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Conservation of historic timber roofs: knowledge, monitoring, strengthening

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ABSTRACT: The lack of knowledge of structural behaviour often led to their substitution with modern structures, or to invasive strengthening operations. If ignorance was the first cause of this loss, knowledge is the first goal to be reached. In unfavourable environmental conditions wood can undergo rapid decay, thus it is necessary a monitoring plan. The theories of preventive conservation underline the need to reaffirm the maintenance practices, and modern technologies could help to lower the cost and increase effectiveness of this operations. In absence of decay processes, historic structures are still suitable to carry out their bearing function. However the need to prevent damage due to exceptional loads, the increase of loads, or the progress of decay could lead to the necessity of strengthening. Strengthening must be viewed as a part of the discipline of restoration, thus it must aim to the conservation of the structure in its material and immaterial features.

1 INTRODUCTION

Timber has always been one of the most widely used building materials. Since Middle Ages in most of the Italian territory, due to the characteristics of land use (progressive decrease of forested areas) and the high permanence of the people, the tradition of masonry building has prevailed, while the use of wood was reserved for intermediate horizontal structures (with the only alternative of vaults) and roofs.

After National Unification, the industrial revolution began to spread in Italy the use of metals in constructions, with a gradual decline in the deployment of wooden and vaulted structures. The beginning of the twentieth century saw the spread of reinforced concrete, which in a few decades became the main structural material in Italy. This “monoculture of reinforced concrete” (Laner 2003, p. 9) led to the progressive distrust of the construction potential of wood, to the loss of culture of timber as a structural material and to the indifference to the existing structures.

The lack of knowledge of structural behaviour and of residual mechanical performances of existing timber structures, and the lack of recognition of them as a cultural heritage often led to their loss and substitution with modern structures, or to very invasive strengthening operations.

2 THE IMPORTANCE OF KNOWLEDGE

As ignorance was the first cause of this loss, knowledge is the first goal to be reached in the perspective of the preservation of this heritage. In fact, knowledge plays a double role: on the one hand, the understanding of the multiple features that characterize these artefacts fosters their recognition as a cultural heritage, and therefore generates in the population and in the technicians the moral requirements of conservation, on the other hand, the knowledge (both of the general behaviour of wood and timber structures and of the specific structure) provides the data necessary to assess the current performance of the structures and the possible methods of intervention. In this perspective, the knowledge of timber structures must develop at different levels and cover many aspects. The levels to be analysed must range from the particular to the general: from the single member or joint, to the structure (floor or roof) as a whole, and to the structure as part of the building in which it is inserted. The knowledge of a timber structure should include its exact geometry, its material consistency, and the interpretation of the structural behaviour, but it must also deal with several historical and cultural issues of the structure and of the building which belongs.

The knowledge of the material consistency requires:

- the understanding of wooden species, that can be obtained by visual examination (i.e. a macroscopic analysis; Augelli 2006, pp. 22-35), or/and by laboratory tests under the microscope (Nardi Berti 2006);

- the analysis of the state of preservation, in order to find out any form of biological attack (due to fungi or caused by insects and other animals) or physical decay (due to high temperatures or fire, ultraviolet light, mechanical damage, etc.; Ridout 2000);

- the evaluation of the mechanical properties of timber that can be carried out trough visual or mechanical grading, the latter to be done by means of non-destructive, or partially destructive tests.

The structural behaviour to be interpreted must be the current one, but also the one originally conceived by the carpenter, architect or engineer that designed or modified the structure; it is therefore necessary a process of gradual rediscovery of the technical culture that generated the historic constructions (Zamperini 2013b) and recovery of knowledge of historic construction practices (Zamperini 2012a).


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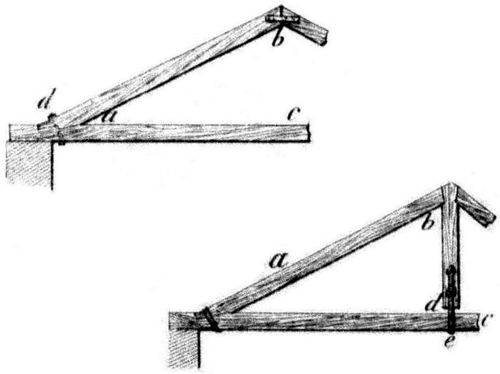
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Figures 1-2. A rustic timber truss built at the end of 19th century and the schemes proposed in technical literature in the same period to be adopted for trusses of the same span (about 7 m). The comparison between the two examples shows clearly the difference between vernacular and academic models.

Specific attention should be given to each sign that characterizes the uniqueness of a wooden structure and too often go unnoticed thus being deleted or hidden by refurbishment interventions who lack the knowledge required to work on a historic artefact. Among the signs that are important to be recognized and surveyed there are: those that reveal the original processing techniques (i.e. signs of cutting or sawing; Zamperini 2012a); trade marks that provide information on the origin and the commercialization of timber (Doglioni 1993); signs (the same for all the members convergent in one joint) originally functional to assemble the structure (fig. 5). Similar attention needs to be paid to the knowledge of metallic elements for joint reinforcement (nails, metal strips, straps, etc.; fig. 3-6) and to the technical solutions applied in the interface between timber structure and masonry walls.

As Paolo Torsello (1988, p. 48) affirms, if considered as a set of data, the artefact «stands as a virtually inexhaustible source of knowledge, as an ever new start […] of processes of interpretation», and the progressive expansion of the fields of historical and technical research sheds light on ever new features to be analyzed and interpreted.

Ario Ceccotti (2001) also proposes a method of timber structures' analysis that proceeds by progressive knowledge deepening. He suggests to «proceed step by step to further analysis, using increasingly sophisticated structural models» every time a given step of analysis shows the need of a strengthening, but the real structure demonstrates its own safety by means of the centuries-old testes that it had passed.


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Figures 3-6. Joint between rafter and tie-beams in four different trusses. A careful observation of these examples (all belonging to the Po valley and built in the late nineteenth and early twentieth century) shows that a single joint can be a witness of several building masteries: the joint in fig. 3 is reinforced with both an iron strip and a U-shaped strap; the joint in fig. 4 is protected from moisture with a bitumen coating and reinforced with a corbel and two different type of iron straps; the joint in fig. 5 is reinforced with a iron strap and the two members convergent in the joint show clearly a notch intended to facilitate the assembling of the truss; the joint in fig. 6 links the rafter to a tie-beam made of two thick boards, the connection is obtained by means of two bolts that pass trough iron dogs.

3 THE NEED FOR MONITORING

As just written, an existing centuries-old structure demonstrates its own safety to ordinary loads due to the fact that it is still intact; however, being made of a biological material, in unfavourable environmental conditions any timber artefacts can undergo rapid decay. Therefore it is strictly necessary a periodic or continuous monitoring of the structure to find out as early as possible any form of incipient decay, and to prevent that its progress could significantly decrease the performance capabilities of the structure, and bring it in conditions of insecurity needing for invasive and expensive interventions.

As well-known worldly wisdom affirms that "prevention is better than cure", and Leon Battista Alberti himself affirmed that «the primary cause of damage in all parts of the building is the carelessness and neglect of man» (De Re Aedificatoria, Book X). In the past, building owners used to order periodic inspections and maintenance, especially to roofs: control and rearrangement of roof tiles, and cleaning of the gutters were usually required at least once a year (Farina et al. 2011, pp. 21-27). Nowadays these preventive operations are often considered too expensive and therefore neglected, furthermore some issues concerning the safety of workers and the delays in the award of public works make routine maintenance more difficult to be performed (Farina et al. 2011, p. 19).

The contemporaneous theories of preventive conservation underline the need for continuous monitoring of the state of preservation of the building in order to intervene with maintenance practices before the required interventions become too invasive (Della Torre 2003).

The first option for the monitoring is in line with the tradition: in the past, inspections were always done by technicians with a direct visual survey of the structure. This approach is thus based on periodical detailed inspections of all the structure or only of the most critical points (i.e. the ones that are characterized by an high risk of seepage from the roofing or of condensation of ambient humidity); this allows a periodical updating of the survey, but it requires very long and expensive operations.

Other low-tech methods include: positioning of flypaper or other special traps near to the light sources (windows or lamps) to catch adult insects emerged from timber, thus detecting the infestation of xilophagous coleoptera; positioning of food baits made of cellulose to detect the presence of termites. Both of these methods requires the periodical check of the trap/bait.

However modern technologies could help to lower the cost and to increase effectiveness of monitoring. Three relevant aspects that can easily be kept under control are: environmental conditions, timber moisture content, and timber colour variations.

The control of environmental conditions of the attic by means of sensors to measure temperature and relative humidity can find out whether the ambient is favourable to a general progress of timber decay, and sudden rises of relative humidity could warn against possible infiltrations from the roof.

The local monitoring of timber moisture content could be easily done by placing permanent sensors in the points that are suspected to be most at risk of wetting (e.g. near the walls); although it allows to obtain very reliable local data, this approach seems to be too expensive (in a quite simple structure the critical points can be very many) and of limited effectiveness, since not always the points most at risk are those in which the decay actually occurs.

Another approach includes the use of cameras equipped with lighting systems, installed in the attic in order to periodically take photos of the structures. The pictures could be also taken by the technicians during the periodical inspections, but in this case the operators should follow a specific protocol for photo-documentation (Arcolao 2008, pp. 79-84) with a view to have images easily and reliably comparable in respect to colour and brightness. These photos could be analysed by specific software to identify chromatic alterations which may be symptoms of a fungal attack.

Kisternaya and Kozlov (2012) have also proposed and tested the possibility to record with audio sensors the acoustic emissions generated by the larvae of xilophagous insects while boring the wood. This system proved its efficiency in detecting insects even while visual signs (i.e. emergence holes), are not yet visible. In relation to environmental conditions, each species of larva has periods of activity and inactivity, therefore, the presence of an attack can be detected with this instruments only at certain times of the year.

Another strategy of decay monitoring of timber trusses is based on operational modal analysis. By placing accelerometers on the structure and relying on ambient sources of excitation (e.g. wind, movement of persons in the building, etc.) this kind of analysis can identify the dynamic properties of the system (e.g. the vibration modes, natural frequency, etc.). Monitoring the variations of these properties along time, it may be possible to identify structural degradation in the absence of visible manifestations, and also to assess whether a form of degradation visually detected significantly influence the structural behaviour. However, some researches demonstrate that dynamic properties of timber structures depend on many environmental variables; in particular the natural frequency of the structure is subject to seasonal variations, probably due to natural dimensional changes in wood resulting from the moisture exchange with the environment (Hayashi et al. 2005). Furthermore, timber roof structures are quite lightweight in relation to the loads they bear, so their dynamic properties could be affected by factors that are not related to degradation (e.g. displacement of roof tiles, interaction with materials stored in the attic, etc.). Therefore, the application of operational modal analysis to characterize damage and deterioration of timber structures requires further testing.

4 WHY AND HOW TO STRENGTHEN TIMBER STRUCTURES?

As we have already said, in absence of new decay process, historic timber structures are usually still suitable to carry out their load bearing function. However some reasons could lead to the necessity of strengthening (Zamperini 2012b): the need to prevent damage due to exceptional loads (e.g. earthquakes); the changes in safety and serviceability standards; the presence of pre-existing damage (e.g. due to exceptional loads or timber defects); the addition of new functional layers (e.g. thermal insulation); or the progress of decay.

Dealing with heritage structures, strengthening must be viewed as a part of the broader discipline of restoration, thus it must aim to the conservation of the structure in its material and immaterial features. Therefore, preservation of the constituent materials and respect of the technological conception of the structure are two very important purposes to be taken into account, always pursuing the well-established principle of minimization of invasiveness. However in order to pursue the aim of strengthening, we have often the need (but also the freedom) to chose between one of these two purposes: we could give priority to the preservation of material authenticity (also protecting all the additions, the deformations and the signs of degradation if they do not affect resistance; Tampone 1996, p. 285) or of authenticity of technological conception and behaviour (Laner 2011, p. 55; Munafò and Grilli 2005).

Clear examples of the divergence of the two different approaches to strengthening are the different types of interventions proposed for the restoration of the joint between rafter and tie-beam deteriorated as a result of fungus attack. The solutions preferred by Gennaro Tampone (1996) are always aimed at the maximum preservation of the original material, even at the cost of inserting internal prosthesis made of metal plates, that punctually deprive the wood of its structural function (see also Stumes 1975); others allow the replacement of decayed parts with prostheses in solid wood or glulam (Uzielli et al., 1998; Laner 2011) or epoxy resin, maintaining unchanged the conformation of the joint. Instead interventions that involve the realization of a monolithic epoxy joint between rafter and tie-beam are now widely regarded as totally inadequate, because they completely change the static scheme of the truss.

However there are cases in which there is no possibility of protecting the structural behaviour of the structure: seismic structural response is a crucial feature of timber roof; even if they have hold up for centuries subject to ordinary loads, some timber structure may provide an inadequate response to seismic actions and constitute for its own conception a cause of vulnerability for the building and of risk for users. The factors that could cause the vulnerability of the roof or of the entire structure are many: the possible not eliminated thrusts that may not be countered by upper vertical loads, being at the top of the building; the absence of a stiffening planking (joists they are often covered directly by laths and roofing), the connections between members made simply by overlapping and nailing, and the lack of bracing in the single roof slope and between the trusses can promote the disconnection of the parts of the roof under the effect of an earthquake. In all these cases it is strictly necessary to intervene changing at least in part the overall behaviour of the roof to reduce its seismic vulnerability: the not eliminated thrusts can be countered with the insertion of tie-rods; the in-plane stiffness of the slopes could be increased with a double layered planking or with steel cross bracings; the tendency of the trusses to rotate out of the vertical plane around the tie-beam can be eliminated through specific bracing systems.

Beyond the fundamental issues related to the conservation of the authenticity of the structure, the design of strengthening solutions must aim at some other target: compatibility, durability, and – according to many – also removability.

These three targets are strictly interrelated: the abstract principle of “compatibility” contains in itself the aspiration to implement interventions that do not have (immediately or over time) side effects resulting from the interaction between the addition and the existing wooden structure; it is therefore clear that respect for compatibility is a prerequisite for the durability of the intervention; on the contrary, the occurrence of subsequent incompatibility between added and existing parts, means that it can be necessary the removal of the addition to ensure the conservation of the structure.

The issue of compatibility is bringing increasingly to prefer solutions which provide for the strengthening of the timber structures with the addition of other wooden elements; knowledgeable technicians tends increasingly to avoid the use of metal plates with large surfaces in direct contact with timber, to avoid formation of condensation, which would favour the appearance of forms of decay.

Durability has a dual nature: in addition to the aforementioned long duration of the materials, it is crucial the persisting in time of effectiveness of the intervention. This means that the intervention must be effective since its implementation, and for the entire life of the building, which (for cultural heritage) should ideally tend to infinity.

To clarify the subject it is necessary to make a distinction between two categories of systems for strengthening: passive systems and active systems (see also Zamperini 2012b). The systems from the first category start contributing to the resistance of the existing structure when its deformations are increased by external loads. On the contrary active strengthening systems immediately introduce internal forces in the system, thus ensuring the immediate effectiveness of the strengthening. When making use of steel tie-rods and straps, active strengthening can be easily obtained by means of screw nuts; in the other cases a way to obtain an active strengthening is to reverse the deformation of the structures (e.g. by means of telescopic props) and then apply the reinforcing systems. Furthermore the use of steel tie-rods and straps endowed with screw nuts allows to adjusts over time the effectiveness of the strengthening.

These few examples show how all the aspects of strengthening depend on a priori theoretical choices (e.g. give preference to the authenticity of the material or of the conception) and how the different intervention techniques may be optimal for one aspect, but have serious defects for another.

5 CONCLUSIONS

From what has been written, it is clear that the trinomial "knowledge, monitoring, strengthening" requires the technician entrusted with the evaluation of an existing structure to have simultaneously the various technical skills necessary to carry out by his own the various stages of the complex process or more likely to coordinate other specially appointed specialists.

Technical competence, however, is just one of the skills required to the technician. In fact, as shown, only a complex theoretical reflection on the utmost purpose of his/her action can allow him/her to overcome the aporia implicit in the presumed objectivity of the technique.

6 REFERENCES

Arcolao, C. 2008. *La diagnosi nel restauro architettonico.* Venezia: Marsilio.

Augelli, F. *La diagnosi delle opere e delle strutture lignee. Le ispezioni.* Saonara (PD): Il Prato.

Barbisan, U and Laner, F. 2000. *Capriate e tetti in legno. Progetto e recupero*. Milano: Franco Angeli.

Besana, D. 2008. Progettare il costruito tra conoscenza e interpretazione. Firenze: Alinea.

Bonamini, G, Noferi, M, Togni, M, and Uzielli L. 2001. *Manuale del legno strutturale, vol. 1. Ispezioni e diagnosi in opera*. Roma: Mancosu.

Bonamini G (ed.) 2004. *Manuale del legno strutturale, vol. 4. Interventi sulle strutture*. Roma: Mancosu.

Bravery, AF, Berry, RW, Carey, JK, and Cooper, DE. 2003. *Recognizing wood rot and insect damage in buildings, 3rd Edition.* Watford: BRE.

Ceccotti, A. 2001. Prefazione. In Bonamini, G et al. *Manuale del legno strutturale, vol. 1. Ispezioni e diagnosi in opera*. Roma: Mancosu.

Croci, G. 2001. *Conservazione e restauro strutturale dei beni architettonici.* Torino: UTET.

Della Torre, S. 2003. La conservazione programmata: una strategia per il patrimonio storico-architettonico. *La conservazione programmata del patrimonio storico architettonico*. Milano: Guerrini.

Dalprà, M. 2007. *Degrado biotico del legno. Riconoscimento e metodi di lotta.* Torino: Daniela Piazza.

Doglioni, F. 1993. Per la conservazione degli antichi legni. *Progetto legno.* Milano: PEG Ribera, 38-41.

Farina, P, Tongini Folli, R, Barbò, S, and Rigamonti A. 2011. *Per la tutela dell'edilizia storica. Guida alla manutenzione delle copertura*. Saonara (PD): Il Prato.

Gambetta, A. 2010. *Funghi e insetti nel legno. Diagnosi, prevenzione, controllo*. Firenze: Nardini.

Giordano, G. 1992. L'azione del progettista. *Progetto legno*. Milano: PEG Ribera, 42-49.

Hayashi, Y, Miyamoto, M, Nii, A, Suzuki Y, and Morii T. 2005. Structural health monitoring of huge traditional timber structure in Japan. *Proceedings of the 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure*. Shenzhen (China).

Kisternaya, M and Kozlov, V. 2012. Preservation of historic monuments in the "Kizhi" Open-Air Museum (Russian Federation). *Journal of Cultural Heritage*. 3/13, 74-78.

Laner, F. 1992. La concezione strutturale, come guida al progetto di recupero. Progetto legno. Milano: PEG Ribera, 20-25.

Laner, F. 2003. *Capire le fessure nel legno strutturale.* Milano: Legnoindustria.

Laner, F. 2011. *Il restauro delle strutture di legno*. Palermo: Grafill.

Liotta, G. 2003. *Gli insetti e i danni del legno. Problemi di restauro, 4th Edition*. Firenze: Nardini.

Morandotti, M. 2001. *Recupero: progetti e tecniche costruttive*. Viareggio: Baroni.

Morandotti, M. 2005. Il rilievo integrale dell'esistente tra diagnostica e progetto. Calvi G et al. *Diagnostica per il progetto di conservazione. Metodi, tecniche ed esempi*. Pisa: ETS.

Munafò, P and Grilli, M. 2005. Il rispetto del costruito salvaguardando i cinematismi originari di rottura (codice genetico di rottura). *Conservation of Historic Wooden Structures*, *vol. 2*. Firenze, 51-62.

Munafò, P. 2002. *Le capriate lignee antiche per i tetti a bassa pendenza*. Firenze: Alinea.

Nardi Berti, R. 2006. *La struttura anatomica del legno ed il riconoscimento dei legnami italiani di più corrente impiego*. Sesto Fiorentino: CNR-IVALSA.

Piazza, M (ed.) 2009. *Consolidamento delle strutture in legno*. Benevento: Helveius.

Pracchi, V (ed.) 2008a. *Lo studio delle tecniche costruttive storiche*. Como: Nodo libri.

Pracchi, V (ed.) 2008b. *Pratiche costruttive storiche: manufatti in stucco e strutture lignee di copertura in edifici lombardi*. Como: Nodo libri.

Resta, F. 1990. *Edifici in muratura*. Bari: Edipuglia.

Ridout, B. 2000. *Timber decay in buildings. The conservation approach to treatment.* Abingdon: Spon.

Ross, RJ and Pellerin, RF. 1994. *Nondestructive testing for assessing wood members in structures. A review*. Madison: Forest Products Laboratory.

Stumes, P. 1975. Testing the efficiency of wood epoxy reinforcement systems. *Bulletin of the Association for Preservation Technology*. 3/7, pp. 2-35.

Tampone, G. 1996. *Il restauro delle strutture di legno.* Milano: Hoepli.

Torsello, BP. 1988. *La materia del restauro. Tecniche e teorie analitiche.* Venezia: Marsilio.

Uzielli, L, Bonamini G, Ruffino M. 1998. *Il restauro conservativo di capriate lignee*. Torino: CLUT.

Zamperini, E. 2011. Le strutture lignee dall'inizio dell'Ottocento alla metà del Novecento. Sviluppo storico e tecniche di conservazione e recupero. *L'attività di ricerca nel Dottorato: verso un sapere tecnico condiviso (CODAT2011)*. Roma, 251-254.

Zamperini, E. 2012a. Evoluzione delle tecniche di taglio e segagione dei legnami da opera tra inizio Ottocento e metà Novecento. *Storia dell'Ingegneria (4° Convegno Nazionale).* Napoli, 729-740.

Zamperini, E. 2012b. Axiological approach to strengthening of timber load bearing floor structures. *Structural Analysis of Historical Constructions, vol. 3*. Wroclaw, 2097-2105.

Zamperini, E. 2013a (in press). Structural Analysis of Timber Trusses (1800-1950). Capecchi D, Lukešová A, Pisano R. (eds.) *Physics, Astronomy and Engineering*. *Critical Problems in The History of Science*. *Proceedings of the 32nd International Congress of the Italian Society of Historians of Physics and Astrnomy,* Siauliai: Scientia Socialis.

Zamperini, E. 2013b (in press). Structural engineering for timber and steel-timber trusses in Italy (1800-1950). To be presented at the *International Conference Structures and Architecture 2013*. Minho.