Structural Failure Analysis of timber Floors and Roofs in Ancient Buildings at Valencia (Spain)

Liliana Palaia
Polytechnic University At Valencia-Icomos Spanish National Committee

Introduction

A meaning for *failure* may be "deterioration or decay, esp. of vigor, strength, etc." It means that there is an expectation about the structure performance, which is not satisfactory.

Timber structure failures have different causes that must be identified carefully. Not always causes are due to the material decay, but also because timber was introduced not seasoned to the building, timber quality was not the best one and the carpenters were not as accurate as they should have been. (Figure 1) Diagnosis is the most important phase in the conservation of timber structures. To determine the condition of the structure and its components is essential in this process. This can be done by traditional methods, involving visual inspection and destructive testing, or also by means of non destructive testing (NDT).

An approach to an effective method by using visual inspection and NDT methods to determine causes of structural failure has been developed by the author.

Figure 1. General view of a timber roof structure. Gran Asociación Valenciana de la Caridad. Valencia.

Aspects involved in conservation of timber structures

There are many aspects involved in the conservation of timber structures. In fact we have standing structures for centuries, very well maintained and cared of. Those aspects that should be considered are:

- Wood quality
- Material decay
- Original construction system and detailing
- Former repairs
- Treatments (preservation or consolidation ones)
- Structural movements
- Wrong criteria for re-using the historic building

Wood quality:
Not always the timber elements were of the best wood quality. It depended on the budget of the owner during its construction and design, in relation with his wealthness status, and also on the timber resources in the surroundings of the building site.
Differences involves timber dimensions, its defects (knots and its sizes, grain direction, introduction of unseasoned timber) (Figures 2, 3)

Figure 3. Timber floor structure built with joists of important cross section, positioned quite separate, around 1,00 m. Alaquàs Castle.

Figure 2. Timber floor built with very small joists, positioned quite close to each other, around 0,45 m. Villa Ivonne, Meliana.

Material decay:
Wood is a building material that depends directly on natural resources to be substituted, and is one of the most vulnerable ones, because of biological attach, many times in relation with high moisture content and lack of ventilation.
As softwoods are present in historic buildings in this area, the most extended attacks are fungal damage (white and dark rot), and insect attack produced by common beetle, house log horn beetle and termites, being the last ones the most dangerous for our timber structures.
Damage produced by rot is more frequently localised at the timber element endings, that may be coincident with insect attach as that produced by termites, or it may be extended

all along its length. (Figures 4, 5)
Another important enemy of timber structures is fire, making them vulnerable to this element.

Figure 4. Long horn beetle attack in timber joists. Alaquàs Castle.

Figure 5. Brown rot in a timber roof element. Villa Ivonne, Meliana

Original construction system and detailing
Traditional construction systems are based on experience. An evolution could be traced [1], based on successes and failures improving former designs. Always happened that not all constructors were skilled ones, sometimes producing negative consequences for the building standing. Accurate jointing is very important for structural stability and load transmission. A deep knowledge in timber construction is required to detect this sort of possible failures [2], There are historic treatises to be consulted as an approach to resolve this lack of information [3] [4] [5] [6] [7] [8] [9].
Many times, lack of fundamental elements, as king posts, had very negative influence in the stability of the whole structure, producing rupture of rafters in triangulated trusses, for example.

Former repairs
Finding former repairs can denote previous disorders in the original structures. The reason for introducing these repairs could have had different origins, such as wood decay, previous failures due to wrong detailing or design of the whole structure, deficient dimensions of the square section of timber elements. Some times gypsum mortars o lime mortars have been used to reintegrate a square section of a beam or rafter, or any other timber structural member. (Figures 6, 7)
Inspection can find out the extension of previous repairs, different woods present in the construction, metallic elements as prosthesis, epoxy resin repairs, and detection of diverse finishing or coatings, for example.

Figure 6. Coffered ceiling joist repaired with gypsum mortar, and then painted to simulate timber.

Figure 7. Floor joist wrongly reinforced in a previous repair. The metallic element is inversely orientated, being useless.

Finishing and Treatments
Finishing and changes of the surface quality may indicate original/substituted elements. Previous treatments could be of different products, for diverse purposes: chemical for wood preservation, resins for wood repairs or paintings consolidation in polychrome timber elements. Each one of those products may produce a different effect on the remaining timber structure, so that it is necessary to identify them, in order to take decisions about its possible effects on sound wood and decide its removal

Structural movements
Settlements of different magnitude in a building may produce structural movements. In traditional constructions, considered as articulated construction systems have diverse consequences in the load bearing system.
Walls may settle down due to mortar creep, foundations may be weak or cohesive soils may change its internal structure and resistance due to variations in its moisture content. Special attention must be taken to analyse these aspects, looking carefully the whole structure.

Wrong criteria for re-using the historic building
Ancient buildings, considered as huge containers, may invite to change its original use, generally residential. Those required a determined load bearing system that are increased when another public, administrative or education use is introduced in an existing building.
Sometimes it is very damaging to the building to adjust the new use to the standing walls and floors.

Diagnosis

Determining the condition of the structure and its components is essential in this process. The proposals of intervention come out directly through the analysis of its failure.

Different phases are involved in this process:
- Inspection, traditional and NDT methods
- Data analysis
- Structure evaluation

Inspection

As a first measure, questions to answer after the inspection must be clarified. Once it is defined the problem, the best methods for inspection can be designed.

Previously, all the possible documental and graphic information of the existing building must be gathered in order to date the timber structure, that may not be original, but introduced later on, during some repair works or refurbishments. Documental information consists of contracts, history of the family owners; and graphic information involves pictures, photographs and drawings about its construction.

There is established a discussion about the use of traditional or NDT methods for timber structures inspection. At this moment there is developing an I+D project for diagnosis by means of non destructive testing at the Polytechnic University Valencia.[1] The instruments we are applying are ultrasonic, hardener testing (Pilodyn), and micro

[1] An I+D+i Project financed by the Ministerio de Fomento, 2004 (Spain), L. Palaia J. Monfort, P. Navarro, C. Pérez, R. Sánchez, L. Gil, A. Álvarez, V. López, S. Tormo. All these are professors at the Polytechnic University of Valencia, members of as follows: Liliana Palaia (Chair professor in Architectonic Construction and responsible of the project); Professors Luisa Gil, Ángeles Álvarez, Santiago Tormo and Vicente López also belonging to Architectonic Construction Dept., Rafael Sánchez (TEU) belonging to Applied Physics Dept., Pablo Navarro (Chair professor in Graphic Expression in Architecture) ,José Monfort (Chair professor in Structures), and Carmen Pérez (Chair professor in Conservation and restoration of cultural heritage)

drilling (Resistograph), besides visual inspection. The fact is that each one of the technique applied give different information about the structure

Our experience has demonstrated that there are many non-destructive techniques that can reduce producing damage to existing structures or time consuming for the technician, but visual inspection can not be avoided. This conclusion is coincident with some other specialists in timber structures [10] [11] [12].

Visual inspection

The main objective for visual inspection, done at a very short distance to the timber element and very well illuminated, is to determine the main aspects of the structure and its state of conservation. It should be done by a skilful technician, with deep knowledge no only of the material but also in timber structural construction, to establish the cause and extent of timber decay, including the potential risk to the health of occupants before specification of repair works.

Before starting the inspection, all timber elements are identified with chalk, when possible, and taken photographs of all element endings and jointing. (Figures 8, 9)

It must be recorded:

Information about the general structure:

- Disposition of the main structural elements, vertical and horizontal ones, dimensions, significant alterations of the main structural system, repairs, building extensions, detecting of missing or defective roof tiles, leaking, blocked gutters, broken cornices, defective flashing or missing rendering of walls, measuring its moisture content,

Figure 8. Complete identification of all timber elements of the structure.

Figure 9. Roof rafter ending showing its rotten ending.

Information about the timber structure:

- Its geometry and jointing, dimensions of its elements, (length and square section), possible deflection of the timber elements, previous repairs, prosthesis, surface finishing, polychromy, carpenters marks
- wood species, determining its quality by measuring knots, grain deviation and cracks, for its classification, based on the applicable standards.

Information about its state of conservation

- presence of fungal or insect attack measuring its extension and depth, specially at the ends of timber elements, moisture content with hygrometers, identification of possible carbonised areas, or any other altrations.

As a result of this inspection an individual data chart comes out, resuming all the information as illustrated in figures 9 and 10. (Figures 10, 11)

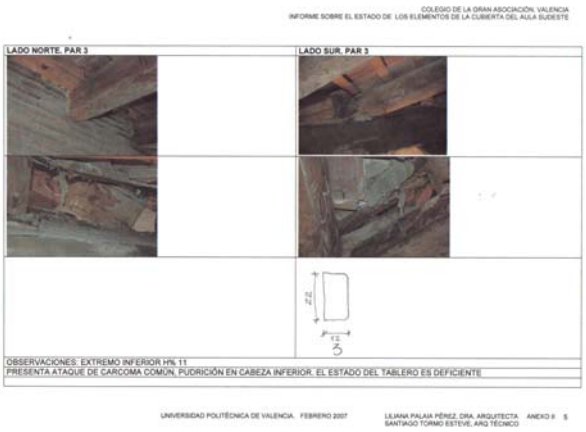

Fig. 10. Individual timber elements data chart. Diagnosis of a timber roof at the Gran Asociación Valenciana de la Caridad. Valencia.

Figure 11. Individual timber elements data chart. Diagnosis of a timber roof at the main house building. Ajuntament d'Alzira.

Destructive testing

Determination of wood density and moisture content in stoves, are the only destructive testing we use during the inspection process. It requires a very small quantity of wood, so a few damage is made to the structure.

For that purpose we use a suitable circular drill, obtaining a cylinder that lately is measured, weighted and oven dried until constant weight. The same samples may be used for anatomic identification, when necessary.

Non-destructive techniques for diagnosis

Through a methodical process it is possible to decrease the cost of timber inspection and to obtain semi-quantitative data for the timber structure evaluation. These techniques allow to approach to the wood elasticity modulus (MOE), its density, and to be sure about the extension of previously identified attacks, to confirm suspected problems of wood alterations [13],[14],[15], [16].

After visual inspection is done, some apparel for non destructive testing is applied to the inspection:

- Ultrasonic as an approach to determine dynamic elasticity modulus value
- Pilodyn to have an approach to wood density and surface consistence
- Resistograph, to "observe" the interior of the timber element

Ultrasonics

Ultrasound is a widely used technique for non-destructive assessment of timber, stone and ceramic materials in historic buildings, and it is also used on concrete and metals. In timber it is particularly useful to give an approach to the dynamic elasticity modulus value, as the velocity of sound propagation is in relation with mechanical characteristics

$E = v^2 \rho$,

being E, dynamic elasticity modulus, v, sound propagation velocity in wood, and ρ, its density. [17].

The modulus of elasticity calculated according to this equation is 5% higher than determined with bending test.

Access is required to opposing sides of the material being tested. There are many studies done in order to characterize different wood spices (Figure 12)

Figure 12. Ultrasonic testing.

Figure 13. Pilodyn testing.

Wood hardener tester

The Pilodyn wood tester is a portable tool used for estimating wood density, by measuring the depth penetration of a 1,5 mm diameter pin, which is shot into the outer millimetres of the timber element, with a constant force. The depth of the pin penetration is inversely related to wood density.

There is many research done on this field becoming this instrument a reliable one to estimate wood consistency, allowing to make approaches to its mechanical properties. (Figure 13)

Microdrilling

A 1,5 mm diameter drill probe penetrates up to 45 mm into the timber. The motor increases the force applied to maintain the same speed. As it is linked to a computer, a complete record of these variations can be obtained. These variations are due to the different consistence of the annual rings, its thickness, knots, voids due to different attacks. Only a hole of 1,5 mm diameter is left, similar to the exit hole of the common beetle. (Figure 14)

This technique not only is capable of accurately measuring the severity and extent of decay, the ratio of sound to decayed timber remaining, and its position within the cross-section, but also give a reference of its density. As this parameter is in relation with its mechanical resistance, some of these characteristics can be estimated. The data obtained is recorded by a computer and print out, being possible to observe at the x axis the progress of the depth penetration. The y axis indicates the relative magnitude of the torque required by the bit moving at a constant speed. (Figure 15)

This is extremely valuable as it can be used to assess timber behind surface finishes such as decorative plaster, panelling, window linings and render.

The information obtained from the micro-drill need an interpretation made by the experienced technicians, and be compared with results obtained from another NDT as ultrasonic or wood hardener data.

Figure 14. Resistograph testing

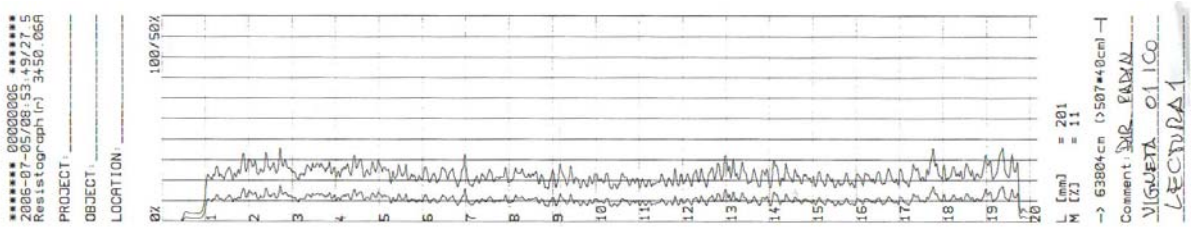

Figure 15. Print out Resistograph test

Data analysis

All data coming from:

1. Visual inspection of all the structural members
2. Pilodyn testing in all elements
3. Resistograph testing, one out of three elements, to determine general characteristics of wood
4. Additional Resistograph testing when some defect or alteration is detected.
5. Ultrasonic testing, one out of three elements

is compared in a data basis and conclusions about wood quality, mechanical characteristics and damages come out with great accuracy[2] (Figures 16, 17).

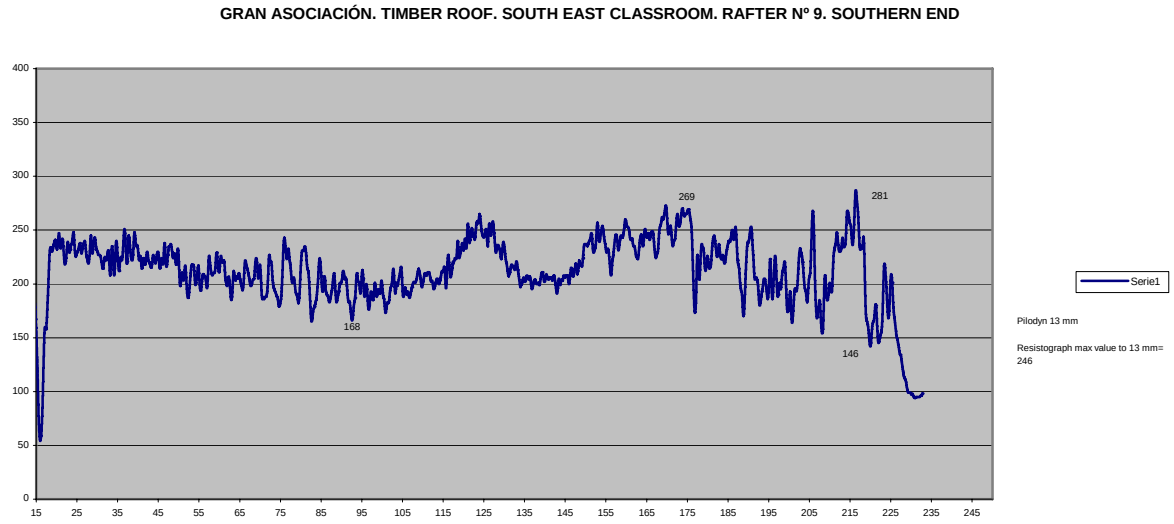

Figure 16. Resistograph xls graphic of an individual element.

[2] Evaluation of the roof structure at the Gran Asociación Valenciana de la Caridad. This work was done in collaboration with Santiago Tormo Esteve, Technical Architect.

Wood spices: Pinus sylvestris

Rafter 9, southern side	PO nº	Media Value	vert	horiz	H%	Quality	Dimensions
Resistograph media value	13	202,00					
Pilodyn northern inferior ending			12	13	9,4		
Ressistant classification						C 20	
							12 X 22

VISUAL INSPECTION:
Dark rot

Figure 17. Resume chart of an individual element

This method of diagnosis is being applied to an ancient building, Villa Ivonne at Meliana, close to Valencia city. As an advance to the conclusions of the research being developed at the University a Table with the resume of the data is included in thas work[3] (Fig. 17)

Table 1. Resume of data obtained at Villa Ivonne. 1st Floor. Room E

1ST FLOOR		PILODYN	ULTRASONIC				RESISTOGRAPH
ROOM	RAFTER	mm	µs	m	seconds	V	max. value
E (w)	E1w	13					
	E2w	12	83,5	0,12	0,0000835	1437,1257	352
	E3w	12					
	E4w	13					
	E5w	13	99,7	0,12	0,0000997	1203,6108	359
	E6w	12					
	E7w	12					
	E8w	11	129,1	0,12	0,0001291	929,51201	342
	E9w	14					
	E10w	12					
	E11w	17	301,9	0,12	0,0003019	397,48261	283
	E12w	9					

There is a correlation between Resistograph maximum value and the Pilodyn tester result. Visual inspection indicated that rafter nº E11W is completely destroyed by termites, and it is shown with the ultrasonic velocity value.

Structure evaluation

Wood is, generally, in good state of conservation, except some elements. Those are identified in drawings, indicating position and extension of the damage (Fig.18). According to that resume, repair measures are designed as a conclusion.

Based on visual inspection, Pilodyn values confirm what have been observed, giving an approach to its density and consistency.

Graphics printed out, and later analysed by means of data bases reveals what happens in the interior of the timber element, being possible to precise the extension of the damage. Some media values about the mechanical characteristics of timber may be obtained by comparing the results.

[3] This chart show the analysis of the data obtained at one of the attic rooms,Villa Ivonne. Meliana.

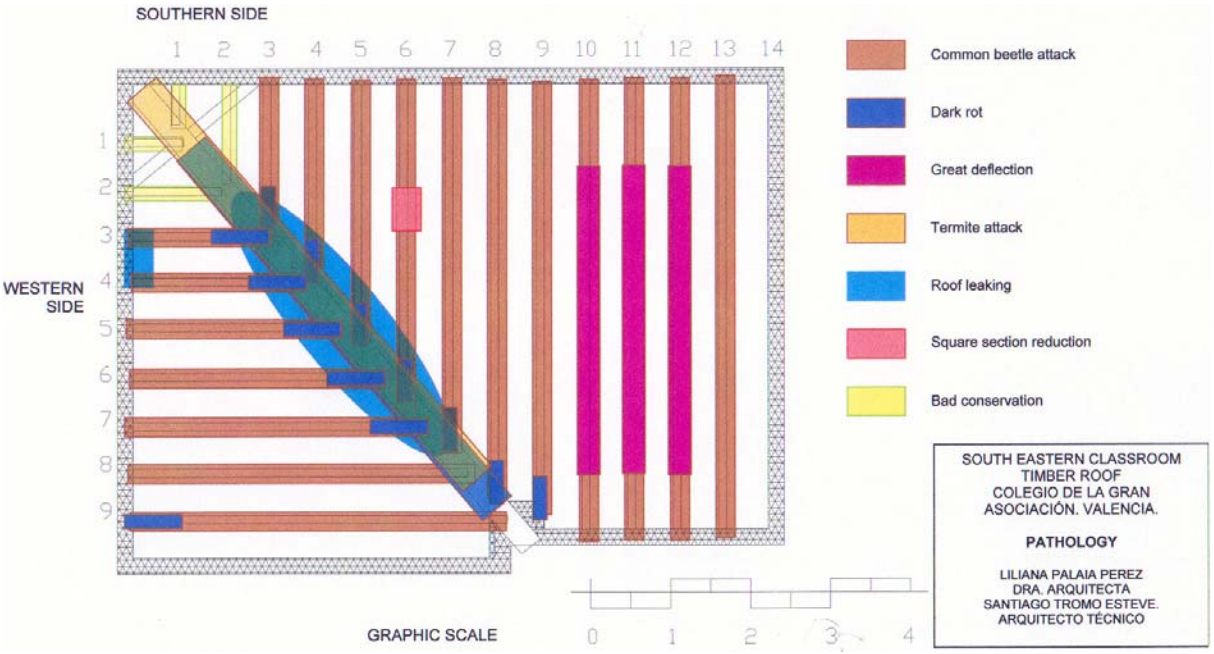

Figure 18. Graphic resume of pathology. Diagnosis of a timber roof at the "Gran Asociación Valenciana de la Caridad". Valencia.

Conclusions

Not only must be studied the material or individual timber element, but also the structure as a whole, to give the answers to the real problem.

Structural analysis of old timber structures is possible when accurate tools for assessing strength and stiffness values for individual members are available. They seem to indicate that it is possible to get a more reliable strength prediction of a timber element.

There is correlated information about the results of many essays that allow us to adopt them as an approach to semi-quantitative values about a single timber element resistance. The approach presented is based on preliminary results and should be taken as a basis for an inspection method, needing thoroughly research, in order to validate the results obtained. For that purpose, the research project mentioned above will allow us, hopefully, to arrive to that target.

Bibliographical References

1. Mainstone, Rowland, 1983, *Development of structural form*, Harmondsworth, Middesex : Penguin Books.
2. Uzielli, L., 1991, *Il manuale del legno strutturale*, Editore Mancosu, Roma.
3. Vitrubio Polión, Marco, 1787, *Los Diez Libros de Arquitectura*, Traducidos del latín y comentados por Joseph Ortiz y Sanz, Madrid.
4. Alberti, L. B.,1977, *De re aedificatoria*, Florencia 1485, traducida por M. Alonso Gómez, 1582, Re-editada por Albatros Ediciones.
5. Palladio, A., 1968, *I Quattro Libri dell'Architettura*, Venecia, 1570, Reeditado por Ulrico Hoepli, Milano.
6. Serlio, Sebastiano, 1986, *Tercero y cuarto libro de arquitectura*, Edición facsimilar Colegio oficial de aparejadores y arquitectos técnicos de Asturias, Oviedo.
7. Tampone, G.,1996, *Il restauro delle strutture di legno*, Editore: Hoepli
8. Fr. Lorenzo de san Nicolás, 1989, "Arte y uso de arquitectura", Madrid, 1639 y 1664. Re-edición Madrid Albatros.

9. Nuere, Enrique, 2000, *La carpintería de armar española*, Munilla-Leria.
10. Singh, Jagjit, *Environmental monitoring and control.* Buildingconservation.com.
11. Demaus, Robert, 1996, *Non-Destructive Investigation,* Buildingconservation.com.
12. Machado, 2007*,* "Strength appraisal of wooden members in service by combining new and old technology", *Stremah 2007,* WIT Press.
13. Palaia, L., et alt., 1998, La conservación de la madera en los edificios antiguos, Valencia.
14. Feilden, B, 1982, Conservation of historic buildings, Buttherwoth Scientific.
15. Binda, L, Cantini, L., Condoleo & Saisi A.,2007, "Nondestructive testing techniques applied to the masonry and timber structures of the Crocifisso Church in Noto", *Stremah 2007,* WIT Press.
16. Arriaga, F., Esteban, M., "Evaluation of load carrying capacity of old timber structures", *Proceedings of the 8th Conference on Timber Engineering (WCTE 2004).* Finnish Association of Civil Engineers (RIL), VTT Technical Research Centre of Finland and Wood Focus, Lahti, Finland 14-17 June 2004.
17. Jorissen, André, "The Dutch Pavillion at the EXPO 2000 in Hannover".