IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)
e-ISSN: 2278-1684,p-ISSN: 2320-334X, Volume 16, Issue 3 Ser. IV (May. - June. 2019), PP 26-36
www.iosrjournals.org

Residual Strength Evaluation for the Damaged Structures of Notre-Dame De Paris: A Way for a Correct Reconstruction

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Abstract
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An impressive fire devastated the cathedral of Notre Dame in Paris, one of the symbols of European architecture. The flames started from the scaffolding embracing the base of the spire on the cathedral roof. The fire blazed up in the church during the religious celebration on April 15th at 6:45 p.m. The fire enveloped abruptly the roof and the spire erected by Viollet-le-Duc in 1860. The collapse took place about 80 minutes around 8 p.m [1-3]. Today, the clamor is all around, the silence is in the heart.
At the time of the present report, the causes of the catastrophe are still wrapped in a dense smoke, like the one generated by the burning "forest"– as the roof structure was called. This is the figure of the disaster. The Cathedral's inferno devastated a world treasure, prompting an outpouring of collective sorrow and soul-searching over whether to recreate the destroyed oak-framed roofing and spire or adapt the cathedral to the 21st century. In the present paper, an original evaluation of the residual strength taking into account the fire effect and the water saturation in the limestone after the extinguishing is considered. The residual strength ratio (RSR) and the compressive strength evolution (CS) are carefully evaluated for the injured structures. An estimation of the effective strength ratio of the Cathedral walls is estimated. At the same time, the proposed approach is based on the solution of an extreme adaptive structure (grid shell) able to offer a strong temporary shelter in a short time and allowing a careful work of documentation and restoration of the roof cathedral by an approach like "how it was and where it was".
***Keyword**: Notre-Dame fire; Lutetian limestone; Safeguard; Grid shell*

Date of Submission: 30-05-2019 Date of acceptance: 15-06-2019

I. Introduction

Over the past few decades we have rediscovered ourselves in all our fragility. We are helpless in the face of terrorist attacks, environmental disasters, such as earthquakes and floods. In the face of massacres and environmental catastrophes, millennia of technology, literature, culture and scientific developments are erased and the human race simply rediscovers an animal feeling: the fear of what it does not know but of which it perceives a risk. This is why we created the symbols. Symbols allow us to maintain the hope during the darkness and difficulties along our history. This is why landmarks and monuments must survive at any costs. Immutable over time. Notre-Dame, like others, is one of these. They represent the dimension of our ability to be resilient in the face of any adversity. This is why when a disaster strikes a symbol it is not the body of a community that suffers but right the community soul itself.

After the stake, it was clear that the structures of the cathedral were not irreparable and totally compromised [1-3]. The collapse of the original timber roof erected definitively in 1326 together with the spire made in the nineteenth century can represent, today, an extraordinary opportunity to show the social, cultural and technological maturity of our Era. In the Author opinion, the goal is to reconstruct the past using a new structure as a temporary protective "machine".

While the structures of Notre-Dame was burning, the collective memory ran to two past disasters that have marked the European religious and cultural conscience (Fig.1a). Three episodes which, for various reasons, have particular similarities with the tragedy of Notre Dame: The first is the burning of the roof of the Turin Cathedral – where the weel-known Holy Shroud is kept [4]. It occurred during the night between April 11st and 12nd 1997. The second event is represented by the collapse of the vault frescoed by Giotto in Assisi in 1290 and stroke by the earthquake on September 26th , 1997, at 11.42 a.m [5]. The third is the collapse of the structure of the Noto Catheral on March 26th, 1996 [6] (Fig.1b-d). The similarities between the fire of Paris and that of Turin are impressive. The first similarity, undoubtedly, concerns the almost perfect anniversary. The dome of the architect Guarino Guarini built in 1680 in Turin, representing a masterpiece of the Italian Baroque, burned 22 years and 4 days before the explosion of the Notre-Dame fire. In both cases the origin of the fire is to be found in the presence of the scaffolding structures mounted on the ancient roofs of the two monuments in order to carry out restoration works. In both cases, the "*treasures*" of the two cathedrals were rescued. The sacred shroud in the case of the first capital of Italy, the Crown of Thorns in the case of Paris. The substantial difference was in the dissimilar fate that the two roof met. In the case of Turin, in fact, the particular structure of the Guarini's dome and the building material allowed to save completely the dome and most of the roof [4]. In the case of the cathedral of Notre Dame, on the other hand, the 12^{nd} century oak structure and the 19^{th} century spire structure were burned and completely destroyed in 77 minutes [2,3]. The destroying pace, in this case, was so severe because of the high concentration of the roof dust characterized by a high explosion effect in conjunction with electric voltage, as reported in recent evidence [7]. The last two examples, here reported, regarded the reconstruction of structures almost completely destroyed by a catastrophic events (earthquakes). The collapses of the vaulted roof of the Basilica Superiore di Assisi and the complete breakdown of the Noto Cathedral represent an analogy with the Notre Dame disaster. The dramatic failure of the Cathedral of Noto in March 13^{th} 1996, damaged after the earthquake that hit Sicily in 1990, it is, without any doubts, an important warning that explains the caution that must be put before using the original walls for the reconstruction. Similarly, the collapse of the vault frescoed by Giotto in Assisi in 1290 and stroke by the earthquake on September 26^{th} 1997 is a very significant demonstration how, from a disaster, the monument can be rebuild "*where it was as it was*".

Insert Figure 1 here

Recent studies considered the consequences of the fire destructions on the static regime of the Cathedral [8]. In particular, recent studies demonstrated the effects of the fire on the stability of the Cathedral. A major consequence of the fire, in fact, is the considerable reduction of the wind strength of the ancient limestone masonry and the structure [8]. In the present paper, a detailed investigation of the residual bearing capacity of the cathedral stone is reported from a static point of view, taking into account the decrease of the compressive strength due to very high temperature effect and water saturation on similar stones. At the same time, the necessity to perform precise investigation on the survived structure is emphasized. Finally, a solution for the quick covering of the cathedral is proposed by a grid shell structure. By the proposed solution the dual target to protect the ancient monument and to give the necessary time for the reconstruction can be reached by a temporary cover with a great aesthetic value.

The burned forest an the surviving Structure

The ancient forest and the nineteenth-century spire: What we lost

Notre Dame's medieval roof structure, known as "the forest," has been lost in the massive fire. The framework from the 13^{th} century took this name, because it required a forest of trees to build it [1,3]. This "charpente" (or frame) was built from 1300 oak trees, enough wood to fill more than 21 hectares of land (Fig. 2). More precisely, the cathedral's wooden frame, which primarily consisted of oak, contained beams that date as far back as the first frame. It features trees cut down between 1160 and 1170, forming one of the oldest parts of the structure. Most of the current frame dates from the year 1220. The hulking framework of wooden beams that supported Notre-Dame is composed of huge pieces of timber, which is ripe for catching light [1-3]. There are not, and certainly have never existed, original drawings and designs for the construction of the "forest", but there are traces left by the dockyards that, in the last centuries have been succeeded, accounted for the purchase of materials, the carpenters' wages, detailed surveys of the performed works. In more recent times, historians an restorers have conducted precise reproductions and precise measurements, which have made it possible to accumulate a huge amount of data on the structure of the roof of the Cathedral. For the spire structure the situation is different. The spire collapsed completely some minutes late the beginning of the fire [9,10]. The spire bearing structure was built in the nineteenth century and was the most evident fruit of Viollet-le-Duc's work in conjunction with the extension and restoration works that the architect carried out at the end of the nineteenth century. The work of Viollet-le-Duc has the great merit of being completely documented and therefore completely reproducible. The consideration remains open whether it is better to reproduce the same structure or replace the coils with another spire that represents a contemporary gesture. A further hypothesis that can be taken into consideration could be to not replace the spire, bringing back the cathedral to the appearance that it has had for about 900 years before the Viollet-le-Duc opera. Before the restoration works of the late nineteenth century.

The spire has represented a symbol in the monument for the last two hundred years but probably with its several hundreds of tons placed at the intersection of the naves and a height of 45 m above the timber structure, it was determinant in the collapse speed of the entire roof. Contrary to what is indicated today, the Author opinion is that a quick questioning to the experts must concern the best solution for the temporary shelter for the cathedral that today is defenseless against weather. This temporary solution is of fundamental importance to be able to operate with the right timing in the definition of the investigation, safety and reconstruction phases. To this end, it is profoundly necessary to consider a preventive investigation on the residual load- bearing capacities of the structure still in place: the Paris stone, better to say th Lutetian limestone. Respect to this the dramatic experiences of earthquakes that hit great Italian cathedrals can be a valid teaching to look at.

Insert Figure 2 here

Insert Figure 3 here

The surviving structure: The Lutetian reserve

Lutetian limestones are main building materials from the centre of the Paris Basin. The marine Lutetian limestones of the Paris Basin cover a large surface area (Valois, Vexin, Tardenois, Parisis, and Soissonnais). Their use is confirmed from the distant past [11-13] to these days when many quarries remain in activity. Limestones are even an integral part of the collective imagination through Gothic cathedrals, such as Notre Dame in Paris and Rheims, or the catacombs [11]: old quarries, infact, were used to store bones from the Parisian cemeteries from 1780 [11,12,14]. The term Lutetian itself refers to the Paris's name during the Roman Empire, Lutetia and thus to the *stone of Paris*. In the Lutetian extraction, some terms originate from quarrymen's language [15], supporting the connection between geological stage and the buildingstones [11]. Different kind of Lutetian building stones exist, three major groups can be distinguished: i) stones with medium porosity (from 12 to 25%), ultrasonic velocities (u.v.) up to 3000 m/s, ii) stones with high porosity (from 32 to 40%), u.v.: 2500 m/s, and iii) stones with very high porosity (about 40 to 45%), u.v.: 2000 m/s (*Banc royal*). Thus, building stones have porosity index from 15 to 45% [16,17], with different mechanical properties, H_2O absorption, durability [11,16-18]. Without a direct analysis of the stone scraps collected by the cathedral, a reasonable assumption is to consider the Notre Dame limestone between i) and ii) assuming a compressive stress of 40 MPa. The problem of the injured cathedral today is a worrying debate involving the four elements. fire, water, air and the earth. A philosophical issue? No! A dramatic emergency. The high temperature generated by the fire before and the amount of water discharged during the extinguishing operation both damaged the cathedral stone. Now these two "*enemies*" have passed and we must defend Notre-Dame from the climatic variations, including rain and wind, which can fall on the open-heart cathedral. The last and the only ally is the ancient stone remained in service. What is the real help we can ask to the ancient bearing walls of the cathedral? The answer to this question is the way of a correct and safe reconstruction.

The fire and water long term effects

The fire performance of stone buildings is always important with respect to historic structures. At high temperatures from 600°C to 800°C, the strength of building-stones is seriously compromised, disintegration happens after thermal shock at high temperature. Damage at lower temperatures, such as between 200°C and 300°C is restricted to colour changes [19]. The Notre Dame's fire was not easy to contrast. Ancient dry timber, melting lead dripping fire-sparking magma weakened all the supports and at the end artworks and sculptures were flooded. Of course, It's not yet known how the Notre-Dame fire began, but it seemed to propagate near the scaffolding at the nineteenth spire, and after across the lead-covered, wooden roof. Although a huge oak beam is generally difficult to get burning, as smaller timbers fuel the fire and the temperature rises, the timbers will eventually spontaneously ignite in a phenomena known as a "*flashover*, when everything combustible suddenly becomes engulfed in fire" as reported by Keith Atkinson, fire safety consultant at Heritage and Ecclesiastical Fire Protection [1].

"The lead covering the roof would have initially slowed the growth of the fire by keeping fresh air from fanning the flames" said Steve Emery, Oxford University fire officer and formerly the fire safety adviser at English Heritage [1]. Lead melts at 324 Celsius degrees and as it dripped away the wind would have hit the fire, causing it to spread quickly across the building [1]. The melting lead would splatter onto other timber beams, with each flaming droplet helping the fire grow larger and larger. Fire peak can reach 800°C

−1000°C. This is high enough to burn timber or to heat up to failure most structural materials like stone or iron [1]. Different studies have been done in the last years to evaluate the fire affect on building-stones. In particular, the most visible immediate results of the testing on different stone types are colour changes and catastrophic failures. Generally failures, in this kind of tests, are defined as the points at which a sample is no longer fit for further testing. In the recent report of Borg et al. [19] different stone types were heated at 400°C, 600°C, 800°C, and 1000°C. The colour changes and any failures observed in each stone is dramatic. The limestone first turned pinkish at 400°C, turned a dark grey colour at 600°C, and then turned white and failed between 800°C and 1000°C. After both oven and flame heating, some samples failed. For the limestone, some samples appeared intact immediately after heating but puffed up and disintegrated overnight after the tests. For the reason reported above, it is of a great importance to evaluate the stability of the limestone of the Cathedral after the fire and the high temperatures reached during the disaster.

During the extinguish phases the rescuers tried to cool the fire by putting vast quantities of water onto the building to extinguish the burning areas, cooling other areas to prevent the fire spread. Which was the bad? To let an extra portion burns or to avoid extra water-load on the ancient structures favouring a more extensive and faster collapse and increasing the limestone saturation? Questions that are now superfluous to answer but that can help us to understand how to do now.

At the same time, the mechanical behaviour and the failure of porous natural building-stones can be changed according to the water content. Several studies confirmed that the mechanical strength of porous stones diminishes with water content [20]. The reduced mechanical resistance is obviously caused by the high total porosity. However, the principal observation displays the high reduction in the compressive strength for the saturated scrapes relative to dry ones. The presence of water plays an important role in the resistance of material; the loss of resistance could be between 60% and 40%. The water effect in the pores of stones leads to a reduction of the mechanical resistance, which can be probably explained by a reduction in the surface energy of contact between the constitutive grains and thus a modification of the intergranular bonds [20,21] according to the micro-scale aspects. Higher reduction of the mechanical resistance due to water saturation can be also connected to the presence of argillaceous minerals in the limestone phases [20].

In Fig. 4 evaluations related to the residual strength ratio (*RSR* – percentage strength reduction vs. fire time), and the compressive strength (*CS*) can allow us to develop an objectively sustainable solution in order to avoid further collapses of the masonry. The *CS* behaviour reported n Fig. 4 for the Notre-Dame Cathedral limestone can be also described by the relation reported in Eq (1) as a function of the fire time (t).

$$CS_t = -at^2 + bt + k \qquad (1)$$

In Eq (1) the constants a, b,c are respectively 0.0141, 0.785 and 31.19. As reported in the previous Section, in correspondence with the maximum temperature reached during the fire (800 °C), it can be considered a reduction of *CS* down to 4 MPa. At the same time, it must be considered that the cooling of the masonry due to the extinguishing works allowed to estimate a restoration of the bearing capacities. In any case, it is believed that the thermal shock suffered by the masonry, in particular in the stone strip close to the roof, generated a non-reversible effects. The bearing capacity in term of *RSR* and *CS* reported in Fig. 4 follow the behavior of experimental tests reported in literature according to the different shock thermal sequence performed on limestone samples [19]. Subsequently, the level of saturation of the stone due to the large quantity of water jet on the structures could have generated further and seriously compromising of the stability of the stone. Under the light of all these considerations and in the absence of a specific "in situ" experimental campaign, a load-bearing reduction to 50% of the Lutetian limestone, placed in the upper order of the cathedral, is estimated 3 weeks after from the fire. In Eq. 2 the fire-water $CS_{w,t}$ value is estimated taking into account the coexistence of the different effects:

$$CS_{w,t} = \frac{\left\{CS_t + \left[k \cdot s(t)\right]\right\} + CS_w}{2} \qquad (2)$$

In Eq. (2) CS_t is referred to Eq. (1), the function s(t) is the function of the saturation in the limestone due to the extinguishing works, k is a constant assumed to be 0.5 for this case and CS_w is the compressive strength function taking into account the saturation level. The $CS_{w,t}$ is calculated equal to 22.5 MPa at the end of the fire shutdown (see Fig 4b). This evaluation appears as an estimation and should be supported by the necessary tests on the cathedral stones or the limestone fragments collapsed after the fire. These results are well adaptable to the Lutetian limestone of the Cathedral.

Insert Figure 4 here

The new temporary protective structure: "The flying umbrella"

Under the light of all the analyzes and considerations carried out in the previous Section, we believe that we can propose a temporary protective solution for the roof of the cathedral that could represent the right contribution of contemporary architecture to the reconstruction after the disaster of April 15th 2019. Moreover, it is believed that the best solution in this case is not to replace the old structures went up in smoke with a permanent sparkling, showy, new roof belonging to a new alien architectonic language respect the Gothic style. The most correct solution, in the Author opinion, from the philological point of view, it is to use an extremely light-weight and flexible cover made by a steel grid-shell [22]. This kind of structure is able to be placed quickly and generating a reduced load on the damaged walls of the cathedral for the entire length and surface of the ancient timber ceiling. This structure will have the unique purpose to offer a shield to the cathedral's masonries and to allow the restoration works, This is the only, effective way for the contemporary architecture to serve Notre Dame. This type of roof had a remarkable development and has been theorized and developed by Frei Otto in the 70s [22]. Later over the decades grid shells have been successfully reinterpreted and used in the design of structures such as the courtyard of British Museum in London (Norman Foster, 2000), the inner court of the Natural History Museum of Hamburg (Jorg Schlaich, 1989), the temporary Japanese pavilion at the Hannover Expo (Shigeru Ban, 2000). These structures combine the flexibility with the lightness by an aesthetic solution. In the case of the Notre-dame cathedral, the structure could cover quickly the cathedral structures and offer a easy removable shelter for the restoration and analysis of the remained limestone blocks.

As previously mentioned, the proposed roof is a single-layer shell. The supports of the shell will have a distance of about 20 meters allowing to develop under the ceiling a volume suitable for the reconstruction works of the roof cathedral (see Fig. 5a). In this way, the restoration could proceed with the reconstruction as faithful as possible to the original structure of the "forest". Fig. 5 shows the sequence of works that could be carried out. Tab.1 shows the sequence of analysis and investigations to be performed for the preliminary phases and for the rebuilding plan of the timber frames. The first step will be to place the covering to protect the cathedral structures (STEP 1).

At a first estimation the weight of the temporary grid shell should be between 5% and 10% compared to the weight of the ancient cathedral roof. Considering a bearing grid of steel beams and a covering surface realized by multilayer carbonate plates the estimated weight per squared meter can be estimated in 687 N/m^2. The temporary shell appears to be perfectly compatible with the decreased load-bearing capacity of the masonry. The next step shown in Fig. 5b concerned the first phase of the reconstruction of the ancient roof trying to respect as much as possible the reference of "*where it was as it was*" (STEP 2). The reconstruction could be obtained by the numerous representations, reliefs and geometric models that had been carried out during the last decades of the ancient "forest". In this way, the exact connotation of the reconstruction can only be carried out after the investigations reported in Tab 1. The new roof will have to take into account the difficult balance between the re-proposal of the old geometries and sizes and the need to reduce the overall weight of the new roof. In the next step the work of reconstruction of the timber roof can be considered completed and it will be necessary to proceed with the reconstruction of the internal masonry vaults that have been damaged after the collapse of the ancient burned frames and the spire (Fig 5c,d). At the same time, it will be possible to proceed with the removal of the temporary metal grid-shell structure for the finished roofing portions (STEP 3, Fig. 5e). The last phase involves the reconstruction of the spire. This feature will allow to reconstruct the base and the necessary connections for the structure of the new spire below the temporary roof. Once the realization of these initial parts of the spire has been completed, the grid shell at the transept will also be removed to allow completion of the spire (STEP 4, see Fig. 5f, Fig 6).

A peculiar consideration can be made for the assembly and disassembly phases of the proposed shelter – the grid shell. Considering the reduced weight of the roof, it can be subdivided into portions of about 400 m^2 and brought into the right position and successively removed by military cargo helicopters (see Fig. 5e). This procedure can greatly speed up the positioning and the removal phases. In addition, taking into account the current capacities of the major flying transporters (30 tons for each helicopter) the phase of dismantling carried out through this system could be almost instantaneous. The roof of the cathedral could revive in front to the "*city of lights*" and the World itself appearing like a miracle unveiled by the helicopter flights. Finally, the grid shell structures that will be removed from the quote of the roof, can be placed on the ground, at the foot of the cathedral, serving in the future by hosting a greenhouse space in order to remember, in a space- saving way and in a gentle way, the rebirth of Notre Dame.

Insert Figure 5 here

Insert Table 1 here

Insert Figure 6 here

II. Conclusions

A very impressive fire devastated Notre-Dame in Paris. The fire enveloped the roof and spire in the evening of April 15th 2019. The entire roof collapsed about 80 minutes later the fire beginning. While the structures of Notre-Dame was burning, the collective memory ran to the past disasters: The dramatic failure of the Cathedral of Noto (1996), the collapse of the vault frescoed by Giotto in Assisi stroke by a violent earthquake (1997), the impressive fire of the Holy Shroud dome in Turin (1996).

In the Author opinion, the goal must be to reconstruct the past using a new structure as a temporary protective super architecture. The solution here proposed is based on an extreme adaptive grid shell able to offer a strong temporary shelter in a short time and allowing a careful work of documentation restoration and rebuilding of the roof cathedral by an approach like “how it was and where it was”. To this end, it is profoundly necessary to consider a preventive investigation on the residual load-bearing capacities of the structure still in place due to their exposition to high temperature and huge amount of water during the extinguishing phases. The residual compressive strength ($CS_{w,t}$) of the Paris stone has been estimated by the Authors taking into account the heating, the cooling and the saturation as coexisting effects. A residual compressive strength of 22.5 MPa is estimated. The evaluation of this value could be corroborated by “in situ” experimental test able to evaluate the effective residual bearing capacity of the Cathedral masonries.

As previously mentioned, the proposed roof is a single-layer shell. The supports of the shell will have a distance of about 20 meters allowing to develop under the ceiling a volume suitable for the reconstruction works of the roof. In this way, the restoration could proceed with the reconstruction as faithful s possible to the original structure of the “forest”. At a first estimation the weight of the temporary grid shell should be between 5% and 10% compared to the weight of the ancient cathedral roof. Considering a bearing grid of steel beams and a covering surface realized by multilayer carbonate plates the estimated weight per squared meter can be estimated in 687 N/m^2.

Under the light of this solution, the super modern architecture represents the high-tech contemporary way for the rebirth of the Notre Dame, just as it remains in our memory. Like a Phoenix emerging from the ashes, the roof Cathedral can be still alive. The endless possibilities offered by technology applied to building systems must be able to offer the way to bring back to life what today seems irreversibly lost and not to replace it with something new but alien to memory.

A peculiar consideration can be made for the assembly and disassembly phases of the proposed shelter – the grid shell. Considering the reduced weight of the roof, it can be brought into the right position and successively removed by military cargo helicopters. The roof of the cathedral could revive in front to the “*city of lights*” and the World itself appearing like a miracle unveiled by the helicopter flights. Finally, the grid shell structures that will be removed from the quote of the roof, can be placed on the ground, at the foot of the cathedral, serving in the future by hosting a greenhouse space in order to remember, in a space-saving and in a gentle way, the rebirth of Notre Dame.

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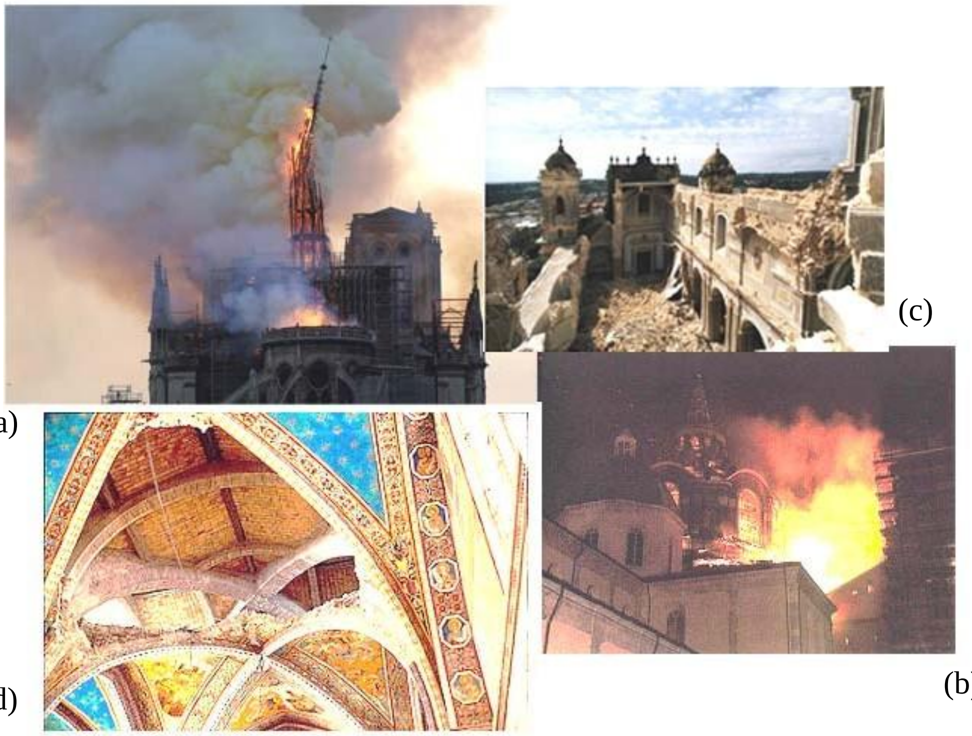

(a) (b) (c) (d)

Fig.1: Notre Dame fire, April 15th 2019. Collapses of the ancient roof and the spire (a), Fire of the Turin Cathedral. The baroque dome of the architect Guarino Guarini built in 1680 risked the collapse, April 11st 1997 (b). Dramatic failure of the The Cathedral of Noto in March 13th 1996 damaged after the earthquake that hit Sicily in 1990 (c) .Collapse of the vault frescoed by Giotto in Assisi in 1290 and stroke by the earthquake on September 26, 1997 (d).

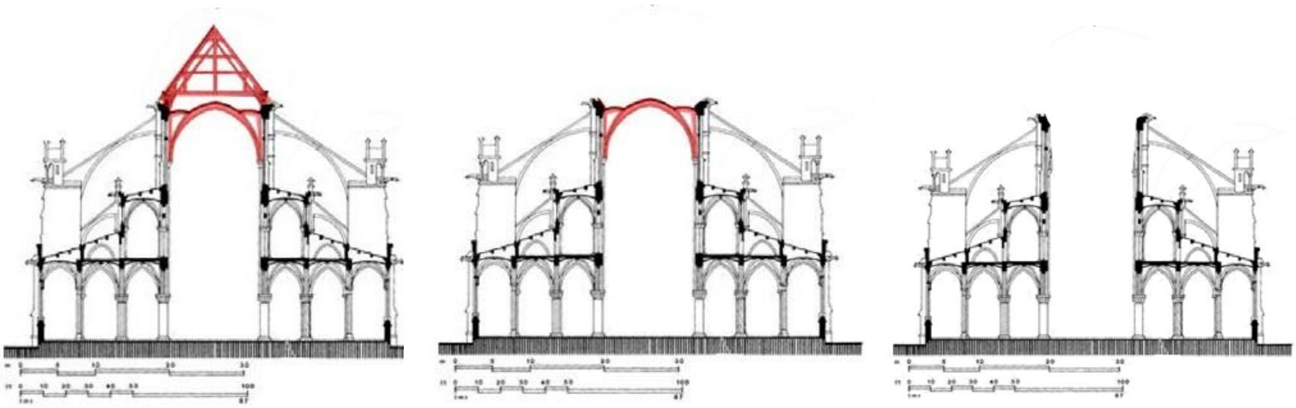

Fig.2: Phases of the collapses of the forest. After the spire breakdown the timber roof collapsed with the masonry vaults above the naves. A the end the cathedral remained without a protection against weather.

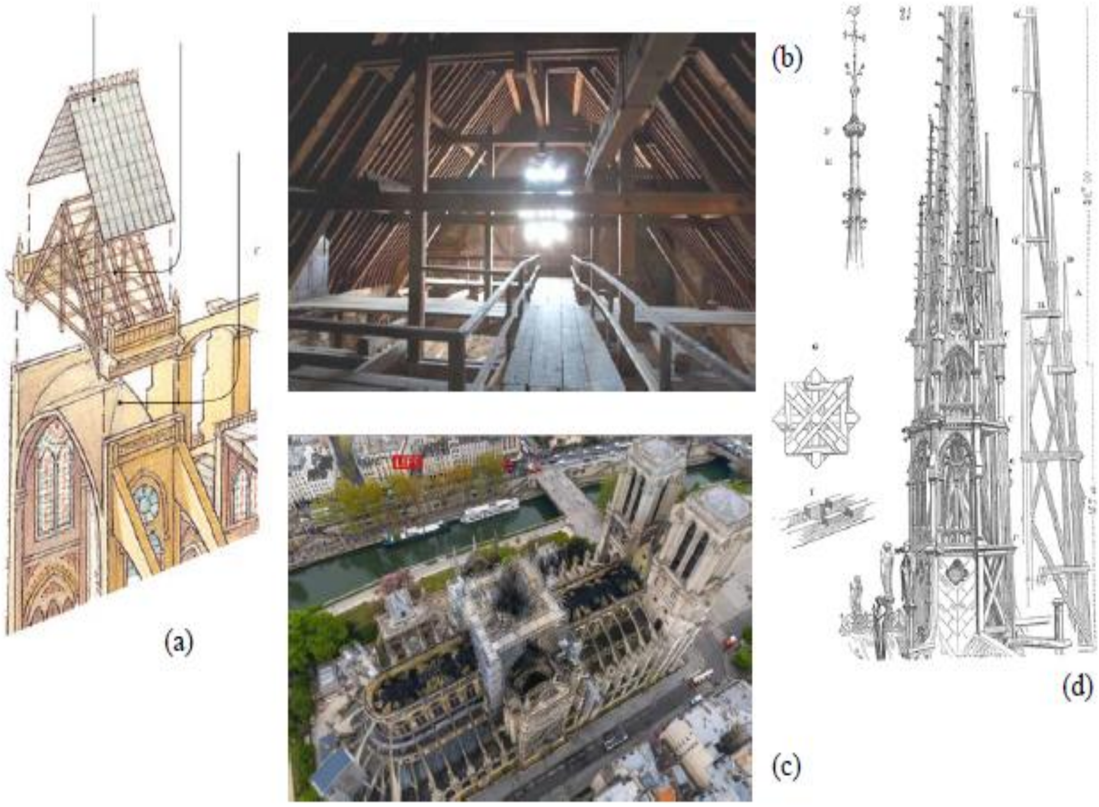

Fig.3: Axonometric view of the Notre-Dame structure of the roof – the original forest erected by Viollet-le-Duc (a). The original structure of the roof get before the fire (b). The state of the burned roof today. Top view from drone recognition (c). Original representation of the spire structure designed by Viollet-le-Duc (d).

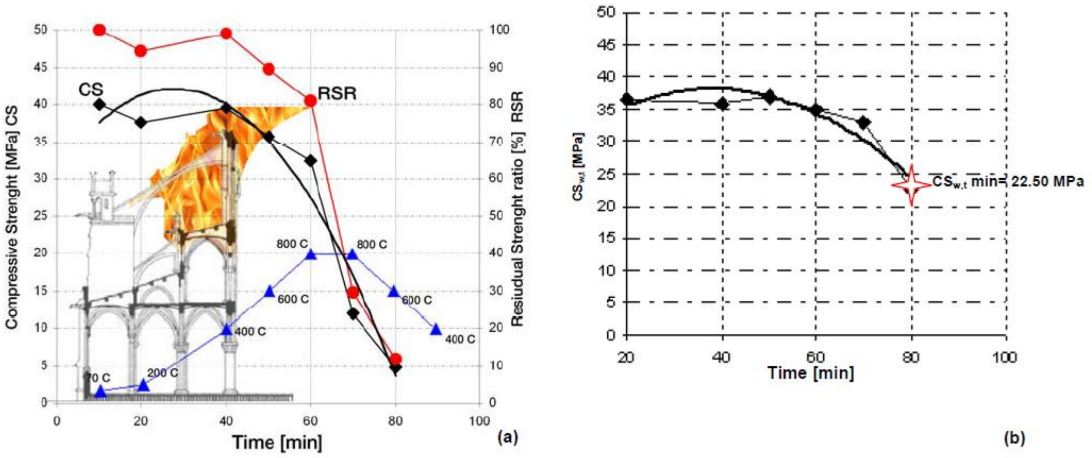

Fig.4 : Compressive strength (*CS*) and residual strength ratio (*RSR*) behaviors, during the fire time, are reported together with the estimated temperature evolution in the masonry (upper level).

Tab 1: Road map of the interventions: A reasoned approach to reconstruction

Phase 1 Preliminary investigation of the residual load-bearing properties of structures – Short term measurements

- Evaluation of the stability of arches, vaults and buttresses (intermediate level)
- Experimental tests on samples of residual stone subjected to the fire temperature (upper level)
- Preliminary evaluation of RSR and CS values after high temperature effects.
- Preliminary evaluation of the water saturation in the masonry (upper level)

Phase 2 Construction of the temporary roof structure – Long term measurements

- The temporary structure must be a fascinating lightweight structure, easily removable, adaptable and characterized by a great flexibility – Grid Shell.
- Precise evaluation of RSR and CS values after high temperature. (long term)
- Precise evaluation of water saturation level of the masonry (upper level - long term).

Phase 3 Investigation and cataloguing of and not collapsed bearing structures

Phase 4 Evaluation of architectural options for the reconstruction.

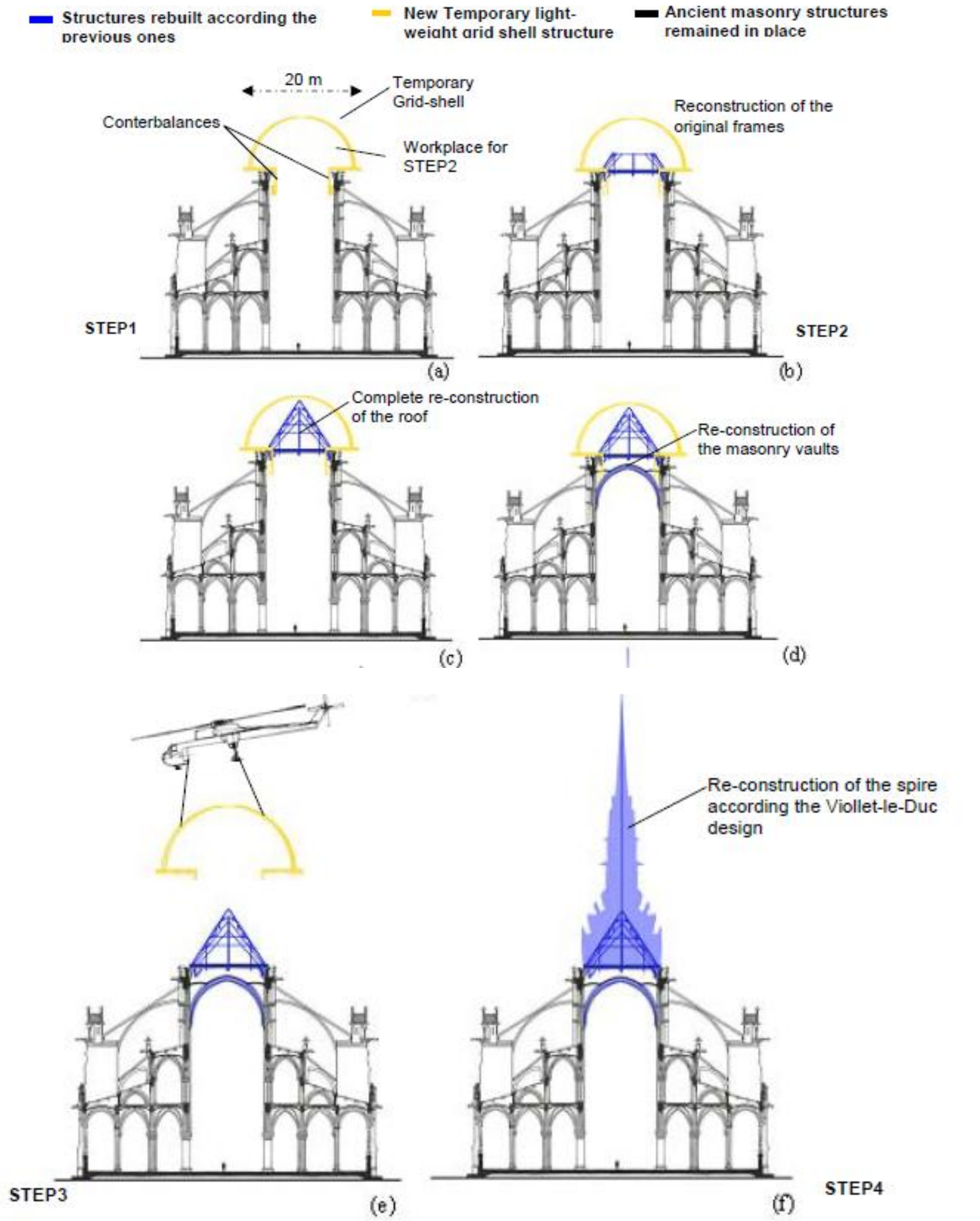

Fig.5: The first step will be to place the grid shell to protect the cathedral structures (STEP 1) (a). The next step concerned the first phase of the reconstruction of the ancient roof (STEP 2) (b,c,d). Successively, it will be possible to proceed with the removal of the temporary grid-shell by military cargo helicopters (STEP 3) (e). Once the realization of the initial parts of the spire has been completed, the grid shell at the transept will also be removed to allow the completion of the spire (STEP 4) (f).

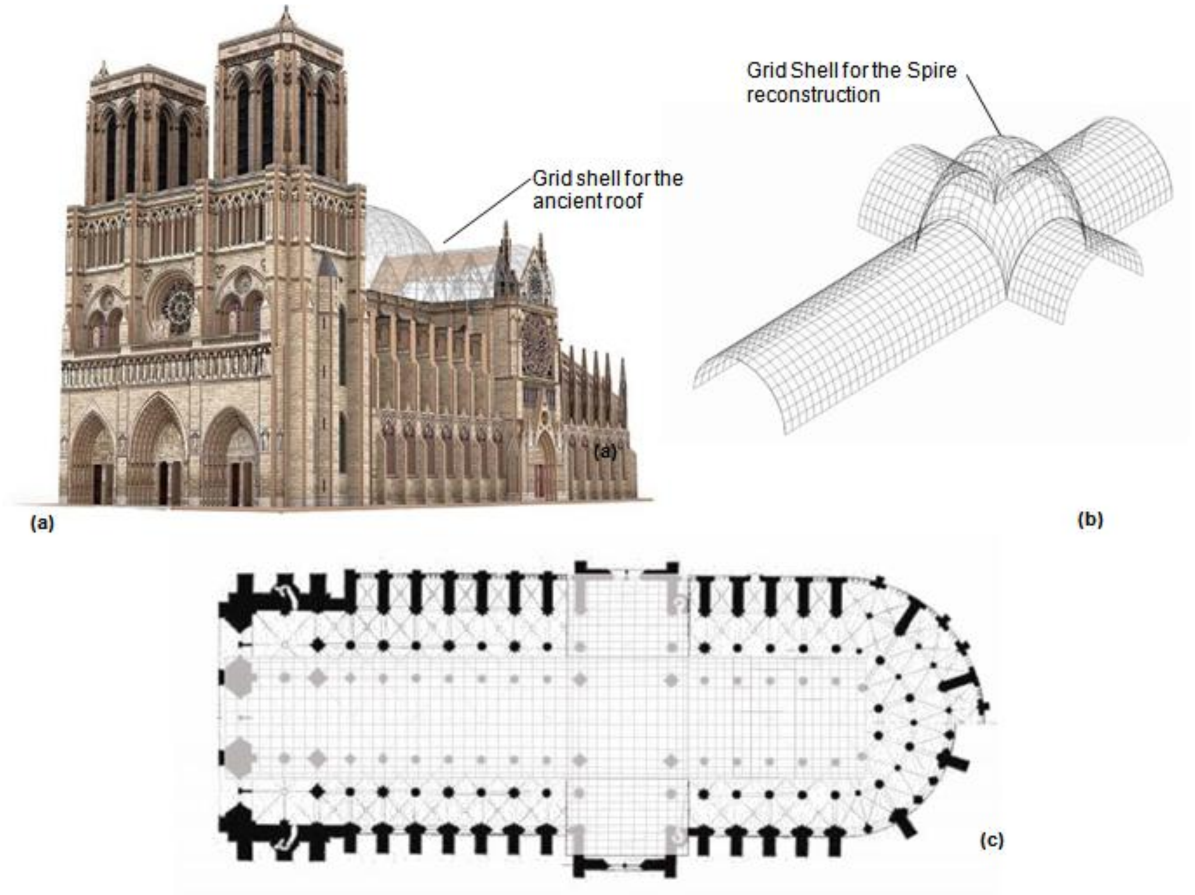

Fig.6: Three-dimensional view of the Cathedral with the grid shell positioned on the top. The reconstruction works can be made under the temporary roof (a). The grid shell presents a reduced shallowness ratio just in correspondence of the previus position of the spire. The greater volume will allow the rebuilding of the spire basement. View of the temporary grid shell in correspondence of the Cathedral plan.

Amedeo Manuello Bertetto. "Residual Strength Evaluation for the Damaged Structures of Notre-Dame De Paris: A Way for a Correct Reconstruction." IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) , vol. 16, no. 3, 2019, pp. 26-36