Notre-Dame de Paris: Pyrolysis Hypothesis and Fire Safety in Historical Buildings

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On Monday 15 April, a fire broke out in the Notre-Dame de Paris. Believers and tourists were invited to leave the cathedral immediately. A race against time was launched which would last more than fifteen hours, defying all human bravery to save the Notre-Dame. Thousands of people gathered around the cathedral this evening to reflect, pray, and witness this catastrophe which none had thought possible to an eight-century old lady that had accompanied people in their joys and sorrows and had survived wars, plagues, revolutions, and occupations. The emotion was felt worldwide and donations for the reconstruction arrived quickly. The fire destroyed the spire, the timber roof structure, and part of the vault, at the level of the transept crossing. Three years later, the investigation to find the cause of this fire is still ongoing.

This article does not claim to be an exhaustive account of the issues associated with the reconstruction of Notre-Dame, nor does it claim definitive answers to an ongoing investigation. It rather seeks to put forward a scientific hypothesis on the causes of this fire, not only for the pure satisfaction of knowledge, but also in the hope to raise awareness about the widespread but relatively unknown phenomenon of pyrolysis during works on monuments.[1] It is crucial that architects and companies working on listed buildings are aware of the phenomenon of pyrolysis so that they can adapt their working protocols, be more vigilant, and request more efficient fire detection instruments to avoid future similar disasters. In recent years, other major French monuments undergoing restoration works had been destroyed without the causes being identified: the seventeenth-century Hôtel Lambert in the centre of Paris in 2013 and the flamboyant gothic townhall of La Rochelle in 2013 are just two examples. In the 1990s, a fire outbreak was discovered just in time at the Beauvais Cathedral the day following some hot-spot work using a blowtorch. It is worth reminding the reader that the vast majority of fires happening during work are caused by hot-spot works.[2]

The phenomenon of pyrolysis and, more generally, of slow combustion are still little known to those working on historic monuments, whether they are architects or craftsmen. The case of Notre-Dame de Paris deserves to be studied in greater depth because this hypothesis remains the most likely, given the conditions that existed during the restoration of the spire in the days preceding the fire.

The current investigation has only shown that the fire started at the foot of the spire. Samples of charred wood have made it possible to locate the fire's starting point in the area of 'the wall plate of the choir at the south-east corner of the transept crossing'.[3]

The blueprints Eugène Viollet-le-Duc published in his *Dictionnaire raisonné d'architecture* give us interesting information on the ancient layout of the spire's framework built in 1859.[4] At the intersection of the roofs in line with the transept crossing, there were wooden posts directly linked to the timber roof structure on which rested sixteen statues representing the twelve Apostles and the symbols of the four Evangelists. The latter, placed at the bottom, were directly connected to the wall plate of the timber roof structure. The hollow statues are made of hammered and

1 Mikaël Faujour, interview with Rémi Desalbres, 'Notre-Dame : un an après l'incendie, la combustion lente 'reste l'hypothèse la plus vraisemblable' (*Marianne*, 15 April 2020)
< https://www.marianne.net/culture/notre-dame-un-apres-l-incendie-la-combustion-lente-reste-l-hypothese-la-plus-vraisemblable> accessed 22 May 2022.

2 ibid.

3 'la sablière du mur gouttereau du chœur à l'angle sud-est de la croisée du transept' Information from a judicial source, Agence France Presse (AFP), April 2022.

4 Eugène Viollet-le-Duc, 'Article flèches de charpenterie' in *Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle* (Édition Bance-Morel 1854-1868) 444-472.

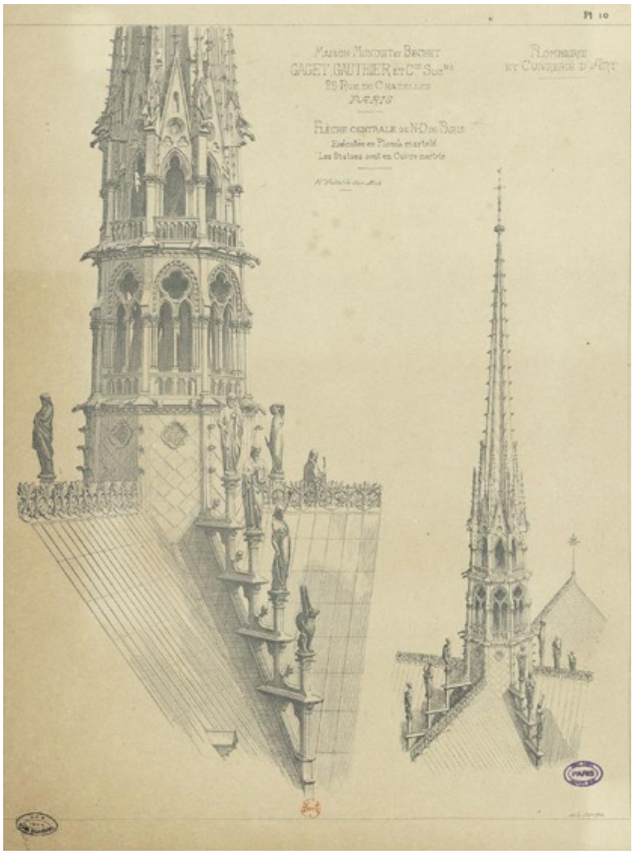

***Fig 1**. Flèche centrale de N-D de Paris*
©Ville de Paris / Bibliothèque historique de la Ville de Paris (BHVP)
The spire, built by Eugène Viollet-le-Duc at the transept crossing, was embellished with sixteen statues, that of the twelve Apostles in the higher parts and the symbols of the four Evangelists at the bottom.

assembled copper sheets, reinforced by an iron frame. Bolts at the base of the statues were used to secure them to the plinths.

The statues were removed on 11 April, using a blowtorch to cut off the heads of the Apostles according to a renovation protocol established by the architect, who was in charge of the site. In addition, it is highly likely that a torch or a grinder was used to unbolt and remove the screws, which were tightened more than 150 years ago at the foot of each statue. Would the advanced oxidation of the internal iron structure have necessitated cutting the head of a screw with a disc, causing slow combustion or pyrolysis? This is what the investigation should be able to determine.

A chemical reaction of the pyrolysis type occurs in a confined environment, in the absence of dioxygen. At temperatures of around 300°C, the pyrolysis of wood releases flammable gases, especially carbon monoxide. The wooden supports of the statues were wrapped in lead foil to protect them from the weather. The conditions here (hot spot and dry wood in a confined environment) were therefore favourable to such a reaction. The slow degradation of wood at low temperatures ranging from 300 to 800°C can take several days and is difficult to notice in the absence of appropriate instruments of temperature detection.[5]

5 The self-ignition temperature varies depending on the wood species, its water content and its density.

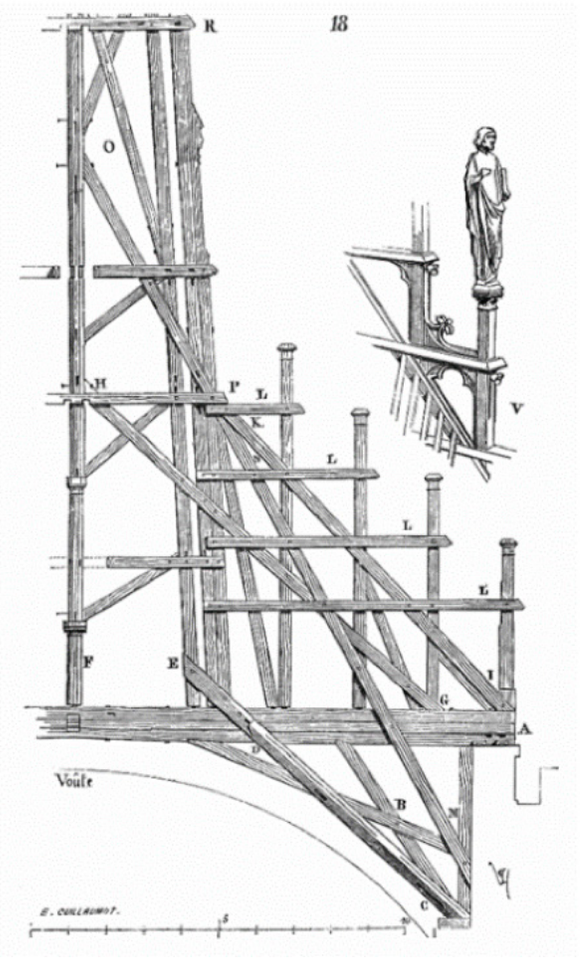

***Fig 2**. Eugène Viollet-le-Duc, Dictionnaire raisonné de l'architecture française du XIe au XVIe siècle (1854-1868)*
The statues rested on wooden posts directly connected to the roof timber structure. At the South-East of the crossing, the lowest post supported the Eagle of St John the Evangelist. It was at its base that the fire broke out on 15 April 2019.

In contact with the wall plate, the wooden post supporting the statue of St John's eagle was no longer covered in lead, thus providing the reaction with a large supply of oxygen, a condition favourable to rapid combustion. The photograph taken in the attic by the security guard who discovered the fire confirms the very vigorous nature of the combustion at the foot of the timber roof structure, at the south-east corner of the transept crossing.[6]

Laboratory tests provide information on the speed of propagation of the pyrolysis during which the wood starts to carbonise.[7] The speed varies from around 0.7 to 0.8 mm per minute.[8] It takes about a hundred hours for a pyrolysis to complete a four-metre-long pole, which is the length of the pole that supported the statue of the eagle of Saint John. This is precisely the time that elapsed between the removal of the statues on Thursday 11 April and the start of the fire

6 Picture taken by the Cathedral steward first published one year after the fire, on 13 April 2020, by BFMTV.
7 Terrei Lucas, 'Comportement au feu du matériau bois : auto-inflammation, dégradation et auto-extinction. Thermique [physics. class-ph]' (PhD thesis, Université de Lorraine 2020).
8 Faujour (n 1).

Fig 3. *© Joséphine Desalbres*
The statues were made of copper leaf after a model by the sculptor Geoffroy-Dechaume. At the foot of the composition, the eagle statue of St John the Evangelist is two metres high.
The Eagle of St John the Evangelist was held at its base by bolts. The support was sealed with shaped lead sheets.

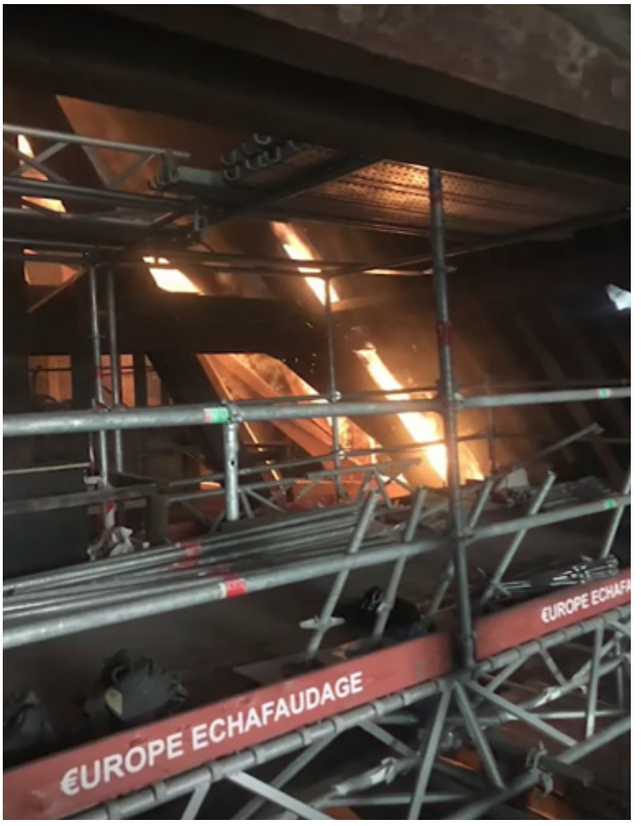

Fig 4. *Unique figure of the fire outbreak taken in the attic, at the bottom of the spire. Credit BFMTV.*

on Monday 15 April at around 6 pm.

The piece of wood affected by the pyrolysis phenomenon would have been completely degraded. The Notre-Dame de Paris fire is today the best documented case in the history of historical monuments in France and abroad. For example, the thousands of burnt pieces of the timber roof structure are inventoried, collected and stored for later analysis.[9] The investigation should therefore be able to identify the missing pieces of wood in the area where the fire started. If the post supporting the eagle of St John is missing from the pieces of wood identified and taken by the judicial police, then the origin of the fire linked to the removal of the statues would be obvious.

9 Louise Mussat, 'Notre-Dame: enquête au milieu des décombres' (CNRS News, 1 October 2019) <https://lejournal.cnrs.fr/articles/notre-dame-enquete-au-milieu-des-decombres> accessed 22 May 2022.