Diagnosis of cultural heritage wooden structures: Two case studies

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Abstract
The paper aims to present the work of the engineer, and its limits, within the framework of restoration of old timber structures. Starting with an overview of some patrimonial building sites (Gallery of Apollo Museum of Louvre (Paris); Chinese living room, castle of Champs sur Marne (suburb of Paris), the tools and methods for diagnosis are presented. In both cases, one of the difficulties of the diagnosis is that wood is not visible (hidden by plaster). The methodology consists in using slightly destructive diagnosis tools that make possible to enhance a mathematical model. In the two examples, the studies propose conservative solutions that are little traumatic for the building. However, architects in charge of the buildings asked for information from the diagnosis but undertook work without taking account of the proposals as results of the modelling. In the second part of the paper, the authors try to explain the contradiction between the carried out prior study and the restoration work. They support their arguments on the lack of efficient diagnostic tools but also on the lack of values to implement numerical models: material characteristics (ageing and durability); numerical modelling assumptions for old timber bearing structures. The questions of security are adjacent with the encountered problems: insurance is generally taken by the project superintendent (decision making process is briefly described).

Résumé :
L’article propose de présenter le travail d’ingénierie et ses limites dans le cadre de travaux de restauration de structures bois. À partir du rappel succinct d’exemples de chantiers monumen
taux (Galerie d’Apollon Musée du Louvre (75) ; Salon chinois, château de Champs sur Marne (77)), les outils et méthodes de diagnostic sont présentées. Dans les deux exemples, une des difficultés du diagnostics est...
liée au fait que le bois n’est pas visible (caché par du plâtre). La méthodologie consiste à utiliser des outils de diagnostic faiblement destructif qui permettent de renseigner un modèle mathématique. Le diagnostic est appuyé sur le comportement du modèle. Dans les deux exemples, les résultats des études concluent sur des solutions conservatrices relativement peu traumatisante pour le bâtiment. Dans la réalité, les architectes vont utiliser les informations du diagnostic mais vont entreprendre des travaux sans tenir compte des résultats de la modélisation. Dans la deuxième partie de l’article, les auteurs tentent d’expliquer la contradiction entre l’étude préalable et les travaux effectués. Ils appuient leur arguments sur la pauvreté des outils de diagnostic mais aussi des hypothèses de numérisation : des questions sur l’approche du matériau, de son vieillissement et de sa durabilité sont posées ; les hypothèses à la base de la modélisation des structures bois sont remises en cause dans le cadre de leur utilisation sur du bâtiment ancien. Les questions de sécurité sont sous-jacentes aux problèmes rencontrés : les assurances sont portées en général par les maîtres d’œuvre (les circuits de décisions seront succinctement évoqués). Aujourd’hui, les méthodes de diagnostic ne font pas l’objet d’avis technique auquel le maître d’œuvre pourrait se référer.

Keywords
Wood, conservation, restoration, diagnosis, modelling, historical monuments

Introduction
Structural works on buildings of cultural interest are usually carried out following structural disorders (due to lack of maintenance) or changes in serviceability of the building. A preliminary study, including a structural diagnosis, is sometimes required. It has been already shown that money and time invested in such preliminary studies provide substantial saving and can even erase the necessity of undertaking works in a building [Bottineau, 2008]. However, criteria of decision are still not reliable [Taupin, 1983, Galimard, 2008]. The first part of the paper briefly presents the main factors of the decision making process of work: the diagnosis tools for the material, the estimation on site of the mechanical properties (mainly, strength, stiffness and weak values) of a timber beam as a structural element, the structural modelling and the estimation of the safety level. In the second part of the paper, two restoration sites are presented. They show that if the diagnosis can provide good information for optimal conservation, the reliability of the diagnosis results can question the conclusion. Nevertheless the project owner or the project manager may opt for heavy works because of the security requirement, no matter with the optimal conservation goal.

Main factors affecting the decision of work
Different parameters can affect the decision of work. The diagnosis has three steps:

- Diagnosis of the material; local alteration estimation.
- Diagnosis of the structure; estimation of strength and stiffness of structural elements, including joints,
- Modelling of the structure using the mechanical parameters determined in the first two steps.

The decision-making is a function of the three steps and their uncertainty, and the safety requirement.

Diagnosis of the material is highly dependent on its accessibility. If it is made possible, direct diagnosis uses visual evaluation as proposed, for example, by Italian standards UNI¹, with the help of basic tools: chisel, knife, brush. For hidden wood, for example by plaster, the diagnosis first requires the localisation of the hidden material. The Infra Red thermal measurement can be very useful as soon as the plaster layer is not thicker than some centimetres. Then, much localised information can be obtained by endoscopy or
drilling techniques (Resistograph). However, no mechanical parameter can be identified by these techniques and, consequently, no grading of timber can be done according to a standard.

Even in the case of a wholly visible timber beam, it is today impossible to estimate the strength of an old beam. There is no evidence between its residual deformation, obtained after a complex loading (load level and climatic history), and its strength. Despite different studies [Obataya, 2007; Yokoyama, 2009], no evidence of relation between age and strength of wood has been shown.

The third point is related to numerical modelling. Results highly depend on the type of model. Simple elastic modelling, as used for designing new buildings, can give wrong information on old designed structures because of complex static systems, bunch of unknown parameters, complex joints. The system becomes more and more complex as it is modified along the years. Attempts have been done to use more sophisticated models. The more complex are the models, the higher is the number of parameters it requires. Moreover, these parameters finally don’t have any physical meaning. These models are not useful because the number of required parameters and their identification increase the degree of uncertainty.

Finally, safety required by the use of the building generally encounters conservation purposes. The estimation of the safety index of the timber structure is based on the three previous points. It can be seen that if uncertainty increases at each step of the diagnosis, the safety level estimation of the existing part decreases as well. The natural trend of the project manager is to remove as much as possible all sources of uncertainty, and replace complex material by “standard” ones.

Progress has to be done in either providing efficient and standard diagnosis tools and methodology, and pertinent knowledge to improve the confidence in the material by standards and rules.

The problem of usefulness of a complete mechanical diagnosis is posed in the two following examples.

**La Galerie d 'Apollon (Paris, Musée du Louvre)**

**Presentation**

First example of a royal gallery intended for Louis XIV, the Apollo gallery would later act as a model for the gallery of Mirrors in Versailles castle [Bresc-Bautier, 2004].

In 1661, a fire destroyed a part of the roof of the Kings Gallery the former name of the building. The works of restoration and enlargement were handed over to the architect Louis Le Vau. In 1663, the roof was built and Charles Le Brun did the design of the decoration (paintings and stuccos) that was completed by students of the Académie Royale (1751-1764).

In 1825, the gallery threatened to collapse. Twenty years later, Félix Duban managed the main works. The basis of the roof was reinforced. Some paintings are redone and decoration was finally finished, mainly by Eugène Delacroix and Charles-Louis Muller. In 1851, the works were completed.

The final gallery is a 61,5 m long, 10,5 wide and 7 m high room which ceiling is a vault. The latter is supported by traditional truss rafter frame. Fourteen frames unequally spaced along the gallery support the roofing [Fig. 1].
The reinforcement of the carpentry realised by Duban modified the basis of the frame by finger jointing and the roof drain: the lower purlin (300x400 mm2 cross section) is embedded in the masonry. The lower support of the rafters is a purlin lying on a stud wall filled and covered with masonry [Fig. 1].

**Diagnosis**

In 2004, leakage from air conditioning system made an appearance of a watermark on the intrados of the vault, between frames 2 and 3 at the level of a bedding beam. Outside survey in the masonry pointed out critical aspects:

*Fig. 1: Drawing of the Apollo gallery carpentry.*
• The masonry is very hard to remove and requires heavy equipment that makes the whole structure vibrate.

• The one meter long uncovered part of the bedding beam supporting one side of the main frames is completely rotten.

The general project manager Mr Goutal (Architecte en chef des Monuments Historiques) has asked:

• for a general investigation of the carpentry,

• for the structural consequences of the decayed parts,

• for solutions.

The diagnosis was hard to perform because a very large part of the wood was inaccessible and uncovering was just impossible. Moreover, localised and fine diagnosis has to be performed to the whole huge building. The survey of the carpentry has been carried out by an engineering consultant (ECSB). IR thermography or radar techniques could not be used because of gilts and sculpture of the decoration. The diagnosis of the wood material has been done by mean of a Resistograph® and endoscopy [Fig. 2]. It shows that the bedding beam is decayed up to 95%. The only safe area is between frames 7 and 8. This zone is naturally ventilated because of the constructive system.

<table>
<thead>
<tr>
<th>zone 1</th>
<th>zone 2</th>
<th>zone 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap between plaster and timber</td>
<td>Undamaged wood</td>
<td>Damaged wood</td>
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</tbody>
</table>

Fig. 2: Comparison between Resistograph® drilling results and endoscopic observations Example frame 2. After the plaster, a gap of 1cm can be seen (zone 1) ; then, damaged and undamaged wood can be encountered.
A numerical modelling has been performed with the finite element software ABAQUS®. The modelling used parameters fitted from the survey data, visual grading of timber, local data and observation from the diagnosis and results from in situ taken plaster samples. It enables to take account of the sensitivity of the parameters.

Fig. 3: Modelling the mechanical parameters in order to estimate their sensitivity to the left support (bedding beam) quality.

Fig. 4: Decay of the lower part of the joists in the Chinese living room in the castle of Champ sur Marne (France).
Assuming in the modelling that the vault plaster thickness is a minimum of 5 cm (often up to 12 cm!) and that the bedding beam is totally decayed (no bearing capacity), it has been proved that the plaster vault, that should be supported by timber arches supported by the timber frames, is capable of bearing the whole structure including frames, roofing and normalised external loads such as snow and wind [Galimard, 2007]. Reinforcement works, localised to the frame supports on the bedding beam, is today being carried out.

**Chinese living room, Castle of Champs sur Marne**

**Presentation**

The castle of Champs sur Marne was built at the beginning of the 18th century. At the end of the 19th century, the castle was bought by the rich financier Louis Cahen D’Anvers who began to restore the buildings: between 1880 and 1890, all the roofing was rebuilt and all the floors were reinforced with metal pieces. In 1947, the castle was changed into a museum.

In September 2006, during a night following a public cultural event, about 6 m² of the 64m² of the ceiling of the Chinese living room felt down. The lower face of the timber joists carrying the plaster ceiling was decayed up to about few centimetres [Fig. 4] although no humidity has been seen for decades.

**Fig. 5: Map of decay of the joists from the Resistograph investigation in the Chinese room.**
Diagnosis

The project manager has decided to remove the remaining ceiling. A visual observation of the timber joists became possible. The lower face was often decayed. A diagnosis was carried out in order to estimate the bearing capacity of the old floors. The decayed areas were estimated through the localised investigation of a Resistograph® [Fig. 5]. The consequences on the safety level of the floor were checked by applying the standard requirements of the European design codes [Table 1] to the more decayed joists.

<table>
<thead>
<tr>
<th></th>
<th>Final deformation with creep (mm)</th>
<th>Deformation with service load (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without decay</td>
<td>beam 8: 15,4</td>
<td>beam 16: 8,4</td>
</tr>
<tr>
<td></td>
<td>beam 16: 22,8</td>
<td>beam 16: 12,4</td>
</tr>
<tr>
<td>With decay (-90 mm)</td>
<td>beam 8: 17,5</td>
<td>beam 16: 14,1</td>
</tr>
<tr>
<td></td>
<td>beam 16: 25,5</td>
<td>beam 16: 19,8</td>
</tr>
<tr>
<td>Eurocode 5 requirement</td>
<td>Less than 30,4</td>
<td>Less than 25,3</td>
</tr>
</tbody>
</table>

*Table 1: Serviceability of joists 8 and 16 according to EUROcode5*

Despite these results, the project manager chose to rebuild, and reinforce with metal I beams, half of the joists of the floor of all the rooms in the surrounding of the Chinese living room.

Conclusion

These two examples (carpentry of the Apollo gallery in the Louvre and ceiling of the Chinese living room in the Castle of Champ sur Marne) showed that if a standardised method of diagnosis is not set up, results and recommendation of diagnosis will not be followed. Without this document, the maximum safety criterion prevails. If the expertise and skills of the engineer are underestimated, this leads to unnecessary modifications of the building, which is contrary to economic objectives and conservation goals.

Notes:

¹Normes - CB71 : règles de calcul et de conception des charpentes en bois, AFNOR NF P21-701

References:


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