second of the above-mentioned cases (aggregate facility under fire), what is needed is:

- data on structural fire resistance of the aggregate facility, in particular temperature capacity;
- data about the mutual structural influence between aggregate and focused heritage facilities (e.g. common structural walls);

Facility scale

At the facility scale (our focused cultural heritage), the FHA should be conducted in heuristic terms: a set of design fire scenarios has to be defined together with their likehood/probability. The last can be assigned as shown above by an event-tree analysis assigning mutually exclusive probabilities to branches at the same level. In order to determine the fire scenarios the following data are needed about the facility:

- potential fire ignition locations (commonly it can be obtained from electrical/gas plants drawings);
- location and amount/type of combustible (commonly it can be obtained from architectural design drawings);
- data about air ventilation of compartments (e.g. door, window, air ventilation system)
- compartmentation of the floors (it can be only obtained from a fire evacuation plan of the facility, if present);
- data about active fire protection systems (e.g. splinkers, fire detection systems, if present);
- location of the nearest firefighter station.

- fire resistance of the partitions and slabs (as for the previous point, it can be obtained from material data, and eventually from data about passive protections like tumescent painting);
- fire resistance of structural elements (it can be obtained from material data, and eventually from data about passive protections like tumescent painting).

Risks related with the fire hazard in Historic buildings Cultural Heritage sites, structures and artefacts

Introduction

Knowledge of fire cases involving historic-artistic buildings or cultural heritage, is a crucial task in order to develop an effective procedure for the mitigation of impacts due to natural causes, such as, specifically, due to a fire (MiCHe).

There are well known cases of fire, which have developed in sites of historical and artistic value, and have irreparably damaged not only the structure, but even more seriously the content, erasing valuable evidence of our history. Following cases are particular relevant for highlighting general features and vulnerabilities of such cultural heritage buildings to fire.

- Case of the Palazzo Ruggi d’Aragona – Bilotta Museum in Cosenza (Italy), fire occurred on 18/08/2017, see Figure 5.


(a) (b) (c)

Figure 5: Case of Palazzo Ruggi d’Aragona – Bilotta Museum in Cosenza (Italy). Pre-fire interior view (a); fire development exterior view (b); after-fire interior view (c).

- Case of the Science Academy Library in Moscow (Russia), fire occurred on past 31/01/2015, see Figure 6.


(a) (b)

Figure 6: Case of the Science Academy Library in Moscow. Fire development exterior view (a); after-fire exterior view (b).

- Case of the National Museum of Brazil in Rio de Janeiro, fire occurred on past 03/09/2018, see Figure 7.

(a) (b)

Figure 7: Case of the National Museum of Brazil. Pre-fire interior view (a); fire development exterior view (b).

- Case of the Notre Dame de Paris cathedral (France), fire occurred on past 15/04/2018, see Figure 8.

(a) (b) (c)

Figure 7: Case of the National Museum of Brazil. Pre-fire exterior view (a); fire development exterior view (b); after-fire exterior view (c).

On a sample population of 34 cases carried out from the literature review, it appears that causes of fire in heritage buildings and churches/cathedrals are variegate (see Figure 8), ranging from electricity short circuits to gas cylinders bursting, while the nature of the fire is quite equally distributed between accidental or malicious natures for museums and heritage buildings while it is mostly accidental for churches.

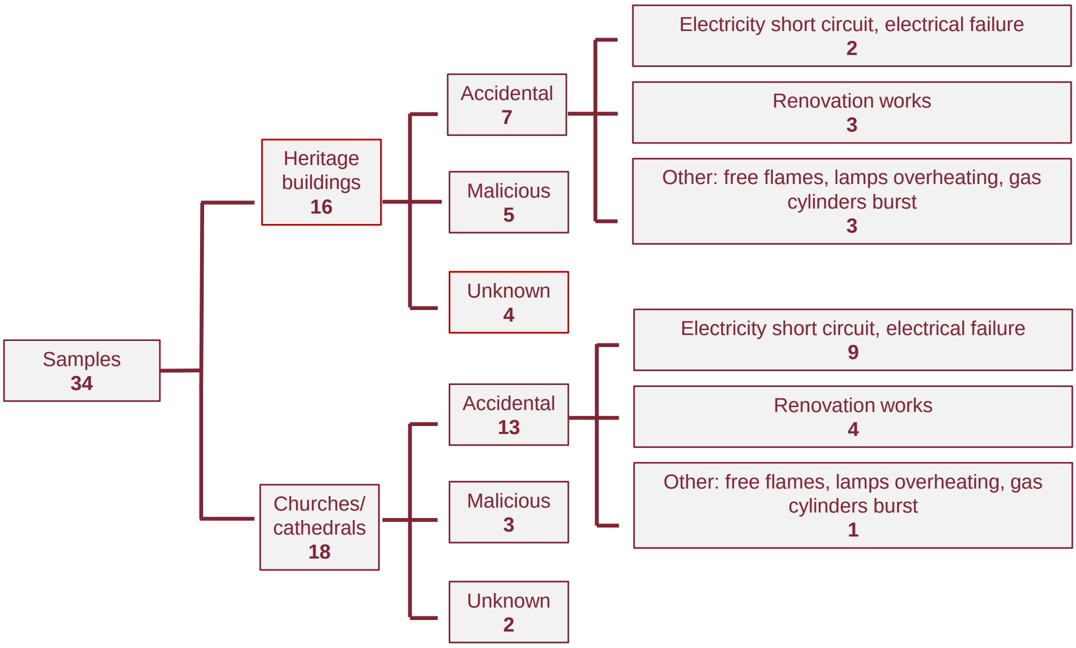


Figure 8: Classification of the nature and causes of fire in heritage buildings and churches/cathedral.

From the critical analyses of such literature cases, it clearly emerges that there are some peculiarities of historical buildings that make them vulnerable to fire-risk and, at the same time, that can prevent the adoption of some common protection or mitigation measures.

Main vulnerabilities to fire in historic/heritage buildings

Main general factors that induce vulnerabilities to fire in historic buildings are examined in the multiscale view adopted by the MiCHe project, and by focusing on the “Outstanding masterpiece Architecture (single building or facility scale)” or to the “Urban (site)” scales as defined by the project. Regarding to the first scale (singe building), the following vulnerabilities can be identified:

- *Massive presence of wooden structural and non-structural elements (or other elements vulnerable to fire)*.
    - *Roofs*. Typically built of wood. The spaces in the attic are often used as storage space for various materials. These are usually not manned (the detection of the fire occurs only when the event has developed such a propagation to "get out" of the room), but also, usually, difficult to reach by rescue services. The spread of flames to the roof structure usually causes the roof to collapse. The size of the volume under the roof is decisive, the propagation occurs very quickly due to the large volumes;
    - *Floors*. The typical structure of the intermediate floors has load-bearing wooden beams, already vulnerable elements in themselves. In general, the presence of voids or passageways can be critical, the wooden beams are supported by inserting themselves into the load-bearing masonry. The

progressive loss of humidity in the wood can lead to new cracks, opening new propagation paths for the smoke of a fire;

  - *Contents*. Benches, artworks, etc.

Figure 9: Massive presence of wooden structural and non-structural elements.

- *Valuable content*. Artworks, sculptures, church organs and inlays are valuable contents that can gone lost during fire. There is large discussion in the community about the fact that the losses regarding such kind of things cannot be merely identified with a monetary value as usually made for modern contents. This is due to their unquantifiable artistic/cultural value.
- *Absence of active protection and of adequate compartmentations.* Heritage buildings, and churches in particular, are often characterized by large compartments and absence of active protection measures. In addition to the fact that fire compartmentation design concepts are not implemented and active protection measures were obviously not available at the construction time, the today implementation of such kind of measures is mostly not practicable due to the invasive effect of them in terms of visual or functional aspects (e.g. active protection pipes and sprinklers would impact on the visual aspect of a church, while compartmentation

would imply the subdivision of the main hall for religious celebrations, and then compromising the functionality).

- *Storage of flammable substances or unsuitability of electrical installations.* Due to their expositive functions, museum, churches and other heritage/cultural buildings are often populated by flammable substances (e.g. think to the library of a museum). In addition, they are often served by electrical installations that do not meet the security codes and then, more exposed and more vulnerable to electrical short circuits.
- *Presence of a large amount of people (churches and museums)*. The presence of large amount of people in receptive heritage buildings like churches an museums make them critical for the safety of people in fire, for which exodus measures becomes an important design aspect.

Regarding the urban scale, vulnerabilities of the single heritage building can be identified in two points:

- *Difficulties of be approached by rescue vehicles (because heritage buildings are located in historical centers);*
- *Possible indirect involvement due to vulnerability of other units of the building cluster which can make the single heritage building subjected to fire spread or collapse spread.*

Fire behaviour of structural materials with specific reference to historic buildings

As said above, one of the main vulnerabilities of heritage buildings to fire is due to the massive presence of wood, which, together with the masonry, is one of the two main structural materials used for their construction. Wood is mainly used for flooring and roofing, while the masonry is mainly used for structural walls. In the following, some specific details about the fire behaviour of these two materials is provided.

- *Wood behavior in fire.*

Wood's behavior is one of the most complex in fire. At the room temperature, wooden structures shows a structural behavior conceptually similar to steel structures: elements remain mainly in the elastic range, and the element fibers are able to behave well both in compression and tension. However, there are some peculiar aspects of wood that differentiate it from steel already at the room temperature (e.g. non-isotropic and directional mechanical properties, tensile strength also depends on the size of the sample, resistance is reduced under long-term loads).

For wood, in fire conditions, there are substantial differences with other construction materials. Wood is a combustible organic material and in case of fire it participates to the combustion by losing mass from the surface exposed to the fire inwards. The fire-exposed layer of wooden surfaces carbonize and no more contributes to the mechanical characteristics of the structural wooden element. Underneath the carbonized layer there is an area called "pyrolysis" or altered zone of variable thickness between 20 and 40 mm in which the molecular bond breaking transformations are concentrated. In favor of safety it is considered that the pyrolysis layer is not able to offer any mechanical properties, while the non-altered zone maintains its mechanical characteristics of non-carbonized wood layers. Under prolonged exposition to fire, the carbonization gradually increase in depth, then gradually involving successive inward layers.

Before the carbonization occurs in a specific layer, non-carbonized heated wood, experiments the decay of its mechanical proprieties due to the exposition to high temperatures. This effect is significant for the structural tension and compression strength in the direction of the woodgrains/fibers. Decay coefficients for fibers' strengths as well as for the elastic modulus with the temperature is shown in Figure 10, the last one differentiating between tension and compression behavior.

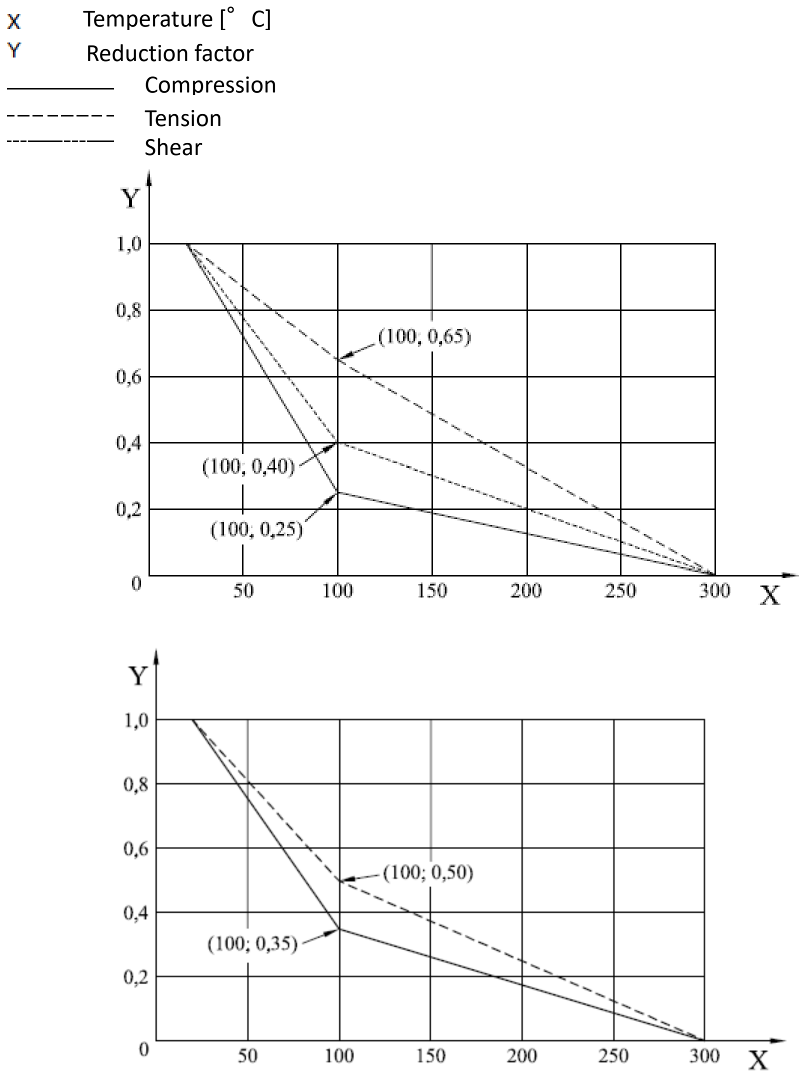
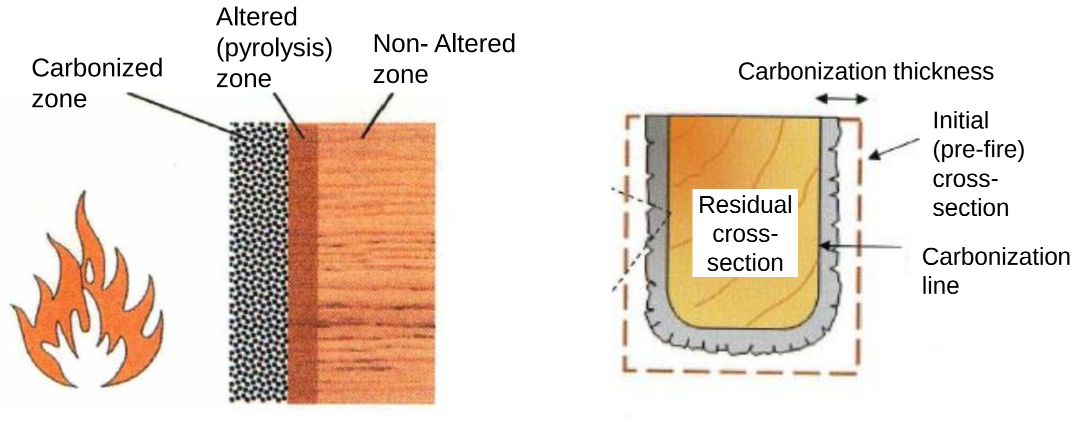


Figure 10: Decay of wood mechanical proprieties with the temperature: strength (upper), elastic modulus (lower).

The carbonization effect described above (also schematized in Figure 11), produces two main effects: from one side, there is a reduction of the resisting cross-section of a wooden structural element (e.g. a beam) when subjected to fire, on another side, the carbonized layer of the fire-exposed element acts as isolation layer for the internal parts (see the temperature conductibility trend in Figure 12), then slowing the above discussed decay of the internal layers mechanical proprieties.



(a) (b)

(c)

Figure 11: Carbonization process for wood elements. Schematization of surface carbonization (a); Schematization of beam cross-section decreasing due to carbonization (b); experimental example of carbonization (c).

X Temperature θ [° C]
Y Conductibility [$Wm^{-1}K^{-1}$]

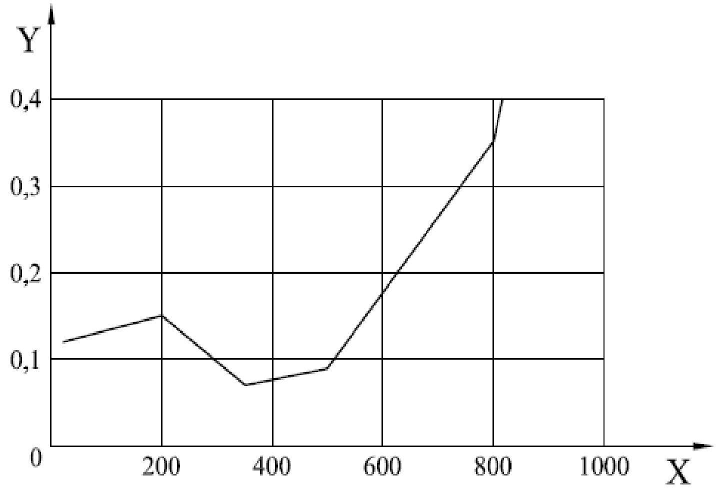


Figure 12: Wood thermal conductibility trend with the temperature.

- *Masonry behavior in fire.*

Very few references are found in literature for the behavior of the masonry under fire. In general Masonry has low sensitivity to fire, something that it is especially true for thick walls like those that are usually present in heritage buildings. When exposed to high temperatures (Sciarretta 2010), the mono-axial mechanical constitutive law of a portion of a wall made by filled bricks shows a gradual decay of the stiffness and maximum strength and an increasing of the ductility as shown in Figure 13. in common heritage buildings built by masonry walls and wooden floors and roof, the masonry is capable to survive a fire who completely burn all the wooden parts, then the masonry can be seen as a non-vulnerable component of the building.

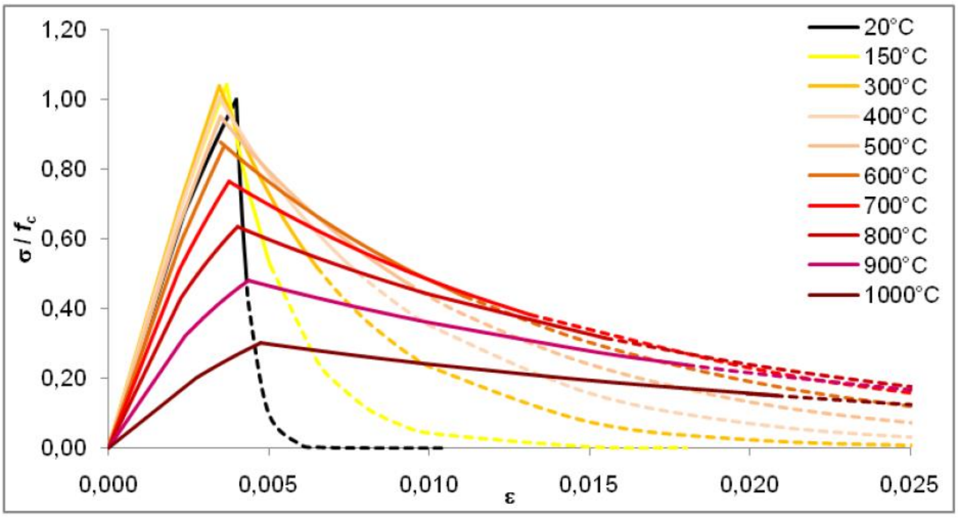


Figure 13: Mono-axial mechanical constitutive law of a portion of a wall at different temperatures.

Mitigation measures of fire risk analysis in historic buildings

Introduction

Different fire risk mitigation measures are available for ordinary buildings. They can be grouped in three main typologies:

- *prevention measures* consist pre-fire working measures like limitation of ignition sources and of human hazardous measures or instruction of occupants about emergency procedures and evacuation. Such kind of measures mainly attain to the management (e.g. vigilance and instruction) and architectural design procedure (e.g. proper design of evacuation paths);
- *protection measures* consist in appropriate measures to decrease the vulnerability of the structures to fire (e.g. protective paints), or the fire hazard intensity (e.g. sprinkler automatic fire suppression system). Protection measures can be subdivided in active and passive protection measures. Active protection measures implies the automatized intervention or the technological activation (electricity is often needed) of an hazard suppression system (e.g. sprinklers or automatic fire doors), while passive protections mainly do not require any technological or electricity-dependent activation. It is important to say that active measures are effective only in the ignition (pre-flashover) phase of fire, while passive measure are effective in both pre-flashover and flashover phases;
- *structural robustness.* The last measure which is able to mitigate the effects of fire on buildings and structure, consist in designing the structural system to retard as much as possible the occurring of significant (global or semi-global) collapses due to

prolonged fire expositions. This last measure aims to avoid the propagation of losses from the fire compartment to the rest of the building: for example, if fire occurs in a floor of a high rise building, that is a single compartment, also if the flashover cannot be avoided and, consequently, all the contents and non-structural parts in the floor are lost (together with the life of the occupants in that floor), the structural components of the floor (and of the rest of the structure designed as a whole) have to be designed for not developing the progressive collapse mechanisms which can involve other floors, and then propagate the losses to the rest of the building. Structural robustness requirement is a matter of structural design.

Then, the effectiveness of the different fire risk mitigation measures can be strictly related with the different fire development phases as described above and shown in Figure 14.

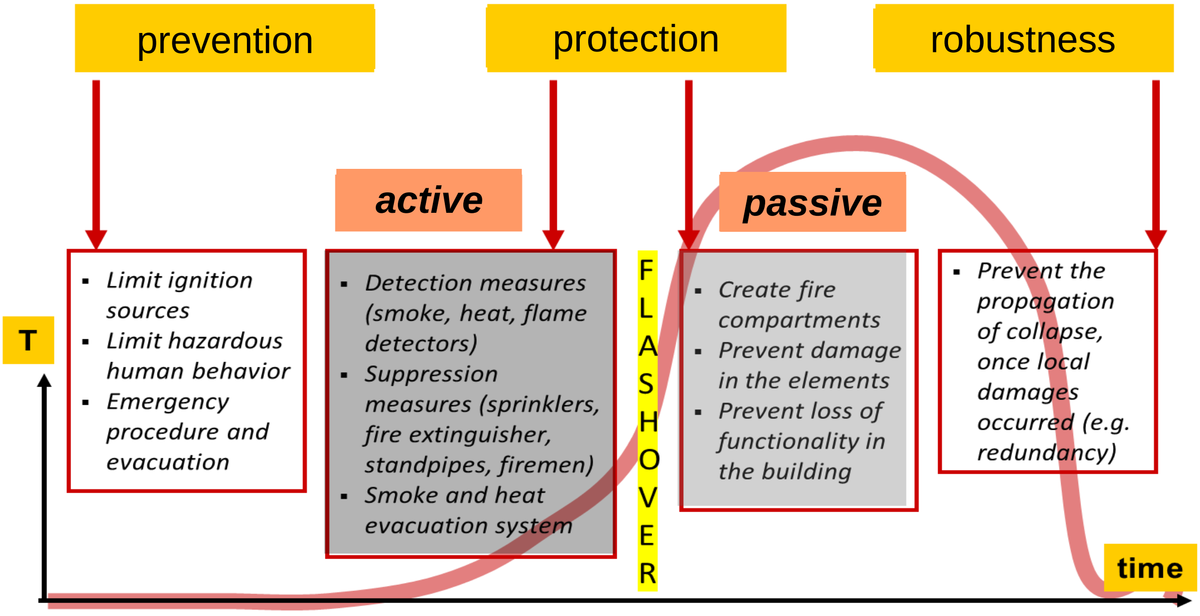


Figure 14: Effective fire mitigation measures in different phases of the fire development process.

In what follow, some more details are provided regarding the active protection put in place by mean of sprinkler system, which is the measure that has been applied to the case study in the MiCHe project.

Sprinkler system

A fire sprinkler system consists of a water supply system, providing adequate pressure and flowrate to a water distribution piping system, until the arrival of the flux to water spatial diffusors (sprinklers), which are usually connected at the compartment roof. The sprinkler automatic fire suppression plant is a complicate system, which implies complex pipes assembly and high-pressure pumps, as schematically represented in Figure 15.

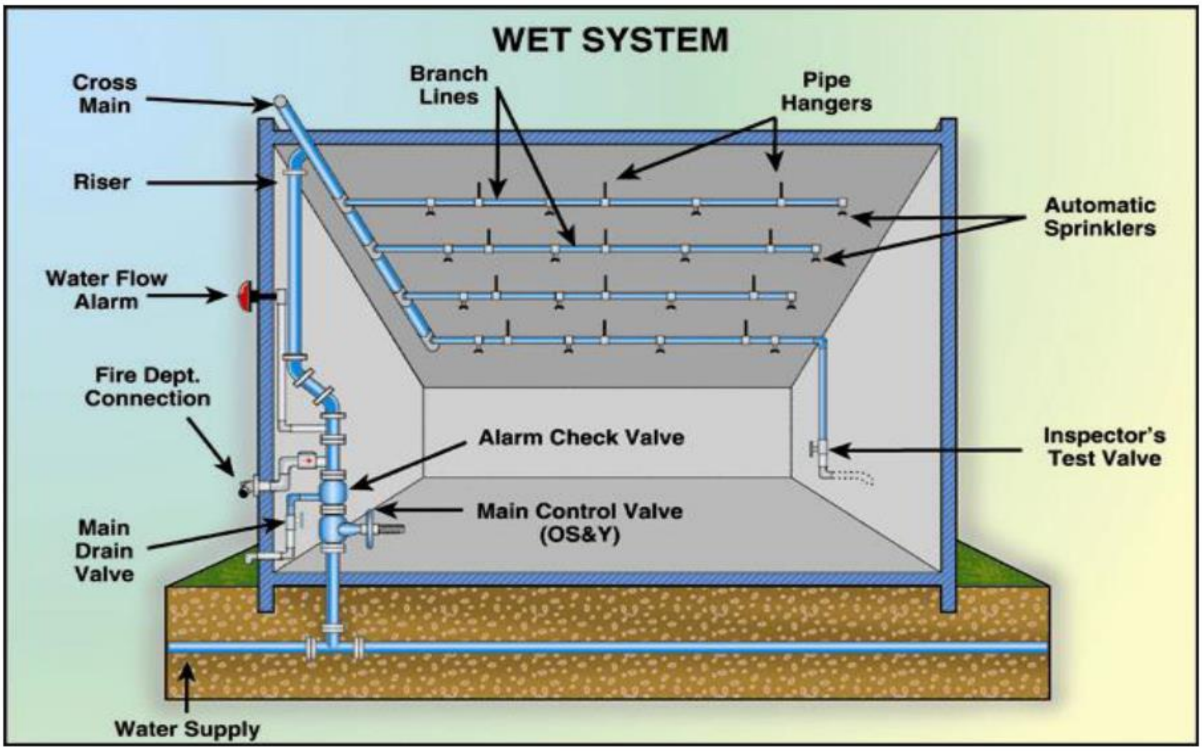
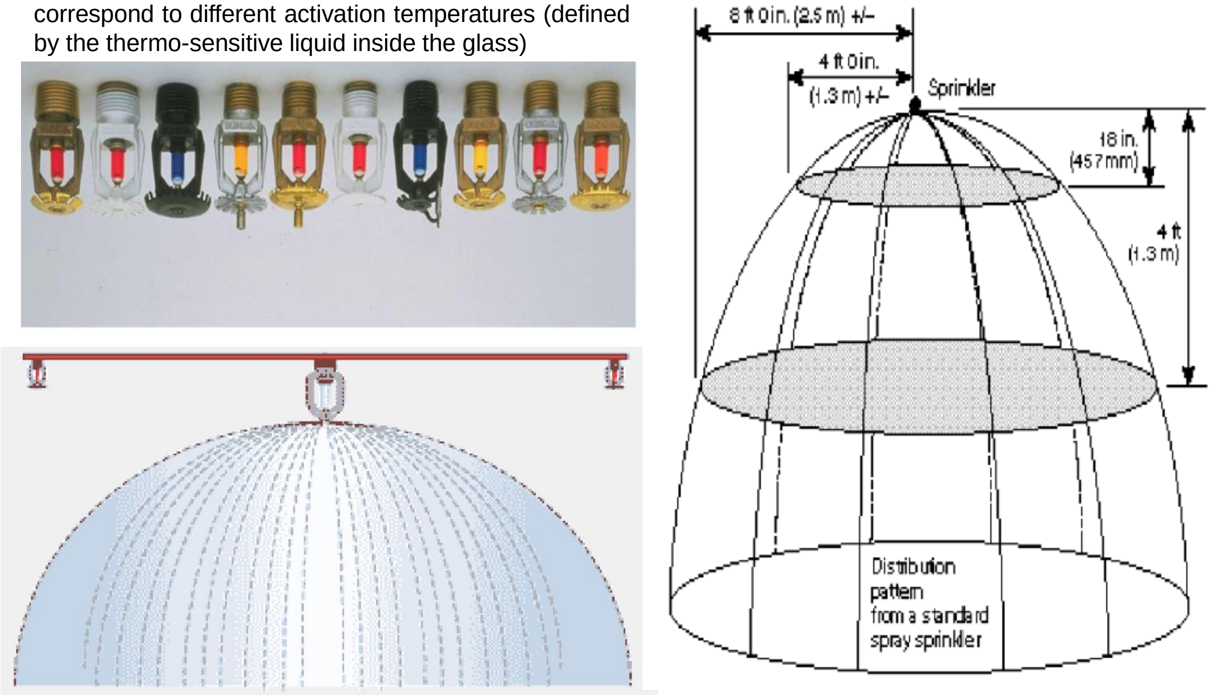


Figure 15: Schematic representation of automatic fire suppression system by sprinkler (after Marotta 2013).

Sprinkles (final component of the line for water rain diffusion) produces paraboloid jet falling on the fire for suppression purposes (Figure 16).



Different sprinkler typologies: different colors correspond to different activation temperatures (defined by the thermo-sensitive liquid inside the glass)

Figure 16: Parabolic sprinkler diffusion area (after Marotta 2013).

Design of the sprinkler system consist in determining the number of water diffusion sprays to cover the compartment surface on the basis of the floor roof height, paraboloid dimensions and the required system water pressure.

Numerical simulations needed for fire risk analysis in historic buildings

Introduction

When a risk assessment analysis is conducted by the scenario approach described in Figure 4 (also Figure 14 below), the probabilities at each branch of the diagram should be mainly assigned by means of numerical studies conducted for investigating both the fire dynamics and the structural response.

Fire dynamics numerical simulations

The fire dynamics numerical simulation is needed especially in presence of wooden elements (which can be involved in the fire) and in order to examine the effect of different combinations of: i) combustible load (“q”), ii) ventilation and, iii) compartmentation conditions.

The most advanced numerical tools consist in mathematical models for the step-by-step resolution of the fluid thermodynamics governing equations (computational fluid dynamics – CFD models). The thermodynamics governing equations of fluids generally consist of a set of three-dimensional, time-dependent, non-linear differential equations known as Navier - Stokes equations (Marchi and Rubatta 1981):

- the continuity equation;

- the three equations of momentum (one for each spatial component re-used in a Cartesian reference system);

- the energy equation;

- the transport equation for the distribution of pollutants, if necessary.

Local turbulence is often expressed with a variable friction energy diffusion coefficient called turbulent viscosity. Usually this viscosity is obtained from two other transport equations called the equation for the turbulence kinetic energy and the equation of the dissipation of the turbulence kinetic energy. The global description of the flow therefore consists of eight differential equations that are coupled (i.e., to be solved simultaneously) and non-linear. Since solution in closed form has not been provided in literature, a numerical method is applied. It is necessary to simulate the fire compartment by dividing the environment into cells (e.g. grid of parallelepipeds): the differential equations must be discretized, written and solved incrementally at each node of the grid. These models represent the most refined fire simulation currently available, but have the drawback of being very expensive in terms of calculation time. Obviously the computational burden depends on the number of grid elements used in the discretization.

A fire simulation software according to a CFD fluid flow current model is the Fire Dynamic Simulator (FDS), developed by the Fire Research Division at the Building and Fire Research Laboratory (BFRL) of the National Institute of Science and Technology (NIST) (McGrattan et al. 2009). FDS numerically solves a form, adapted for low velocity flow, of the above equations, with particular attention to the transport of smoke and heat caused by fire. Together with FDS another software called Smokewiev is distributed, which is used to obtain the visualization of the results of a simulation performed with FDS. The program has been written in Fortran and the input data are provided with a text file in ASCII format. FDS is able to provide as output data the trend in time of:

- temperature, speed and gas concentration;
- concentration of combustion products;

- visibility and pressure;

- activation of sprinkler dispensers and heat or smoke detectors;

- mass and energy flows.

ISO 13387 (ISO 1999) sets out some considerations on the problem of reliability of simulation models. It is necessary to verify the adherence of the representation of the physical phenomenon, and to verify the mathematical accuracy. Verifying a model implies a judgment on the appropriateness of the hypotheses and theoretical bases and the absence of serious numerical errors (Marsella and Nassi 2006).

The CFD model must be able to demonstrate that in comparison with real events or experimental data, the simulation deviates from the experimental data within the expected accuracy limits. This capability does not concern any event, but will have to be widely demonstrated in the field of use of the model. This means that accuracy with respect to a single event does not imply a guarantee of similar behaviour in all situations. The problem of model accuracy has been analysed extensively in ISO, which refers to ASTM E 1355 - 97 Standard guide for evaluating the predictive capability of deterministic fire models, also recalling the methodology adopted by ISO 9000 for software quality assurance (ASTM 1997).

In the following Figure 14 two cases of FDS modelling of fire development in a regular benchmark compartment (internal box) with and without openings are shown as developed in the preliminary phase of the project for code validation purposes, something that is necessary to increase the confidence level for the successive analyses that has been conducted on the case study heritage building. In Figure 15 the corresponding HRR curves are shown, they allows to appreciate the trend of natural HRR curves in the two cases. Just in the trends of these HRR curves, the fluctuations related to the realistic development of the fire can be appreciated.

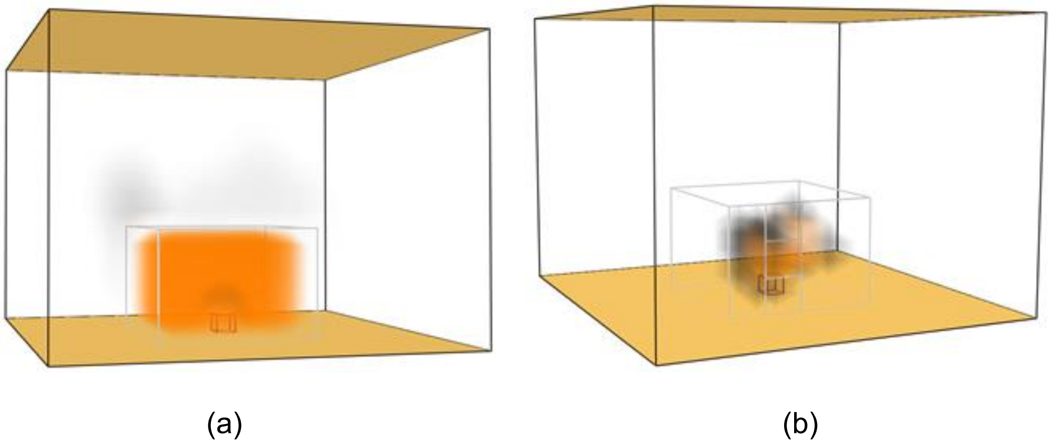
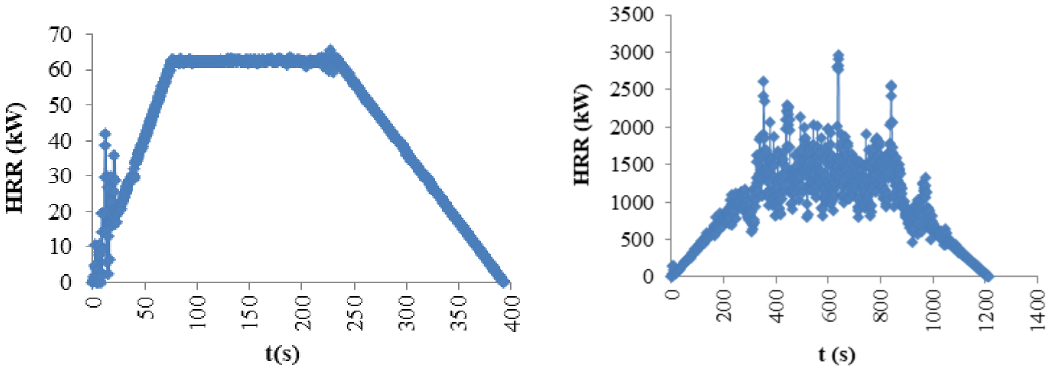


Figure 14: Fire development CFD simulations in regular benchmark compartment. With openings (a); without openings (b)



(a) (b)

Figure 15: HRR curves from CFD simulations in regular benchmark compartment. With openings (a); without openings (b).

Structural response numerical simulations of wooden elements under fire

The numerical simulation of structural wooden elements under fire is quite complicate due to the presence of the carbonization effect described above. The Finite Element (FE) numerical model of the structural components must to be capable of:

- receiving the output coming from the CFD model above, consisting in the time-air Temperature curves in different locations around the structural wooden elements, and using them as input for an initial **thermal analysis** (usually carried out by shell or brick FEs) to investigate heat diffusion and temperature inside the elements. The thermal analysis should take into account the wood thermal conductibility trend with the temperature (Figure 12 above) in order to correctly considering the isolation effect exerted by the external (fire exposed) carbonized layers on the internal ones;
- using the output of the above mentioned thermal FE analysis, consisting in the time-internal temperature curves in structural elements as input for assigning material decay laws to different layers of the structural elements. Then conducting a **non-linear structural analysis** with material decaying (temperature –dependent) and non-linear characteristics and large displacements. Since dynamic inertial effects can be usually neglected in fire structural response (excepting for the final kinematic progressive collapse phase, if present), the analysis can be carried out by pseudo-static solution techniques.

In order to correctly conducting the two analyses above, the cross-section of the wooden structural elements has to be considered as layered. This can be accomplished by using brick elements in a 3D analysis. Nevertheless, due to the complexity of the structures considered in the MiCHe project (historic composite masonry-wood buildings or buildings aggregates), and due to the need of carrying out a global analysis of the case studies, an innovative model made by beam elements is proposed in MiCHe for conducting the non-linear structural analysis phase by limiting the computational burdens.

In the proposed model, a wooden structural elements is schematized by using different superimposed (i.e. connecting the same extremal nodes) beam elements, each one representing a different layer considered for schematizing the above described behaviour. Considering a beam under bending or axial loads, and assuming that the discretization of the cross section can be made by three layers (see Figure 16), the first (external) and the second (intermediate) layer are constituted by hallow core sections, while the central (core) layer is constituted by a rectangular section. Each layer is assigned with the temperature-dependent decay law characterizing the wood material for the elastic modulus and the strength shown in Figure 10 above. In first instance, the thermal analysis can be avoided (especially for normal thicknesses wooden elements) and the heat propagation inside the elements with the gradual involvement of internal layers, can be taken into account by differentiating the beginning time of the temperature-dependent decay laws of layers, e.g. the proprieties of the internal layers start decaying when the adjacent external layer fully losses its proprieties or the wood thermal conductibility re-start growing (T=350°C in Figure 12).

In order to correctly calibrate the thicknesses assigned to the different considered layers, reference can be made to the UNI EN 1995-1-2 (2005) procedure for the determination of the carbonized thickness shown in Figure 17. The procedure implies to set a correspondence (on the base of the time-temperature curve obtained from the CFD analysis) between the time (which is parameter used for the carbonization thickness) and the temperature (IM used in the analysis).

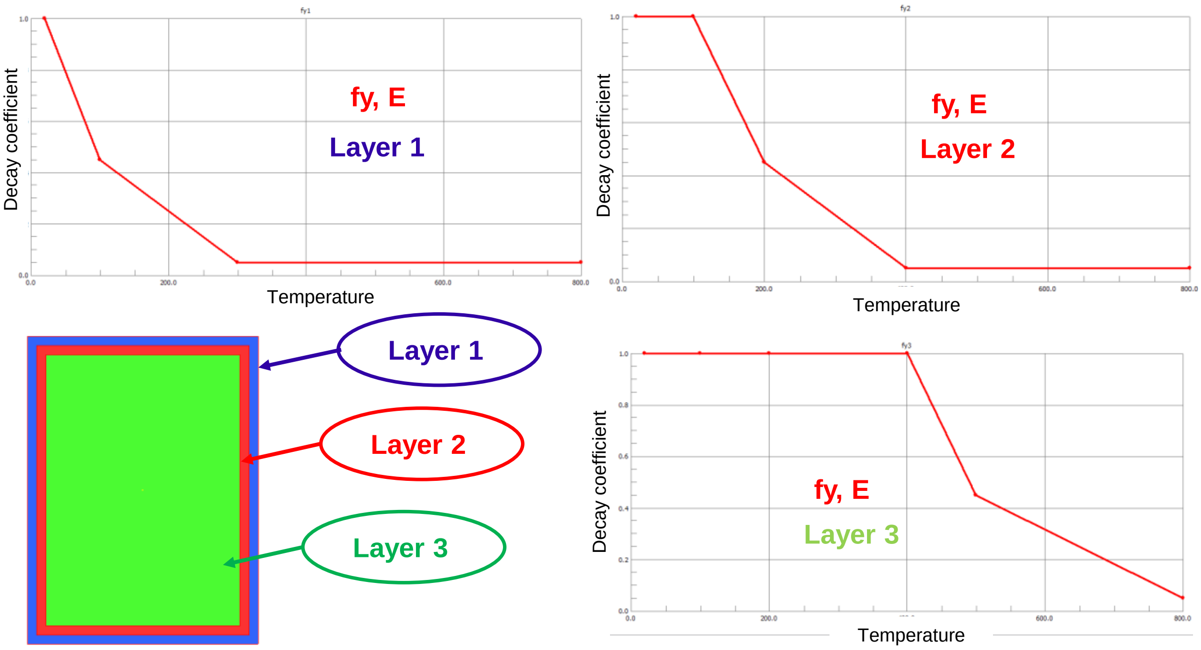
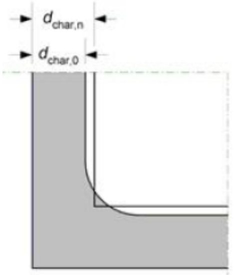


Figure 16: HRR curves from CFD simulations in regular benchmark compartment. With openings (a); without openings (b).

1) **One-dimensional advancement model** that takes into account the real advancement of the carbonization line, including the phenomenon of edge rounding.

$$d_{char,0}(t) = \beta_0 \cdot t$$

where β_0 is the carbonization advancement velocity coefficient.



2) **Nominal (simplified) feed forward model** that neglects the phenomenon of rounding of edges

$$d_{char,n}(t) = \beta_n \cdot t$$

where β_n is the nominal carbonization advancement velocity .

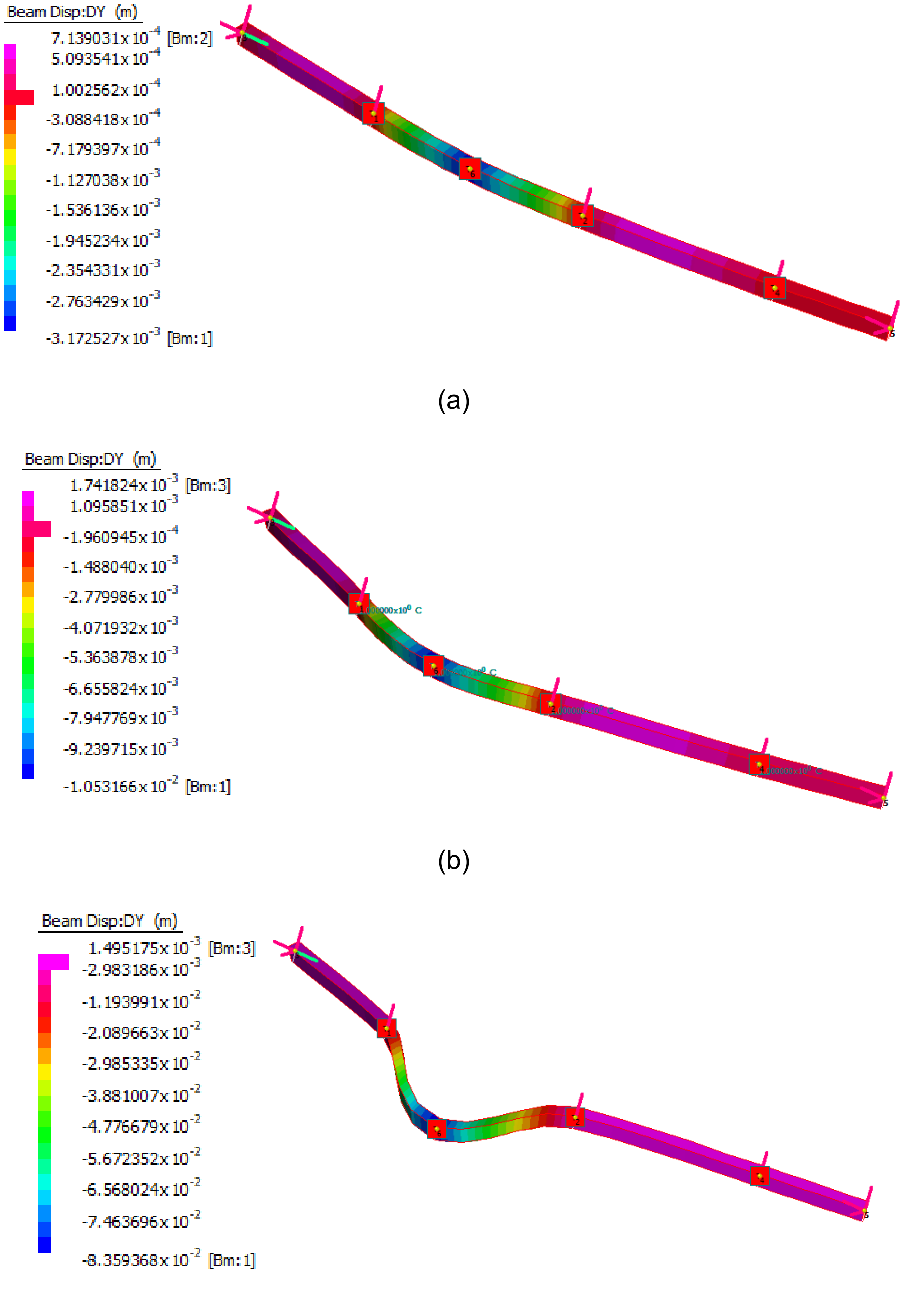
Figure 17: Determination of the carbonized thickness (adapted from Eurocode 5).

The procedure has been tested on the benchmark problem of a simple supported beam under a linear increasing of the temperature.

Benchmark problem

The above-introduced innovative FE model for the structural analysis of wooden elements under fire has been applied to a benchmark hinge-hinge supported beam modelled by the commercial code Straus7 ® (www.hsh.info). The time-air temperature curve is obtained by a CFD analysis carried out in FDS (including both a 90 seconds long heating phase and a subsequent cooling phase), with the combustible concentred under the second of four segments in which the beam has been divided. No loads are applied to the beam in addition to the self weight. The beam has a 6m span and a rectangular 0.3x0.5 cross section. The cross section discretization in layers and the relative temperature-dependent decay coefficients for the strength and the elastic modulus are those shown in Figure 16, while the thickness of the layer 1 and layer 2 are equal to 2 and 3 cm respectively. The analysis consider both material and large displacement non-linearties.

The deformed shape of the beam at different time steps are shown in Figure 18, where the concentration of the vertical displacement (DY) is concentred in the segment of the beam which is more exposed to fire (second over four). The displacement of the most vertically displaced node (node 6) over time is shown in Figure 19, where the increasing of vertical displacements (negative sign, it is followed by a partial recovery of the deformation with a residual displacement due to the loss of part of the resisting cross section (layer 1 and layer 2), and to the plasticization of the layer 3. Finally, the axial forces experimented by the three layers in the most vertically displaced section are shown in Figure 20, where the satisfying simulation of gradual carbonization of the layers 1 and 2 (with consequent gradual transfer of the internal forces to the layer 3) are clearly shown by the gradually decreasing of the internal forces in the layers 1 and 2. Consequently the layer 3 experiments increasing internal forces (changing in sign due to the catenary effect as correctly simulated by the analysis).



(a)

(b)

(c)

Figure 18: Determination of the beam at different time steps: 25s (a); 50s (b); 500s (c).

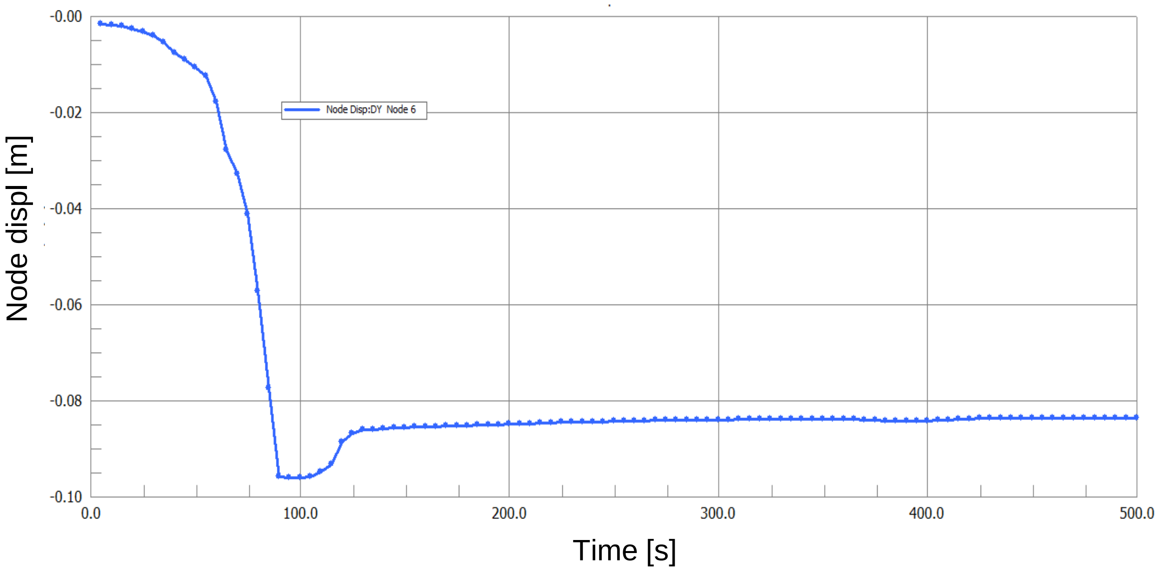


Figure 19: Vertical displacement of node 6 (more displaced node) over time.

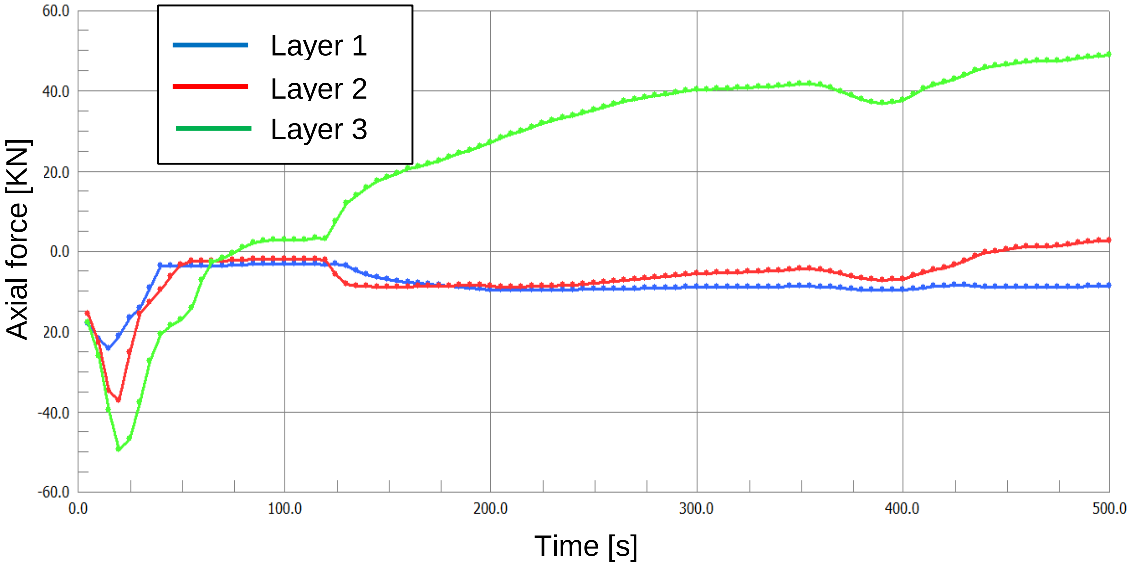


Figure 20: Axial forces in the cross section layers (more vertically displaced cross-section) over time.

THE MODENA CATHEDRAL. The Duomo di Modena case study

Introduction

The Duomo di Modena Cathedral (the “Modena Cathedral” in the following) is one of the case studies of the MiCHe project. Detailed description of the structure and of its history is given in a dedicated report. In what follows, the details of the fire risk analysis conducted for the Modena Cathedral are provided.

Specific fire vulnerabilities of the Modena Cathedral to fire

The first step of the analysis regards the identification which one of the above listed main vulnerabilities to fire in historic/heritage buildings applies to the Modena Cathedral, as discussed below.

- *Massive presence of wooden structural and non-structural elements (or other elements vulnerable to fire)*. The roof structure (both beams and trusses) is in wood, while walls are made in massive masonry (see Figure 21). Regarding the content, there are also many artistic elements made in wood. One of the most important masterpieces is the Inlaid wooden “pontile” made in 1461-1465 (Figure 22);
- *Valuable content*. A number of Artworks, are present in the Modena Cathedral (for an exhaustive list of valuable content please see (http://www.unesco.modena.it/en/plan-your-visit/cathedral?set_language=en and https://it.wikipedia.org/wiki/Duomo_di_Modena). The most important point is that all these contents can be damaged or get lost due to fire.
- *Absence of active protection and of adequate compartmentations.* Although a fire suppression system is not present in the Cathedral, there is a smoke detection

system, important for decreasing the firefighters' intervention time. As for large part of cathedrals around the world, two main (large) compartments are individuated in the Modena one: the main hall for religious functions is the first compartment (which is relevant for evacuation studies), while the loft (the service/ storage cubature under the roof, which is relevant for fire development due to the presence of the wooden roof) is the second one. It is important to say that the two are divided by the floor of the loft, which is made by a mixed wood-concrete structure. This kind of dividing layer between the two compartments is not fully fire-resistant, then it is assumed for it a conventional fire strength of 60 mins when the fire develops in the loft. After that fire exposition time, the floor is assumed to collapse in the main hall.

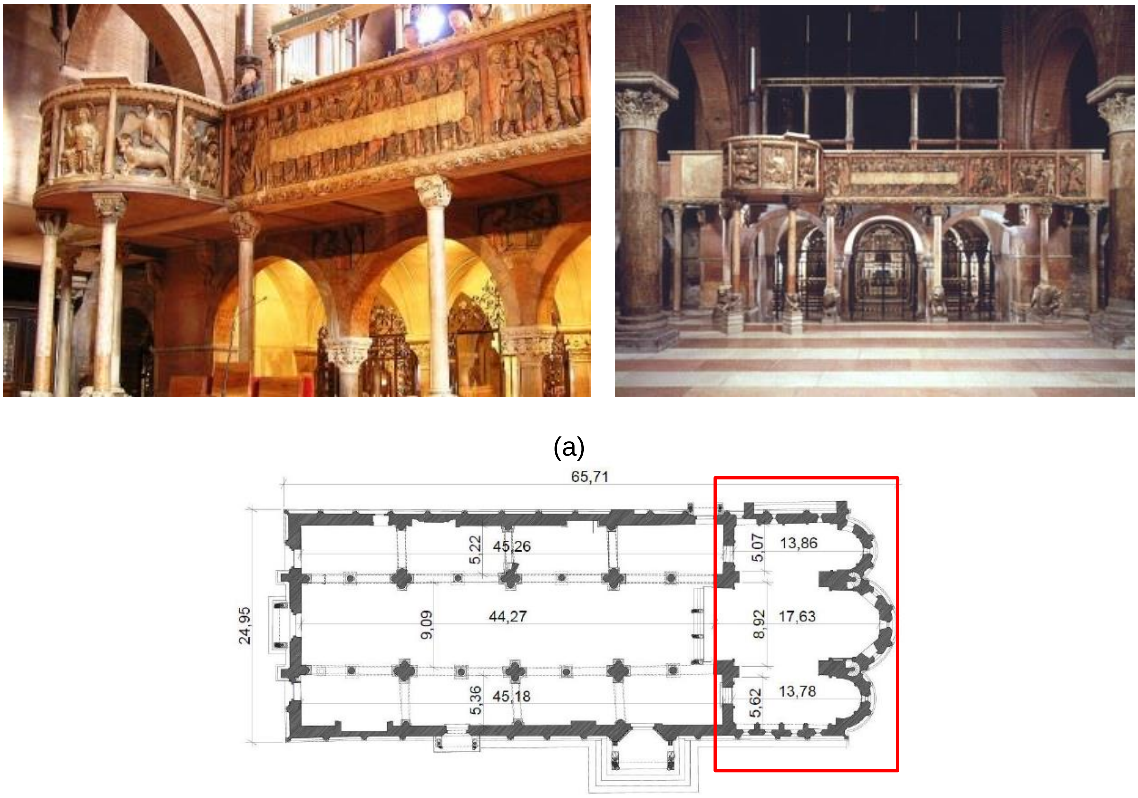
- *Storage of flammable substances or unsuitability of electrical installations.* The short electricity circuit is considered the most suitable fire source in the Modena Cathedral, especially in the loft, where electrical cables and stations are present (see Figure 23).


(a) (b)

Figure 21: Structural elements in the case study Modena Cathedral. Roof and walls schematic representation (a); detail of roof structural elements (b).

- *Presence of a large amount of people (churches and museums).* The possible in the Modena Cathedral, something that can be critical for the safety of people in fire.

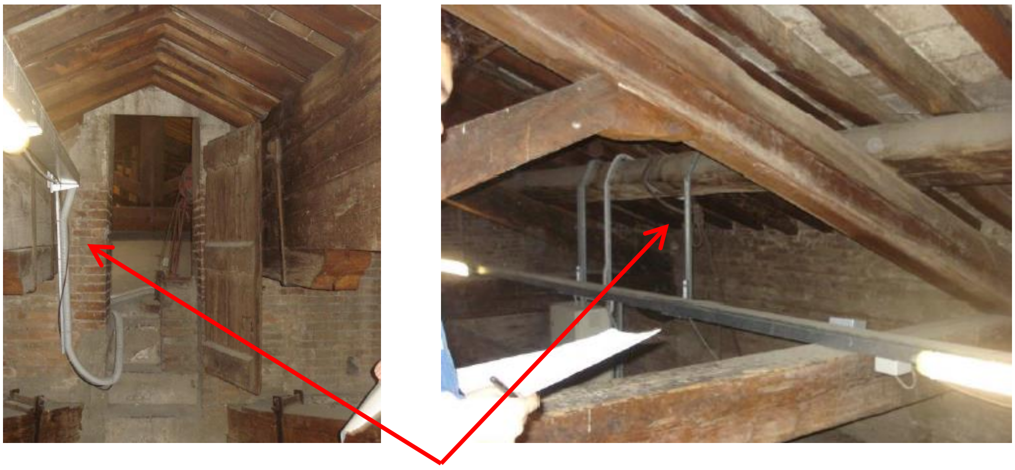
Emergency exits are shown in Figure 24.



(a)

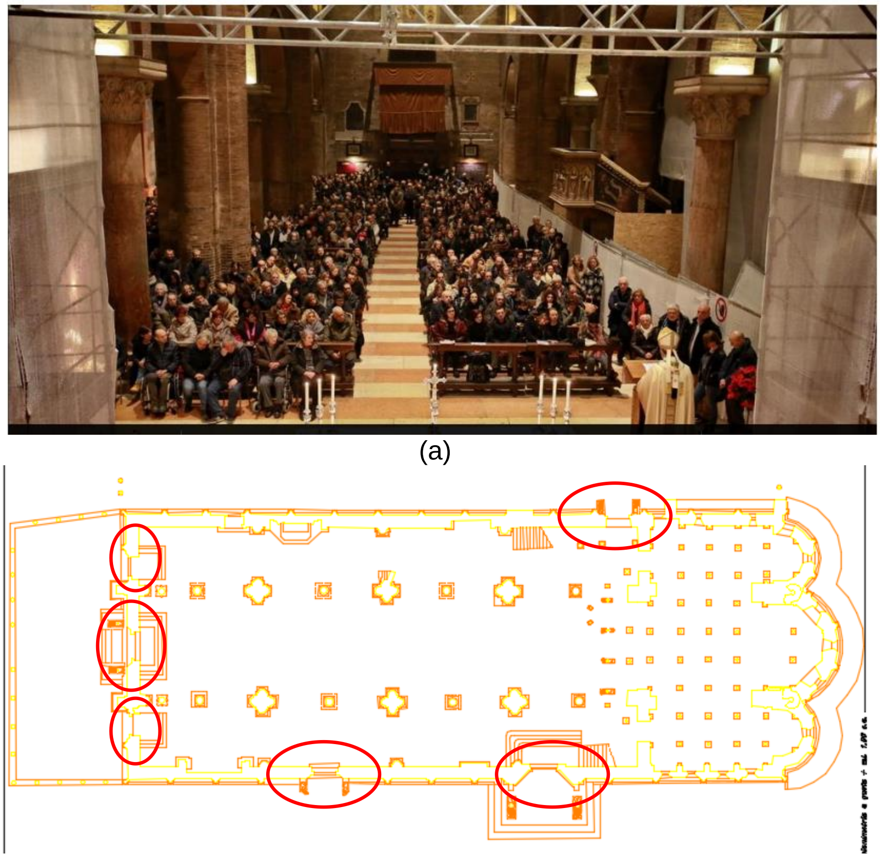
(b)

Figure 22: Inlaid wooden “pontile”. Views (a); location inside the main hall (b).



Electrical cables

Figure 23: Electrical cables as main fire ignition sources (duo to a short circuit) in the loft.



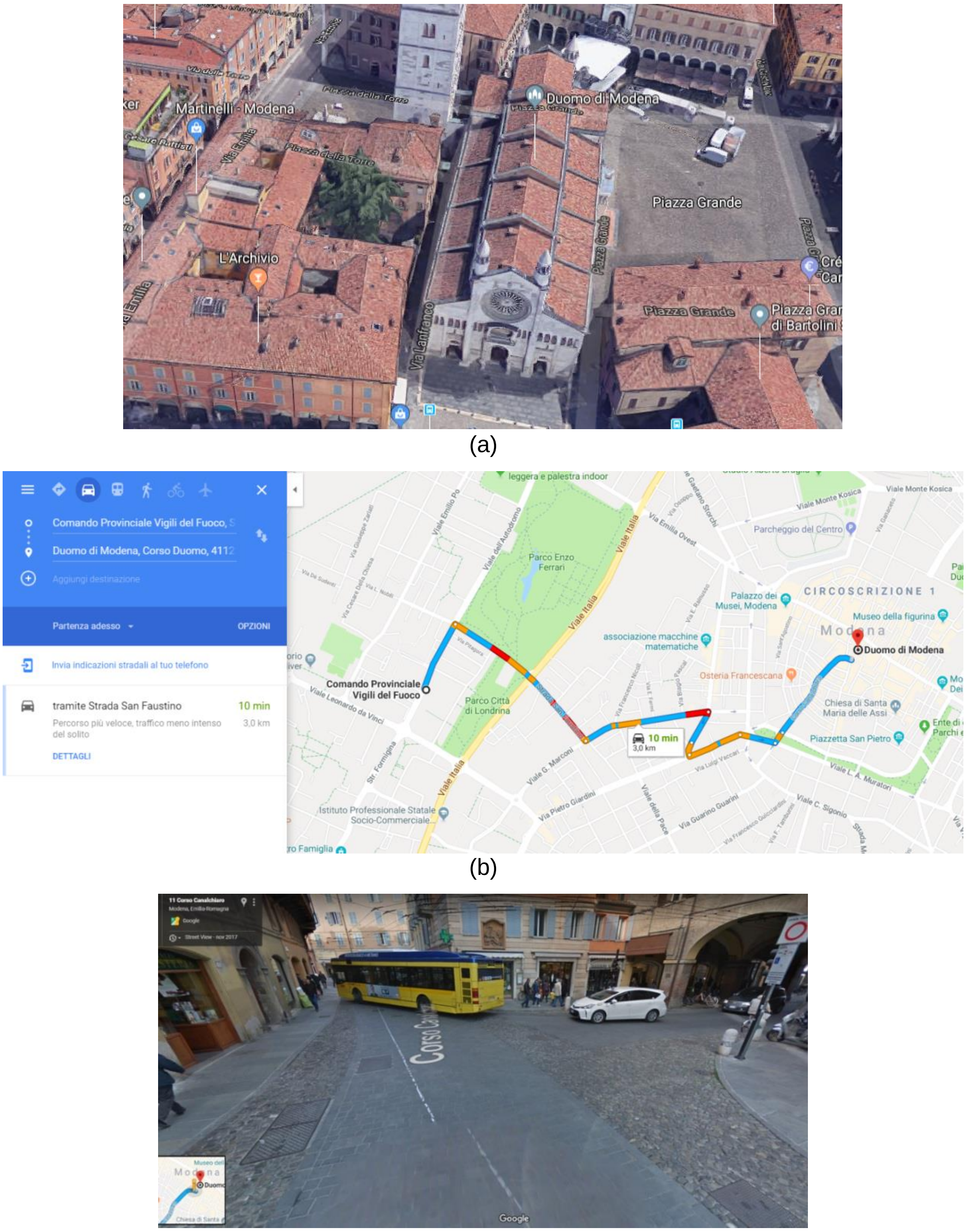
(a)

(b)

Figure 24: Presence of large amount of people. Presences during the Christmas midnight celebration (a); Emergency exits in the main hall (b).

Regarding the vulnerabilities of the Modena Cathedral with reference to the urban scale:

- *Difficulties of be approached by rescue vehicles.* This is a fairly relevant vulnerability for the case study. In fact, the Firefighters station it is quite near to the Modena Cathedral (3 km) but it is also locater in historical center with narrow access ways (see Figure 25). The peculiarities of the location of the case study, together with the above mentioned presence of a smoke detection system, allow to consider a time interval of 10min as a suitable average total intervention time (from the ignition to the arrival of firefighters) in case of fire*;*



(a)

Comando Provinciale Vigili del Fuoco, S
Duomo di Modena, Corso Duomo, 4112
Aggiungi destinazione
Partenza adesso
OPZIONI
Invia indicazioni stradali al tuo telefono
tramite Strada San Faustino 10 min
Percorso più veloce, traffico meno intenso del solito 3,0 km
DETTAGLI

(b)

(c)

Figure 25: Difficulties of be approached by rescue vehicles. Google® aerial view (a); Google® street distance from firefighters (b); Google® street view of narrow connecting roads (c).

- *Possible indirect involvement due to vulnerability of other units of the building cluster* *which can make the single heritage building subjected to fire spread or collapse spread.* The Cathedral Museum is stored in a building located adjacently the case study (Figure 26). The museum is characterized by a significant combustible load due to the presence of the library. There is a certain (small) probability that a fire occurring in one of the two buildings (Museum or Cathedral) can spread to the other.

(a)

(b)

Figure 26: Possible indirect involvement of other units. Google® aerial view of the Museum and the Cathedral (a); Interior view of the Museum (b).

Fire Hazard Analysis (FHA) of the Modena Cathedral

The following parameters cases are pragmatically set in the hazard analysis for the case study (pragmatic scenario approach):

- triggering event
  - fire location inside the building: 1) loft in the zone above the Inlaid wooden “pontile”; 2) main hall;
  - fire ignition causes: a) electrical short circuit; b) free flames;
- fire intensity:
  - combustible load q: i) q=500 MJ/m^2; ii) q=1000 MJ/m^2;
  - ventilation V: x) high ventilation (fuel controlled fire); xx) no ventilation (combustible controlled fire).

From the plausible combination of the above parameters a set of fire scenarios can be considered: for each fire triggering condition above (namely 1)+a), 1)+b), 2)+a), 2+b)), four fire intensities should be analysed: q=500 MJ/m^2+ NO ventilation; q=1000 MJ/m^2+ NO ventilation; q=500 MJ/m^2+ high ventilation; q=1000 MJ/m^2+ high ventilation. Then a total of four fire scenarios are defined each fire triggering condition. For each scenario the Cause-consequence (or “scenario”) analysis is carried out by defining event-tree diagrams like the example one shown in Figure 27 (obtained for all the scenarios coming up from the 1)+a) fire triggering conditions above). As already said, a probability has to be assigned to each couple of arms at each event concurring to the sequence which determines the fire evolution. These couple of probabilities has to be intended as conditional to the previous event occurrence and, inside the same event, the couple of probability values has to be complementary to

100%. Each of these values are assigned on the basis of the numerical (CFD and structural) analyses carried out as described in previous sections and for the case study. One of the most critical point of the risk analysis is about the assignment of the triggering event probability with reference to a specified "return period" Tr (taken equal to 50 years because of the HPLC characteristics of the considered hazard, in contrast to the 1 year Tr usually chosen for the seismic hazard): this probability (occurrence in 50 years) is assigned on the basis of the experience of the risk analysts, and it is then quite arbitrary. This is something that is necessary due to the lack of sample statistics in the literature regarding fires affecting cultural heritage buildings.

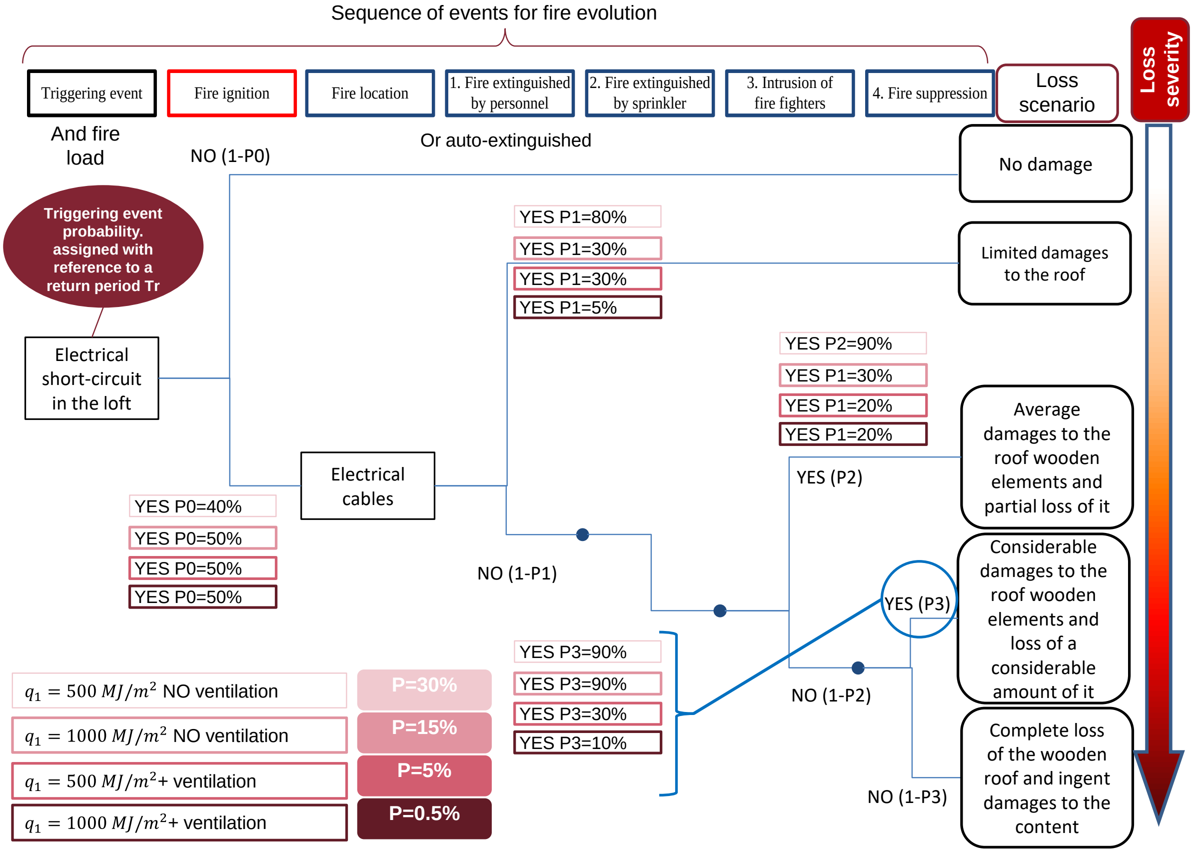


Figure 27: Example of event-tree diagram for fire risk analysis of the Modena Cathedral

For the considered case study, the occurrences assigned to the different triggering events are shown in Table 2.

Table 2: Probabilities assigned (for Tr=50yrs) to the triggering events.

Triggering event (reference is made to the list of parameters provided in the main text above)	Assumed occurrence is 50 years	Comment
1)+a)	50.5%	(short electrical circuit in the loft compartment) Most probable event
1)+b)	0%	(free flames in the loft compartment) Absence of free flames in the loft
2+a)	1%	(short electrical circuit in the main hall) It is less probable of the short circuit in the loft due to continuous visive control of the electrical cables
2+b)	1 %	(free flames in the main hall)

Regarding the Fire intensity, the HRR curves corresponding to the different combinations of q (500 or 1000 MJ/m^2) and V (0 or 1) are shown in Figure 28.

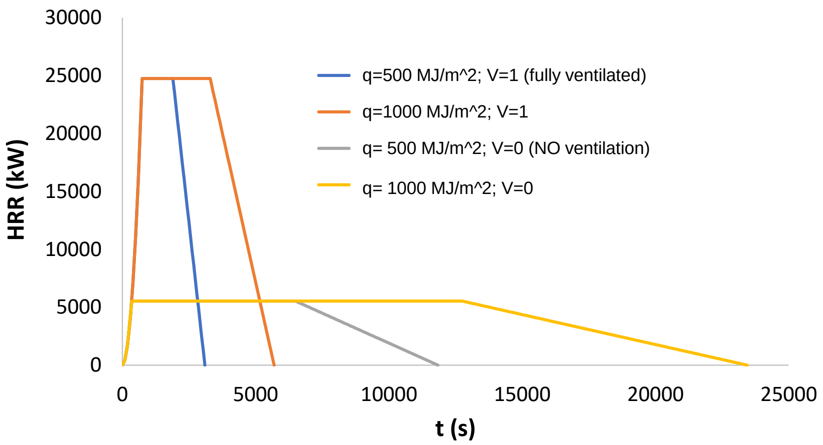


Figure 28: Fire Intensity. HRR curves for different combinations of q (combustible load) and V (ventilation factor)

Numerical modelling of the Modena Cathedral for fire risk analysis

CFD model both of the whole Modena Cathedral and of the loft compartment has been created and analysed in FDS, the wooden elements of the roof (beams and trusses) are modelled as combustible. The structural model is built for a portion of the roof structure, as described in previous sections, and already shown in the above-presented benchmark (single beam) problem, the thermal (heat transfer) analysis is carried out by using beam finite elements in order to investigate the temperature transmission along the beams axes and not along the cross-section. The successive heating of external to the internal layers is modelled as already shown in the benchmark application: i.e. by appropriately calibrating the beginning temperature of the material proprieties decay laws (see Figure 16 above). The FE model for thermal and structural non-linear analysis is built by the commercial code STRAUS 7® (www.hsh.info). FDS models are shown in Figure 29 (whole building) and 30 (loft compartment only). The FE model used for the thermal and structural analysis is shown in Figure 31.

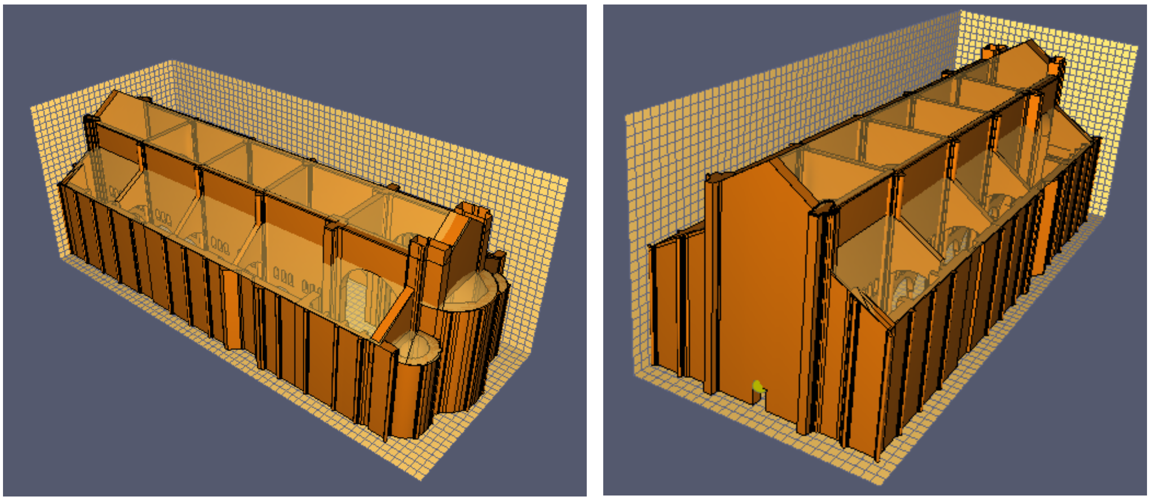


Figure 29: FDS model of the whole building.

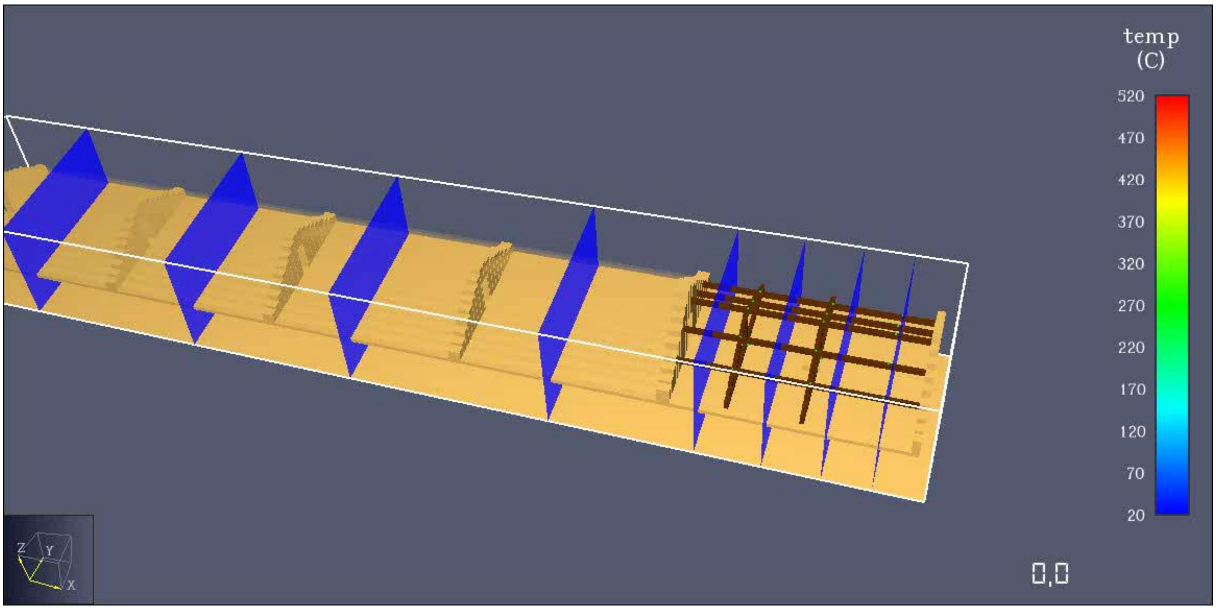


Figure 30: FDS model of the loft compartment (blue layers are for output reading purposes only).

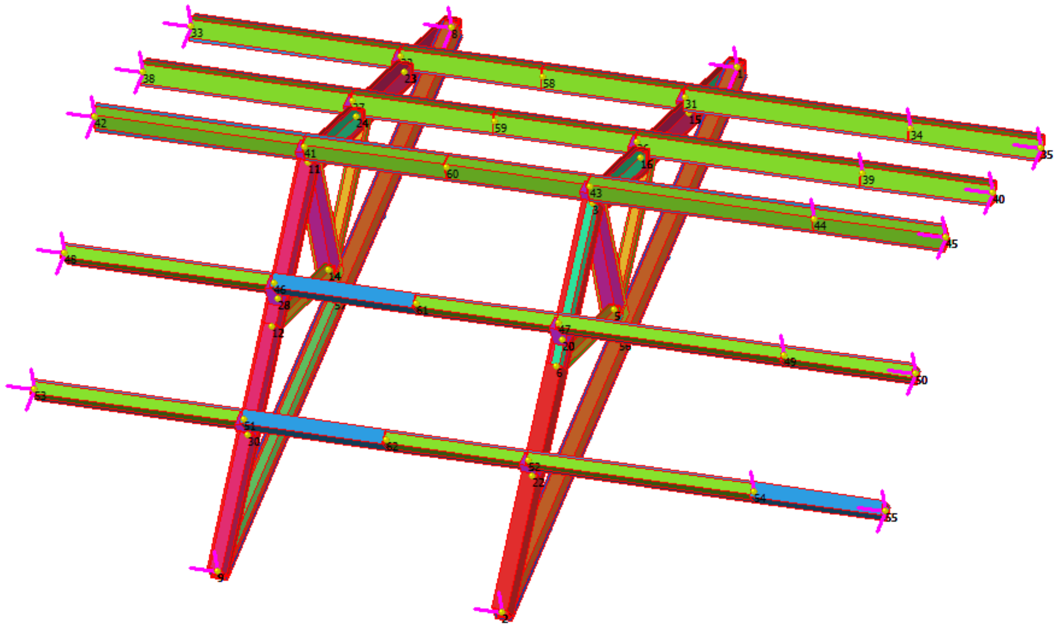


Figure 31: FE model of part of the roof wooden structure for thermal and structural analysis (developed in STRAUS 7 ®).

Fire Dynamics, exodus of people and air temperature evaluation around the structural elements

Simulations for fire dynamics are carried out both on the whole model and on the loft compartment model. The results of the FDS simulations are taken as basis for expert assignments of conditional probabilities to each couple of arms at each event which is solely determined from the fire dynamics (e.g. extinguishment of the fire by the personnel or by the sprinklers or available time for firefighters safe intervention/intrusion), concurring to the sequence which determines the fire evolution (Figure 27).

The whole model is used for the case 2)+b) in table 2 (free flames in the main hall) where the combustible stack is low and it is constituted by cloth drapes and wooden benches. The numerical simulation of this case is mainly relevant for evacuation assessment purposes: human behaviour can be efficiently simulated by available research and commercial codes that can be coupled with the FDS results. In the MiCHe project, human behaviour during the exodus has been simulated with Pathfinder® (https://www.thunderheadeng.com/pathfinder/), an emergency egress simulator that allows the evaluation of evacuation models and produce realistic graphics and animation of the exodus. Figure 32 shows different frames of the output movie representing the exodus procedures obtained as output by Pathfinder in the analysed fire scenario where the fire in the main hall occurs during the religious celebration (the Cathedral is full of people).

The loft model is used for the evaluation of the time-ait temperature curves from cases 1)+a) in table 2 above, to be applied in the successive FE thermal and structural analyses. An example of the results (two different frames) coming from these simulation is provided in Figure 33 below. From the second frame shown there, the combustion of wooden beams can be appreciated from the temperature contour also shown in the figure.

The installation of sprinkler automatic fire suppression system with an activation temperature of 60°C is considered as mitigation measure for fire risk. The effect of the sprinklers is shown by comparing (Figure 34) the fire development at the same time step as obtained without sprinklers and with them. The main effect of installing the sprinklers is then decreasing the air temperature around the structural elements and confining the fire extension.

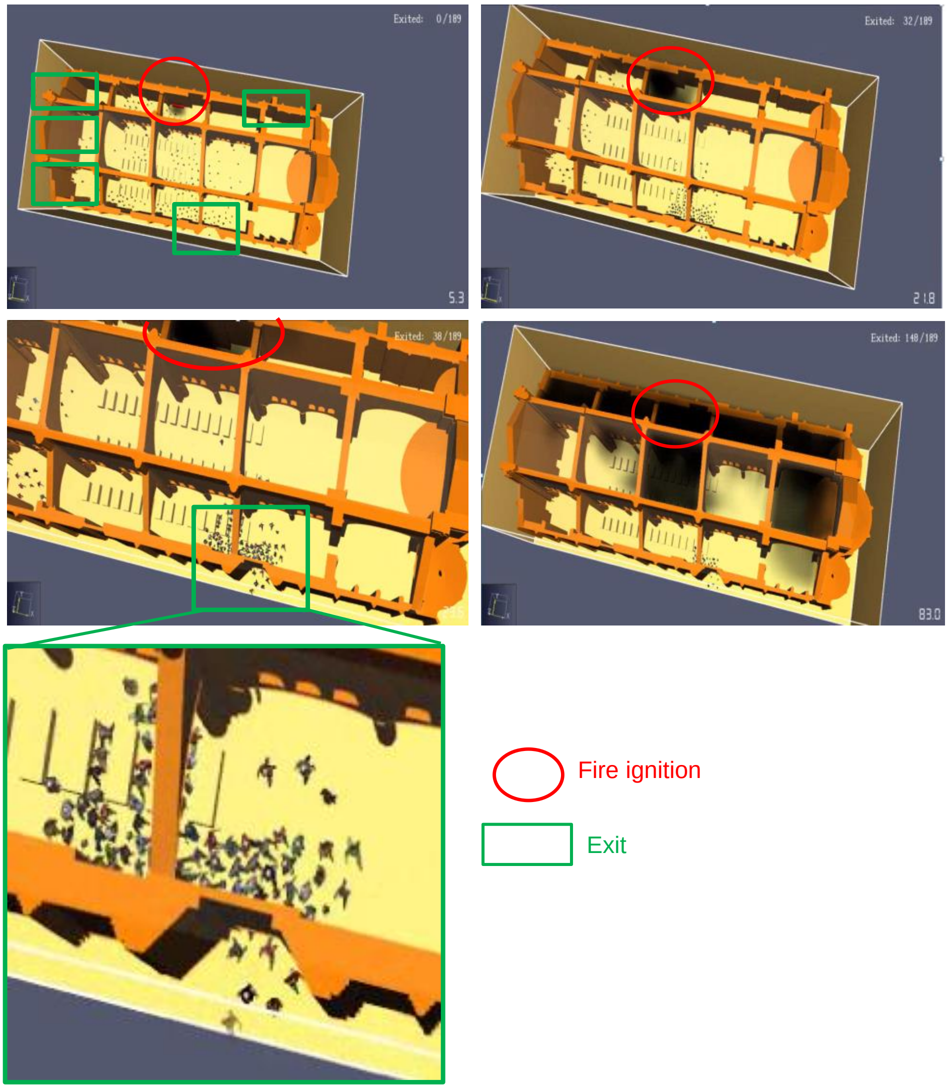


Figure 32: Frames of the exodus movie (developed in Pathfinder®).

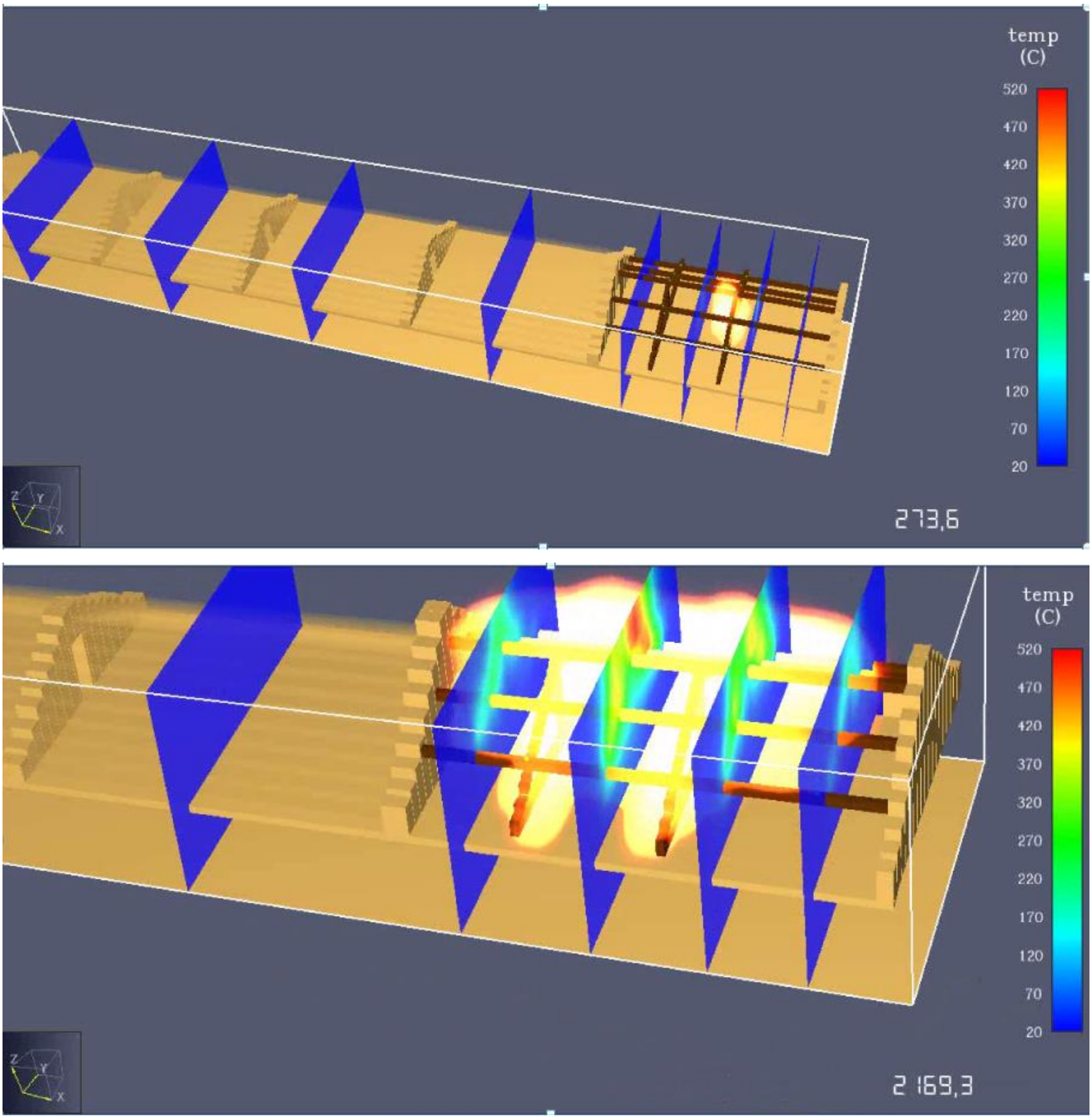


Figure 33: Frames of the fire development in the loft.

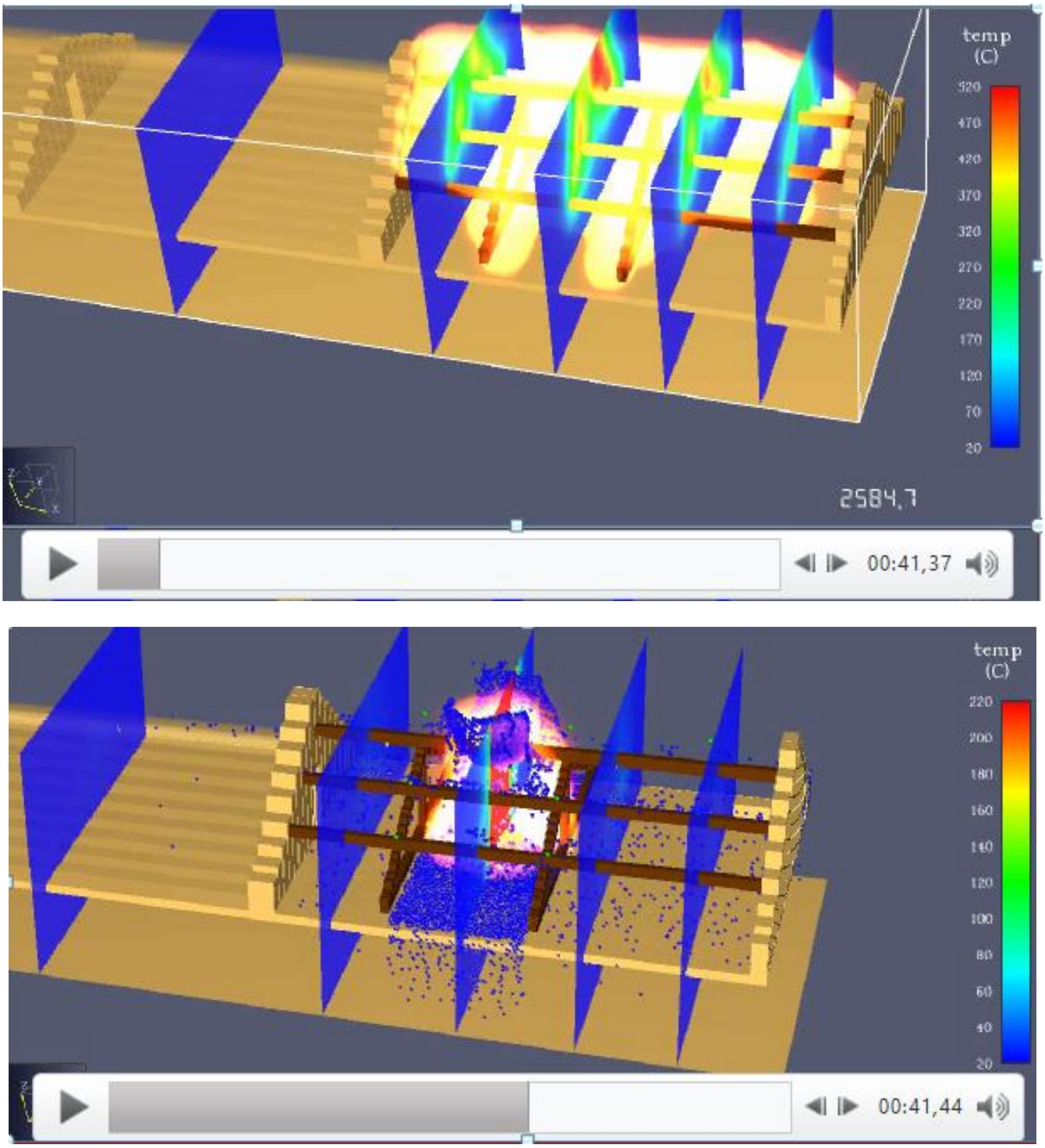


Figure 34: Effects of the sprinklers fire development in the loft.

The final synthetic result of the fire dynamics simulation is the time-air temperature curve to be used for the thermal and structural analyses. In Figure 35, the comparison of such a curves for a location around one wooden beam as obtained for the case 1)+a) and q= 1000 MJ/m^2; V=0 (NO ventilation) with and without sprinklers is shown.

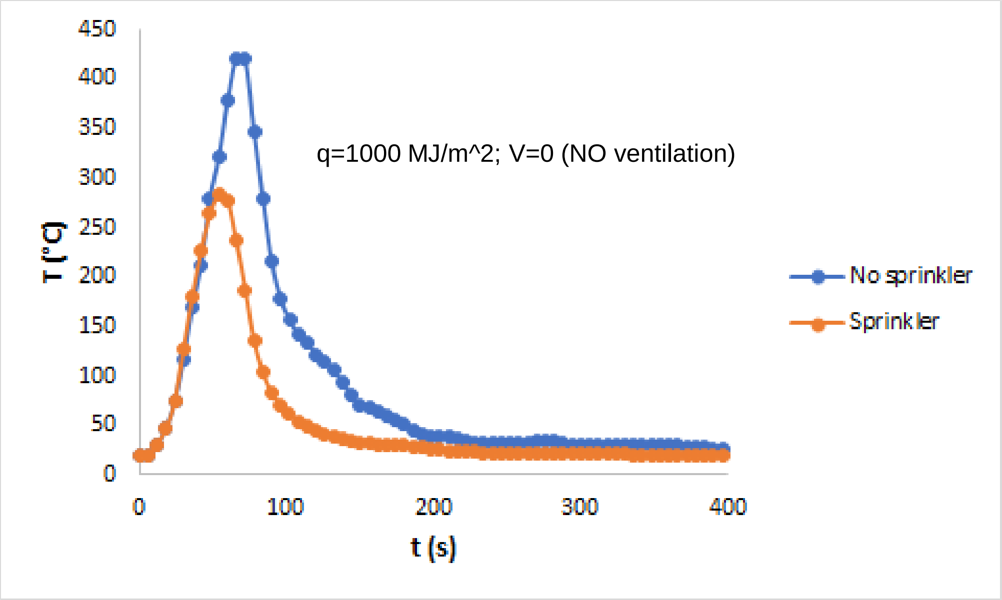


Figure 35: Effects of the sprinklers on the time-air temperature curves.

FE analysis for thermal and structural response evaluation

As already said, the output of the Fire Dynamics analyses in the loft (time-air temperature curves around different locations in structural elements) are used to conduct first an heat transfer analysis on beams finite elements (temperature is diffused along the beam abscissa) and then a subsequent structural analysis to investigate the structural response of the wooden roof in Modena Cathedral. Depending of the response experimented by the structure, pertinent assignments of the conditional probabilities to each couple of arms at each event (concurring to the sequence which determines the fire evolution like the one shown in Figure 27) can be accomplished by expert judgment of the structural response: for example, if large peak vertical displacement are reached in very short time by the roof beams during the fire, it can be pertinently assumed that the probability of suppressing fire before collapse is very low. Results of the FE thermal+ structural analyses are shown in Figures 36, 37, 38. By assuming a maximum acceptable vertical displacements equal to 0.2m for both the transversal wooden beams and the wooden truss, it is evident from the figures that the fully ventilated fire cases are critical for structural performances if the fire is not suppressed (by sprinklers or firefighters).

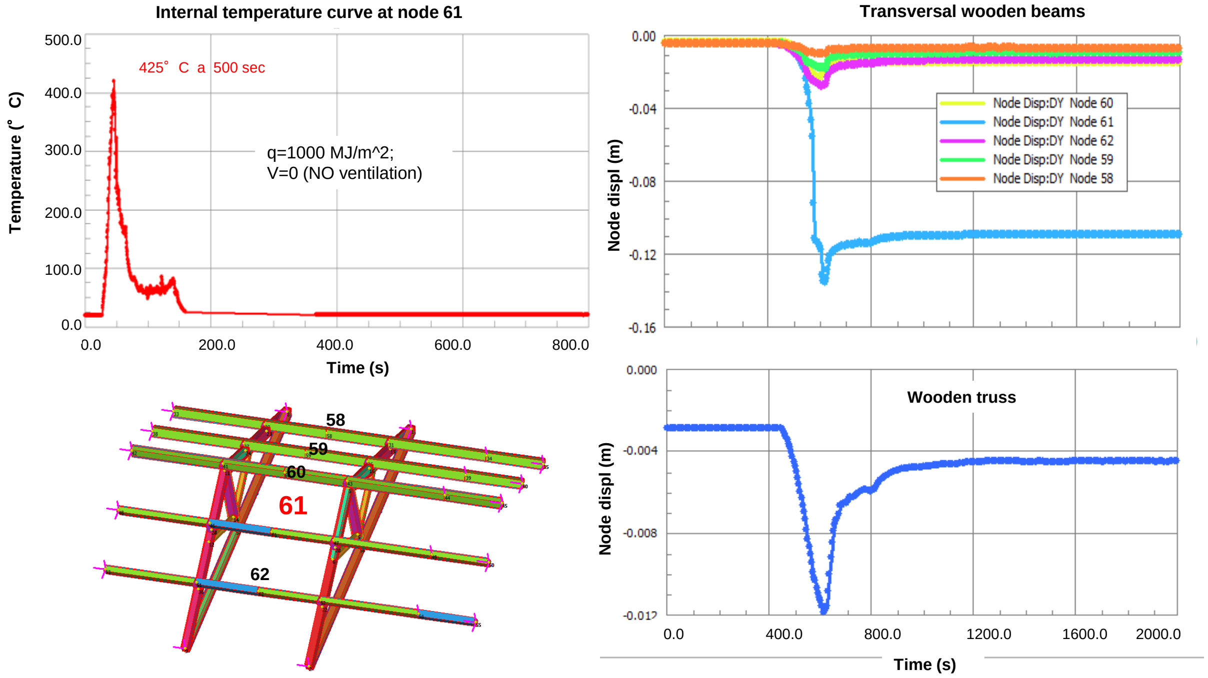


Figure 36: Summary of the thermal/structural response. Location: loft compartment; Ignition: short electric circuit; q=1000 MJ/m^2; NO ventilation.

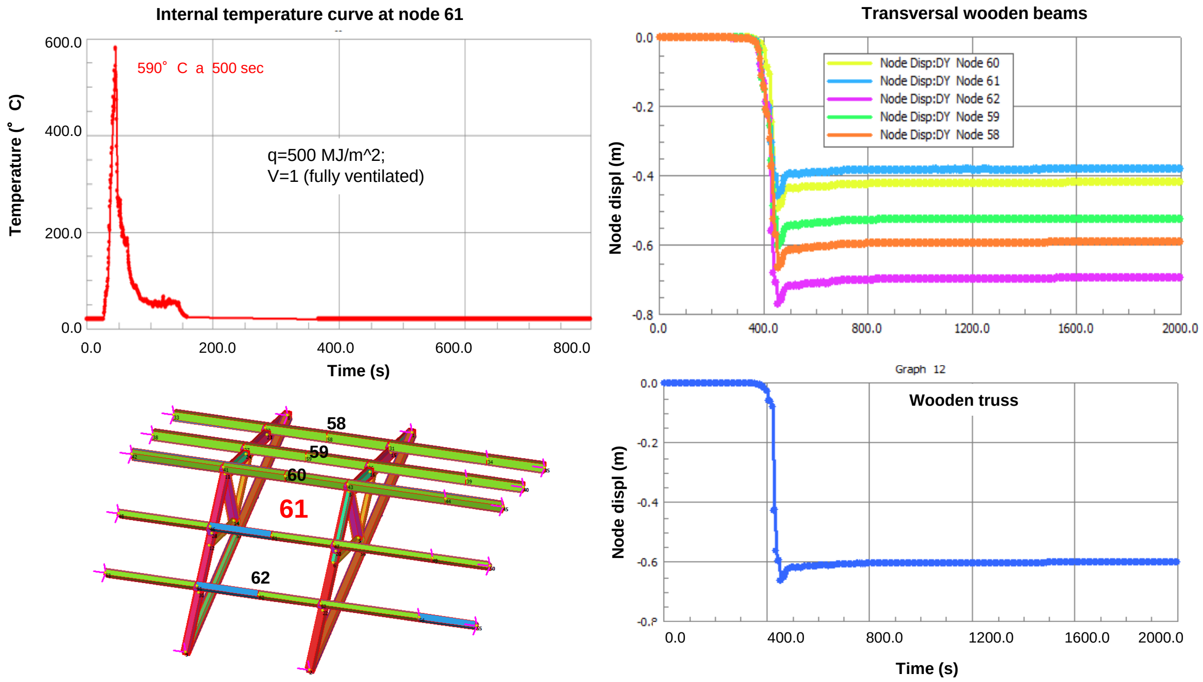


Figure 37: Summary of the thermal/structural response. Location: loft compartment; Ignition: short electric circuit; q=500 MJ/m^2; fully ventilated.

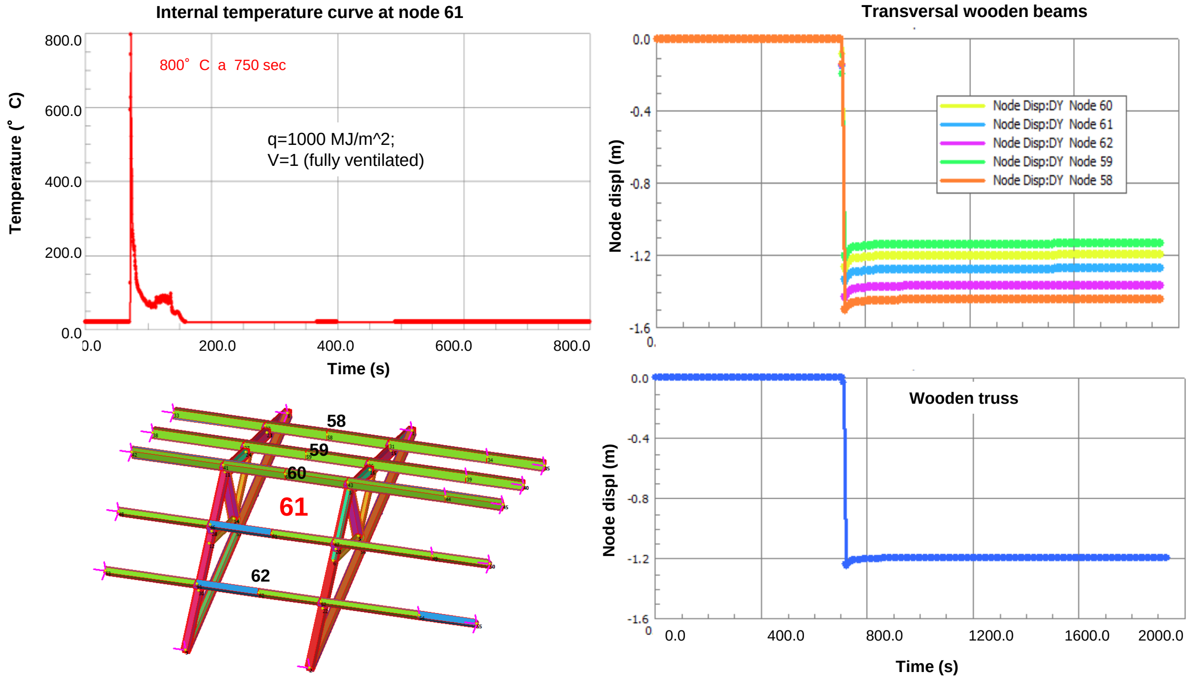


Figure 38: Summary of the thermal/structural response. Location: loft compartment; Ignition: short electric circuit; q=1000 MJ/m^2; fully ventilated.

Fire risk assessment for the Modena Cathedral

The scenario-based procedure for fire risk assessment introduced in previous sections is finally applied to the case study as described below for the fire triggering condition 1)+a) shown in Table 2. As already said (see the fire hazard analysis section above) four fire scenarios are defined for each fire triggering condition. First of all, appropriate (conditional) probabilities are assigned to the different fire intensities (different scenarios) as shown in Figure 39.

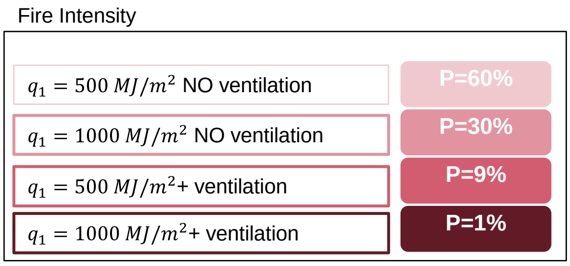


Figure 39: Conditional probabilities assigned to the fire intensity parameters in the loft compartment.

On the basis of the results obtained by the thermal+structural analyses, for each scenario appropriate conditional probabilities are assigned to different paths of the event-tree diagram for fire risk analysis and by the series combination of such a probabilities, the probability of each defined loss severity are obtained as conditional to the fire scenario occurrence probability(Figures 40 to 43). Finally, the total risk assigned to each loss severity is obtained by the sum of those obtained by single scenarios Figures 44 to 47). The resulting total risks assigned to the loss severities refers to a return period of 50 years and are the components of the risk curve shown in Figure 48, representing the complementary cumulative distribution function (CCDF) probability in the return period Tr=50 years, which is also interpolated by an exponential equation. If the loss severities are expressed in monetary terms, the risk curves constitutes the classical output of a single hazard risk analysis.

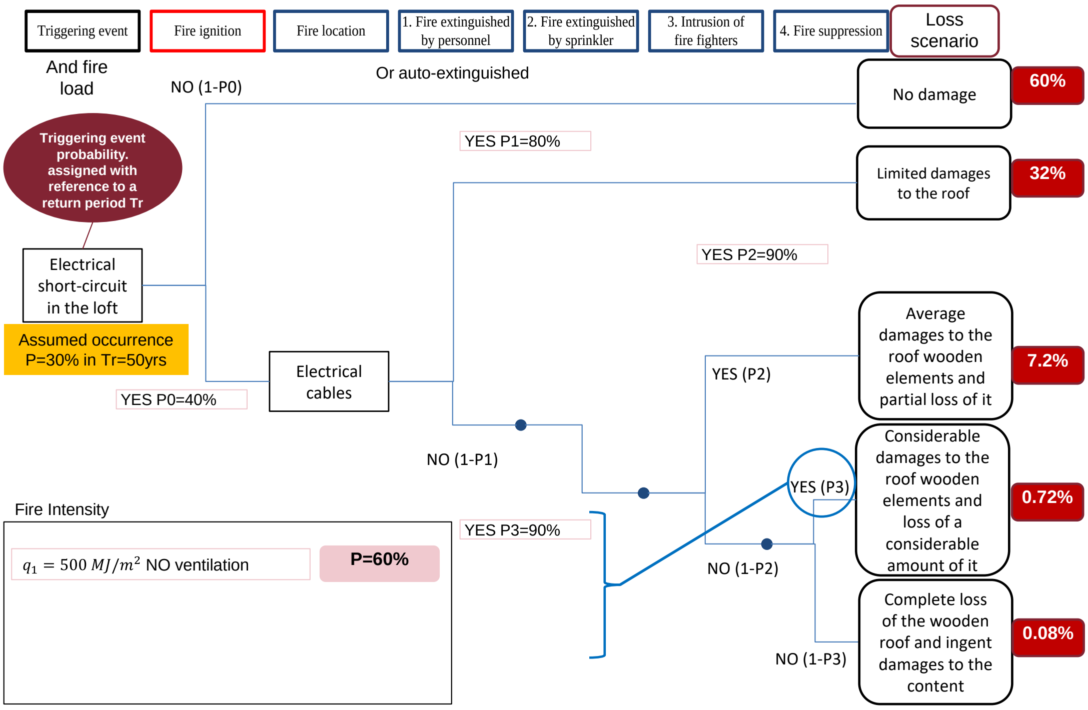


Figure 40: Fire in the loft compartment. conditional probabilities assigned to different paths of the event-tree diagram and probability of each defined loss severity. q=500 MJ/m^2; NO ventilation.

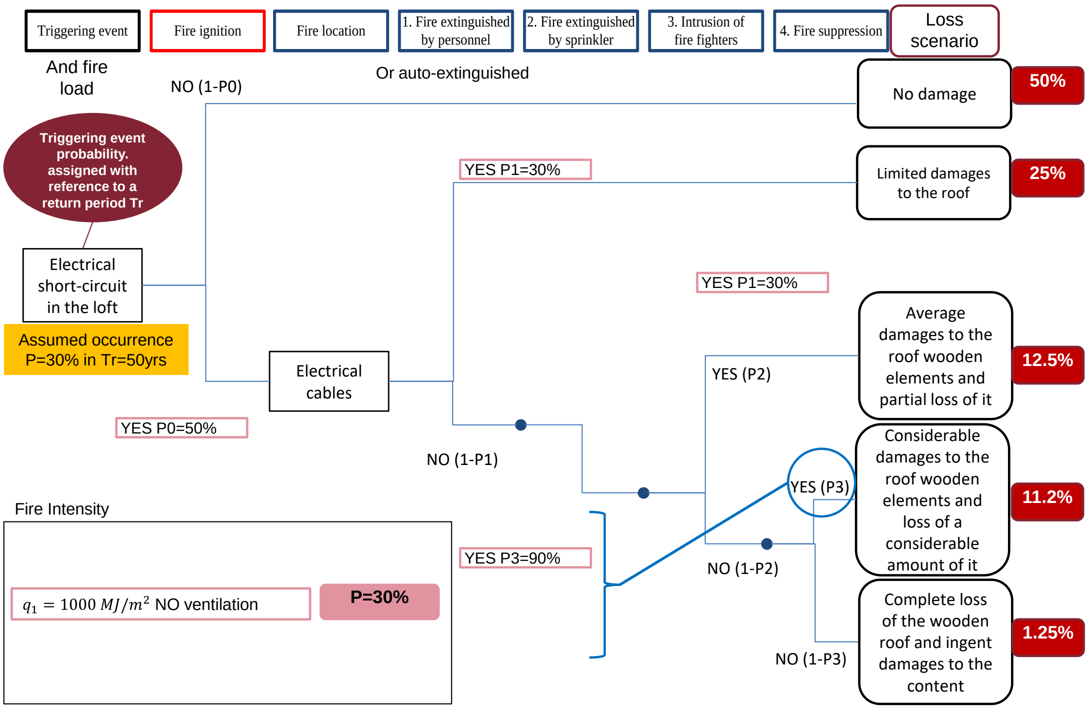


Figure 41: Fire in the loft compartment. conditional probabilities assigned to different paths of the event-tree diagram and probability of each defined loss severity. q=1000 MJ/m^2; NO ventilation.

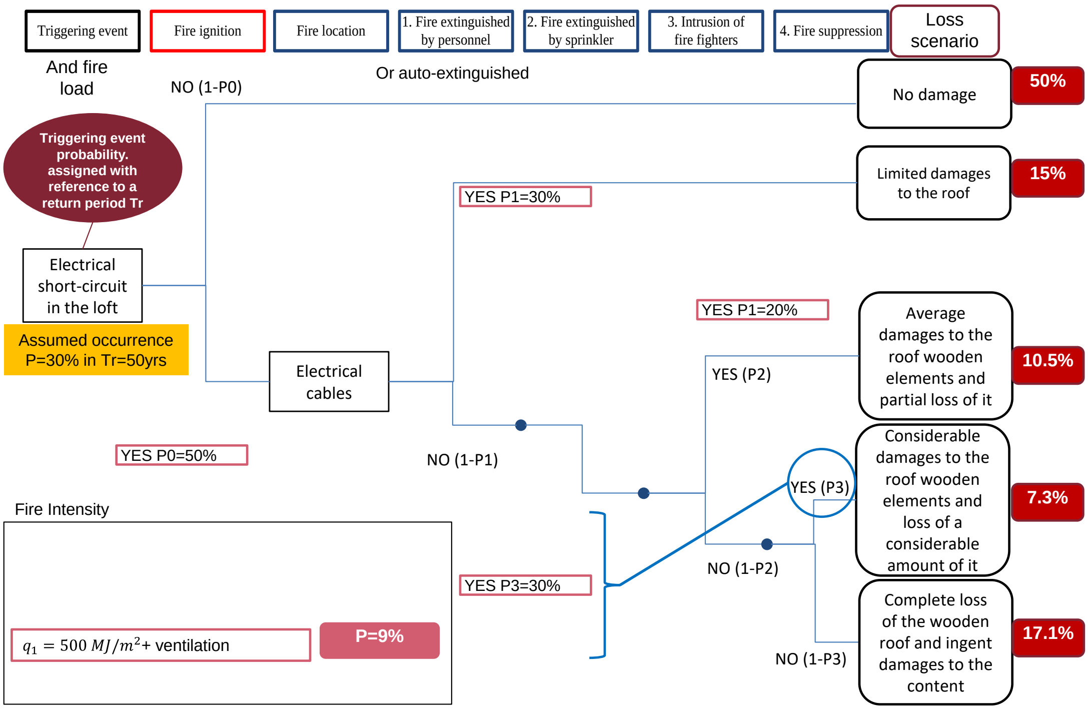


Figure 42: Fire in the loft compartment. conditional probabilities assigned to different paths of the event-tree diagram and probability of each defined loss severity. q=500 MJ/m^2; fully ventilated.

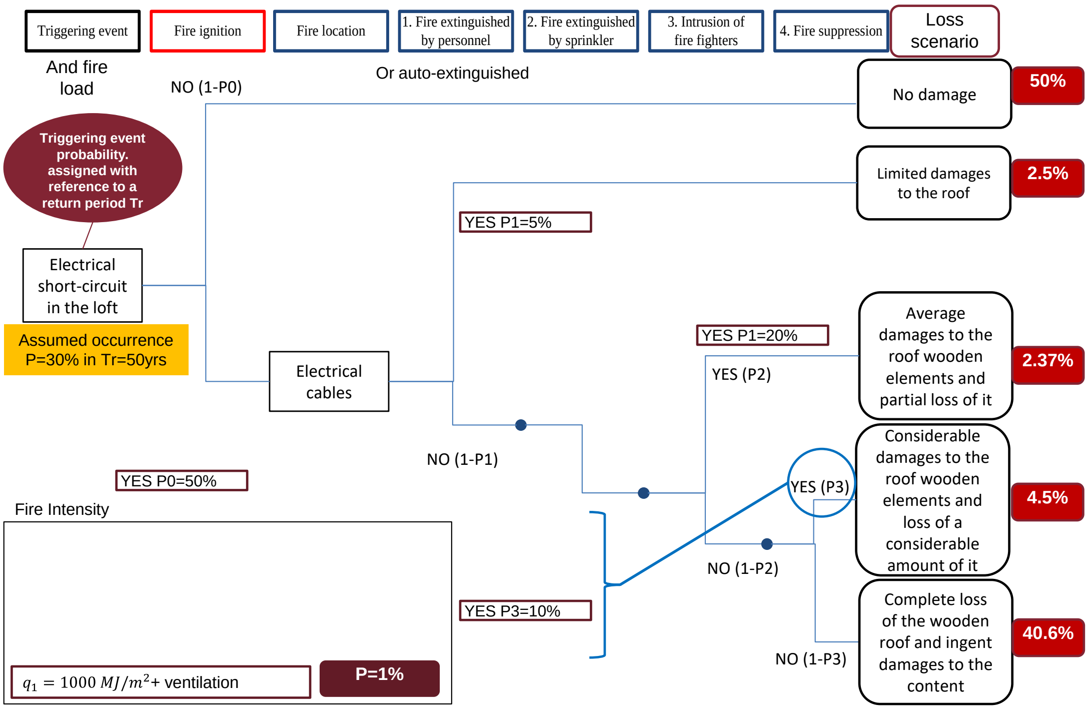


Figure 43: Fire in the loft compartment. conditional probabilities assigned to different paths of the event-tree diagram and probability of each defined loss severity. q=1000 MJ/m^2; fully ventilated.

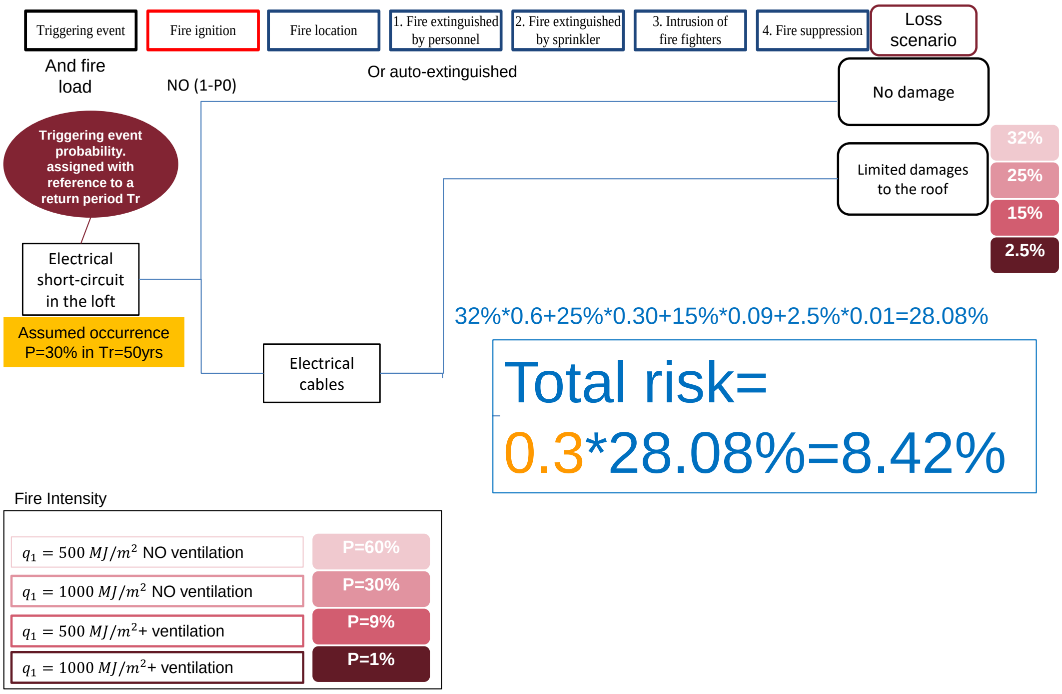


Figure 44: Fire in the loft compartment. total fire risk evaluation for the loss scenario 1.

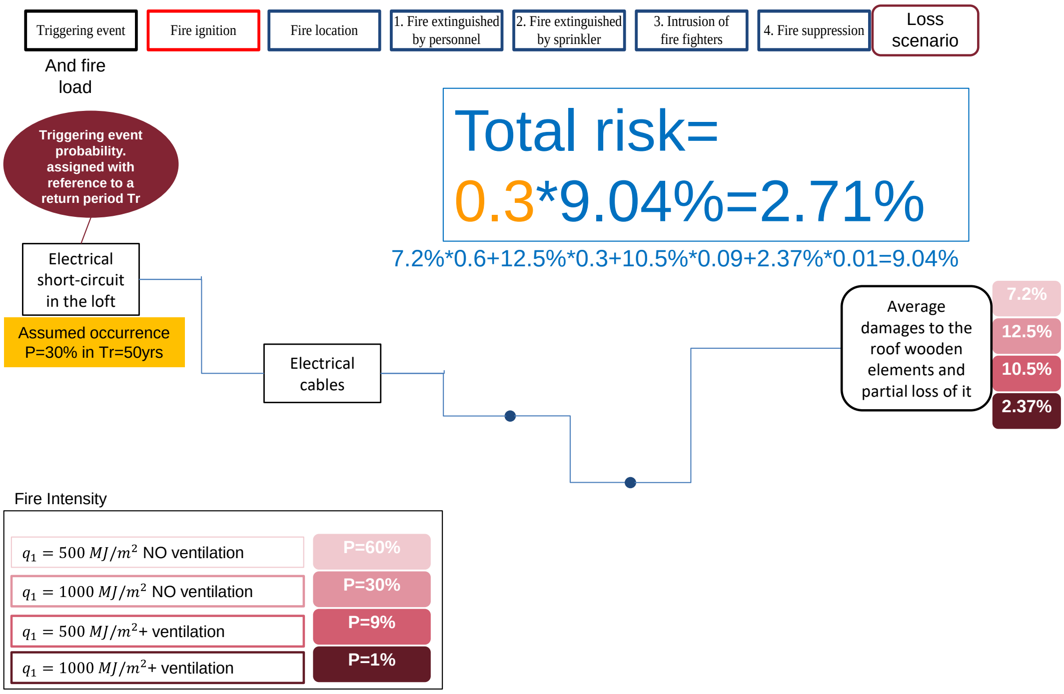


Figure 45: Fire in the loft compartment. total fire risk evaluation for the loss scenario 2.

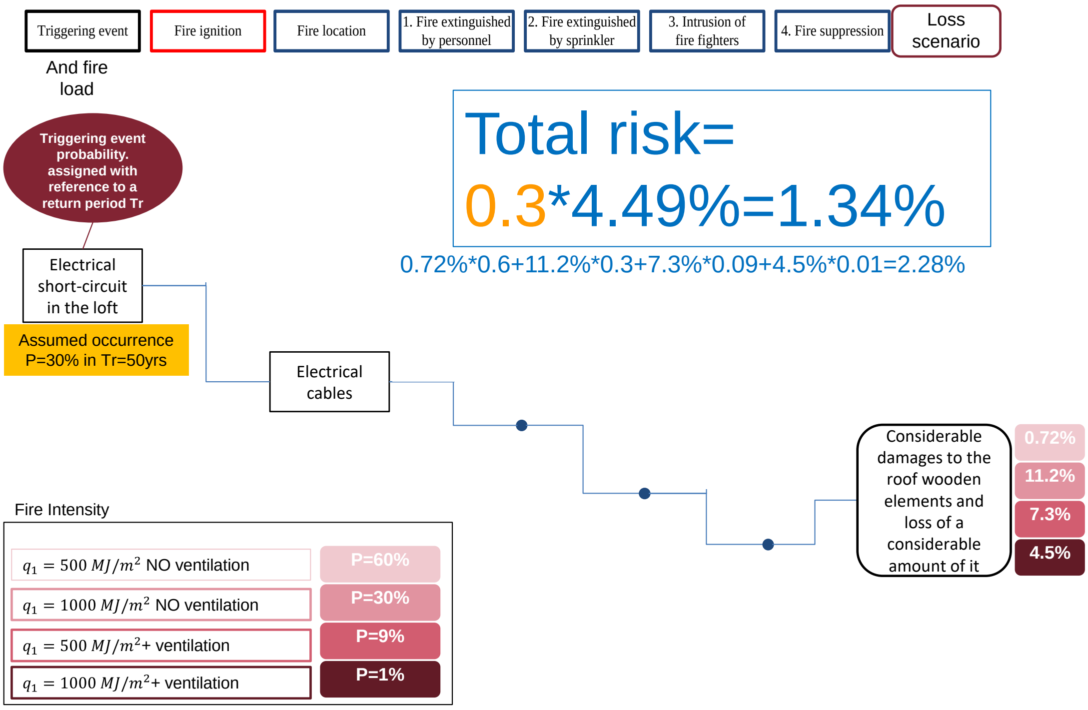


Figure 46: Fire in the loft compartment. total fire risk evaluation for the loss scenario 3.

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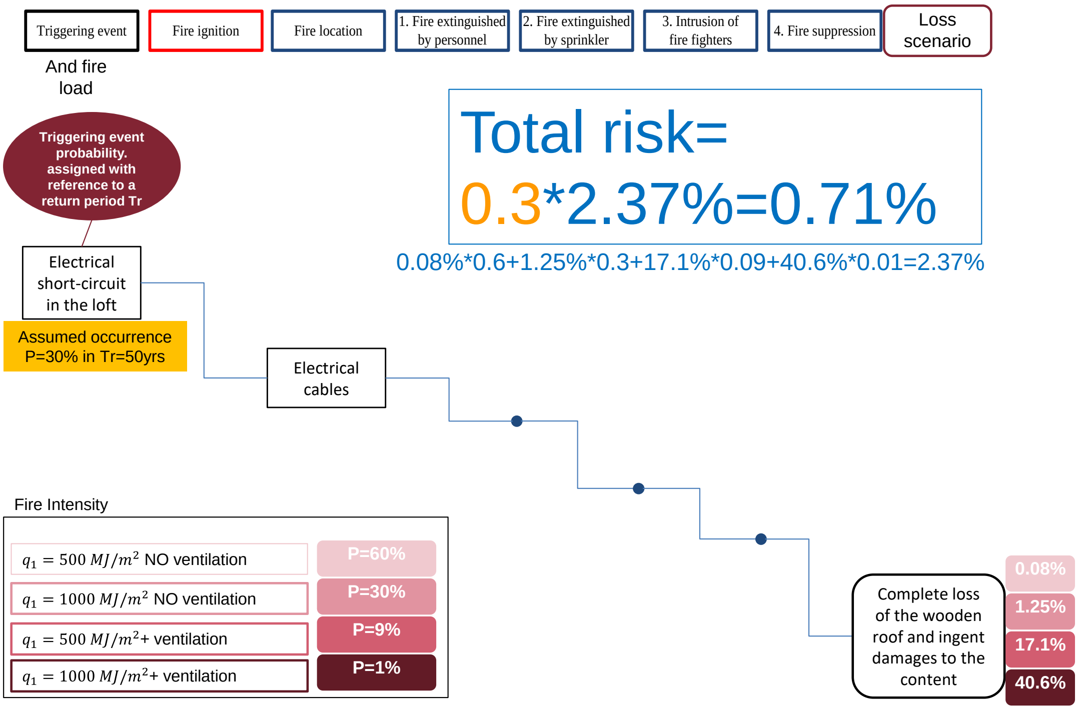

Figure 47: Fire in the loft compartment. total fire risk evaluation for the loss scenario 4.

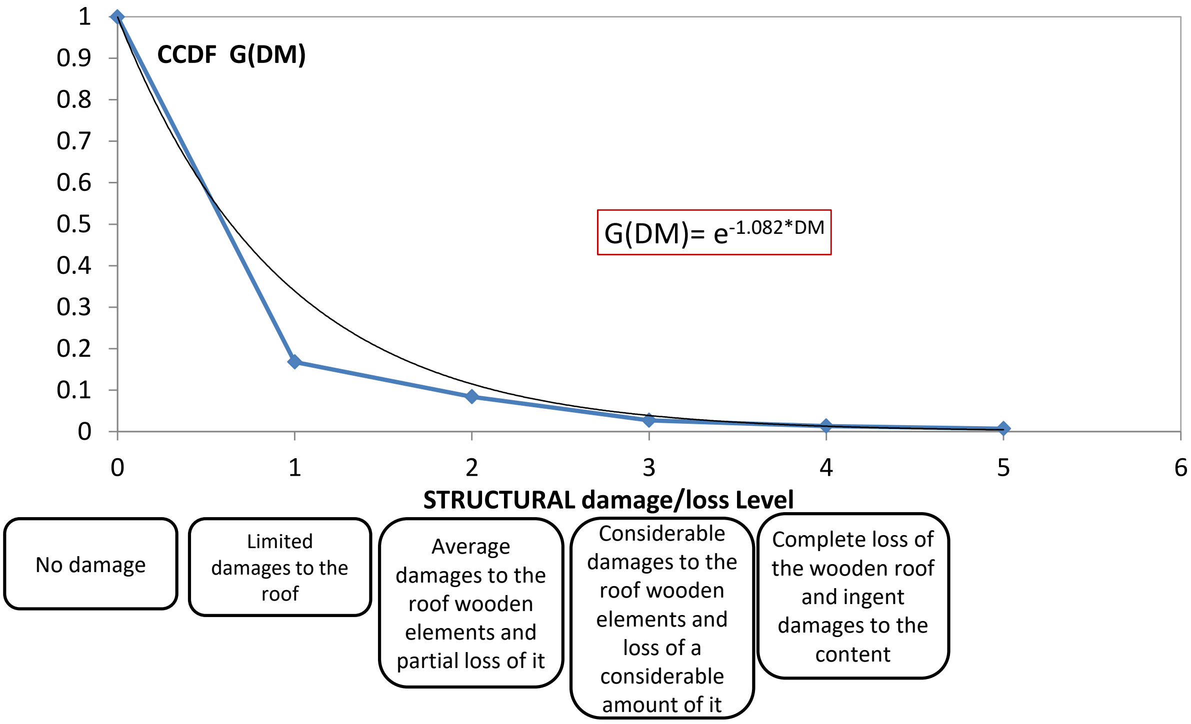

Figure 48: Obtained fire risk curve for the loft compartment with reference to Tr=50 years.

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In terms of risk, the installation of sprinkler fire suppression systems has a significant effect in reducing risk mainly for the most catastrophic scenarios (tails of the risk curve). The change of the risk curve due to the installation of sprinklers is shown in Figure 49.

Conclusions

A detailed methodology for fire risk analysis in Heritage buildings has been conceived and applied to a case study (the Modena Cathedral). Peculiarities of both the Low-Probability-High-Consequence (LPHC) events like fire, and of the heritage buildings (related to specific vulnerabilities to fire) are taken into account. As final result, the procedure produces a fire risk curve to a reference to a pre-defined return period Tr which, for fire hazard, has to be set to 50 years at least.

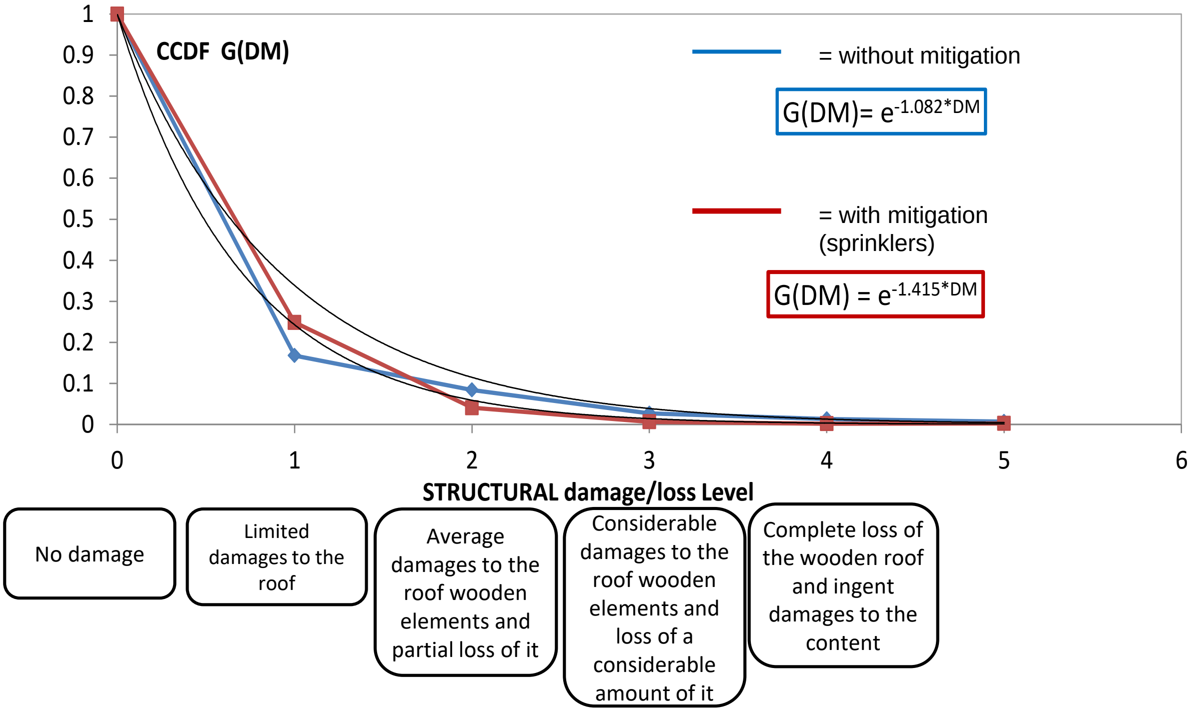

Figure 49: Fire risk curve with and without mitigation measures.

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