SACoMaTiS 2008
International RILEM Conference
1-2 September 2008 Varenna (LC)
Como Lake – Italy
POLITECNICO DI MILANO
www.sacomatis.org
on Site Assessment of
Concrete, Masonry and Timber

ON SITE DIAGNOSIS AND ASSESSMENT OF THE NAVE TIMBER STRUCTURE OF SEGOVIA CATHEDRAL (SPAIN) USING NON DESTRUCTIVE TECHNIQUES

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Abstract

The on-site inspection, diagnosis and subsequent analysis of a historic timber structure require interdisciplinary expertise and the use of techniques that are able to determine the actual state and residual mechanical capacity of its components, even when the structure is partially decayed.

This paper presents the study of the nave timber structure of Segovia Cathedral (Spain), which is one of the latest gothic buildings built in Spain, between 1525 and 1577, at a time when the rest of Europe was under the influence of the renaissance period. It was initiated by Juan Gil de Hontañón and completed by his son Rodrigo Gil de Hontañón.

The timber structure has been evaluated and presented according to a specific methodology developed by this research team, and based on a set of diagnostic techniques selected on the basis of their efficiency as well as on its cost effectiveness. Such techniques include visual inspection, ultrasound velocity measurements (later conveniently corrected as they are indirect measurements), resistography and infrared thermography.

The survey results are presented in a series of plans with graphics, icons and symbols that allow an integrated interpretation of the study.

1. INTRODUCTION

It should be noted that understanding the structural behaviour of historic buildings is one of the most important aspects one is faced with in any restoration project, as all documents and international charters in this field point out. But, at the same time, there are major methodological difficulties in dealing with the analysis of historic buildings, their morphological construction as well as their structural behaviour that were often based on techniques, systems and construction materials that may not be in use at present.

Wood was a material commonly used in the construction of historic structures in Spain, but researchers and technicians have not given it the same attention as other materials have received. This oversight may be due to insufficient information or even clearly erroneous information both scientific and technical on wood structural reliability over time.

The peace of research we present here shows the process of on site inspection, diagnosis and intervention proposed for the wood structure of this important Spanish heritage building: The Cathedral of Segovia’s nave timber truss roof. As it can be seen in the historic report carried out by our team of research, Rodrigo Gil de Hontañón was for the most part the master mason following in the footsteps of his father Juan Gil de Hontañón in the construction of this cathedral, which was built in three constructive campaigns (1525-1684) with the closing of the nave in 1542.

Figure 1. Aerial view.

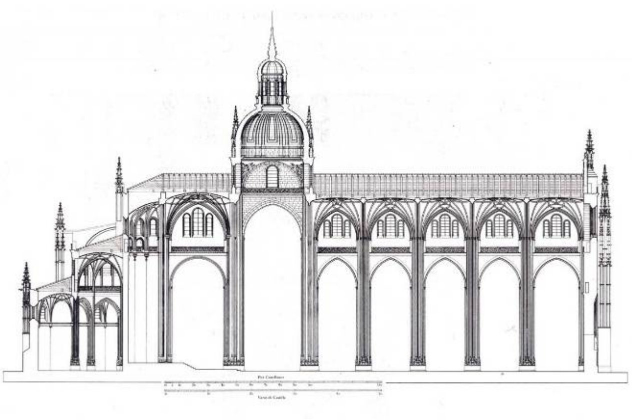

Figure 2. Longitudinal section, according to Merino de Cáceres.

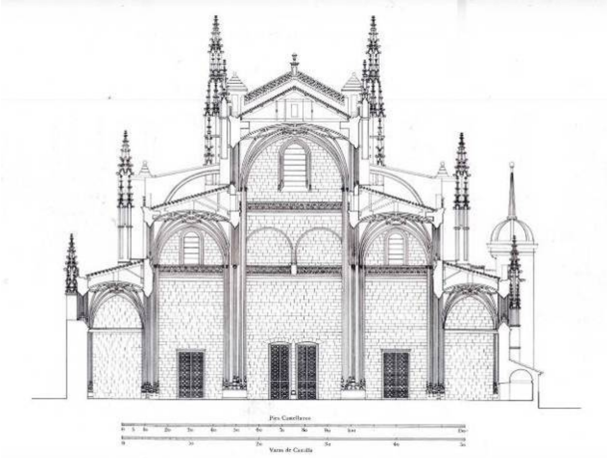

Figure 3. Transversal section, according to Merino de Cáceres.

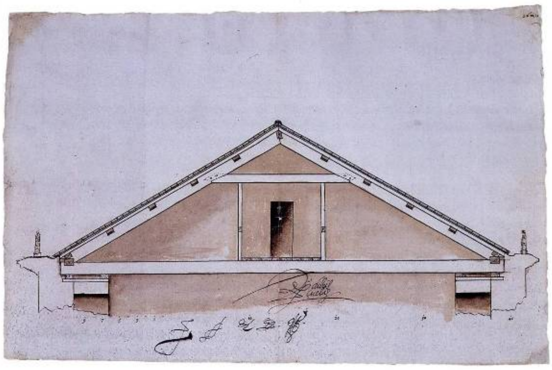

Figure 4. Central nave truss according to Pedro Brizuela (Segovia, 1555, 1631).

2. METHODOLOGICAL PLANNING

Our research has been carried out according to an original methodology (Ramón-Cueto 2007) of documentation, inspection, representation, and analysis referring to the architectural project and the constructive intervention, to evaluate the state of the wooden structural elements in this heritage building. Starting from the Theory of Architectural Restoration, the specific construction techniques and material used, as well as the tests conducted**,** we attempt to develop a contrasting procedure to make the correct decisions in the intervention of heritage buildings with wood structures. Due to all this, we can say that this is a highly interdisciplinary piece of research.

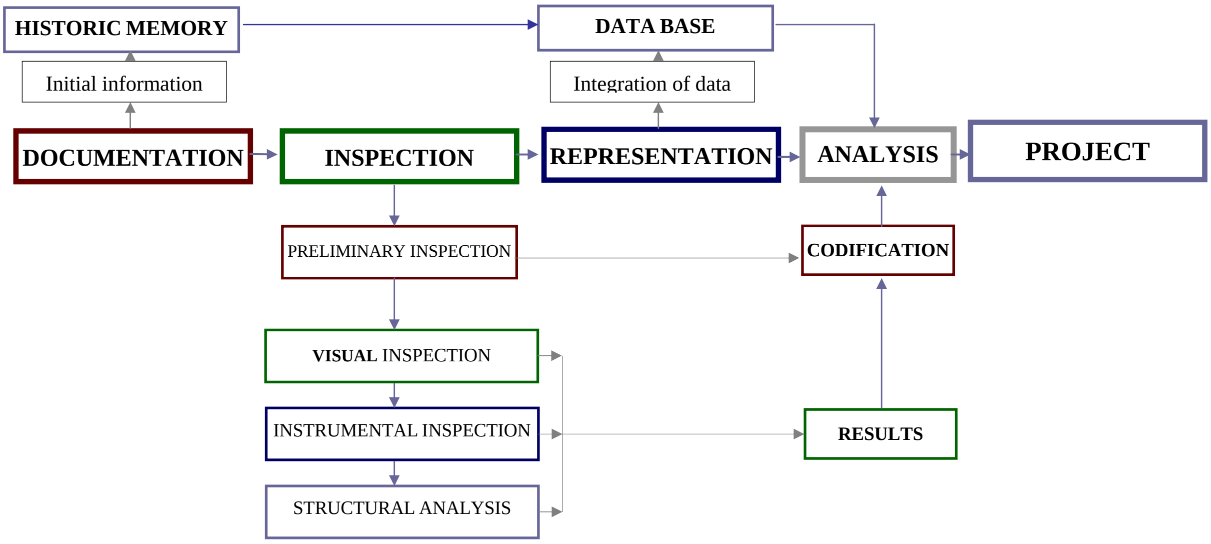

Figure 5. Methodological flow chart.

The diagnostic inspection of each structural element was carried out in three stages:

- **Basic visual inspection**. Each structural element is described, its wood species and location are identified, and then any defects or peculiarities in the timber are evaluated and quantified.
- **Instrumental inspection.** The basic inspection is complemented by using non- destructive diagnostic techniques used in-situ on the timbers marked in the previous stage.
- **Structural analysis and the elaboration of the results**. We have carried out the classification according to its strength class and the estimate of the residual resistant strength of each timber, identifying the timbers least resistant areas and the state of all joints, and, finally, we have made a visual graph bringing together the results of these tests and inspections.

3. VISUAL INSPECTION

Even before the CTE publication in Spain, the *strength classes system* was already standardized through the European standard EN 338:2003. The visual inspection is based on grading wood according to the defined degrees of strength and elasticity properties.

On the other hand, the evaluation of the exterior appearance of each timber, when no defects are detected, was and it continues to be one of the most frequently used methods to know the mechanical properties of sawn timber, even though it is a difficult technique to use with accuracy and requires suitable specific training. In this way, the allocation of a resistance class is determined by a combination of the visual quality, in relation to lack of peculiarities, defects, insect infestations, etc. and the assigned value of the common wood species in each country. For this, the international standards may be slightly different from the Spanish standard UNE 56.544:2007 “Visual classification of sawn structural timber from conifers”.

The application of this UNE norm for sawn structural timber elements is subject to individual experience and a certain degree of interpretation. As it is relatively conservative it causes the rejection of a high percentage of timbers, especially in the larger dimensions. This implies a limited use of the material, and therefore the cost goes up considerably when intervening in a restoration project. Recent studies (Basterra 2005, Arriaga 2007) conclude that the standards, as presented, do not provide sufficient scope to differentiate between timbers for structural resistance with enough accuracy. On this point they conclude that there is a necessity to establish, in dealing with historic timber structures, criteria and parameters that are less restrictive than the stated standards through visual classification and in-situ non destructive techniques of classification. For this reason they propose other complementary techniques to classify this type of structural members.

At the time of the inspection (June 2007) the timber structure was accessible between the vaulted ceiling and the underside of the roof trusses, although planks situated on the rafter ties forming a walkway were precarious at best, and did not provide access to the entire roof structure, specially to the rafter ends.

The timber frame inspected covers the Cathedral’s central nave with free interior spans in plan view of 52.3 x 15.0 m. The main trusses in the roof structure consist of 26 full width trusses with rafter ties and collar braces located horizontally (“par y nudillo”) and non structural vertical strapping (Figures 4 and 7). They are secondary beams placed horizontally between the main rafters, and finally placed on this truss structure are situated small beams (“cabios”) placed vertically with short spans ready to receive the roof planking. On this, the curved ceramic tile (“Arabic style”) is placed in channels, which is conntrary to the original entrenched local tradition.

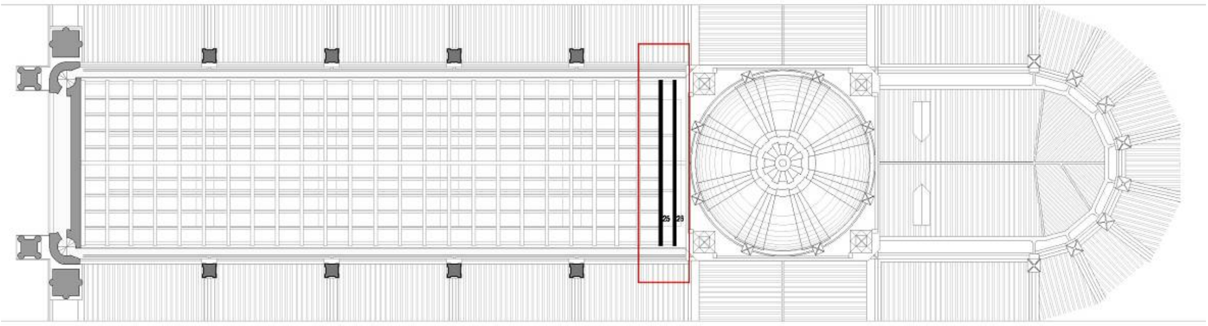

Figure 6. General plan view.

The main trusses are formed in two opposing rafters with a 25 x 32 cm section and a span of approximately 8 m with an inclination of 50.5 % or 26.75º. They sit on a top plate with a section of 22 x 29 cm and are held by an impressive rafter tie with a 28 x 41 cm section and almost 15 m in length. The rafter braced has a section measuring 25 x 25 cm and a span of 4.85 m, located horizontally and at a height of 2.23 m from the rafter tie. Rarely seen are mortise type joints which set 6 cross rafters at 90º into the roof trusses. Each cross rafter has a section of 14 x 21 cm and are 1.8 m in length. The highest of these cross pars forms the ridge plate.

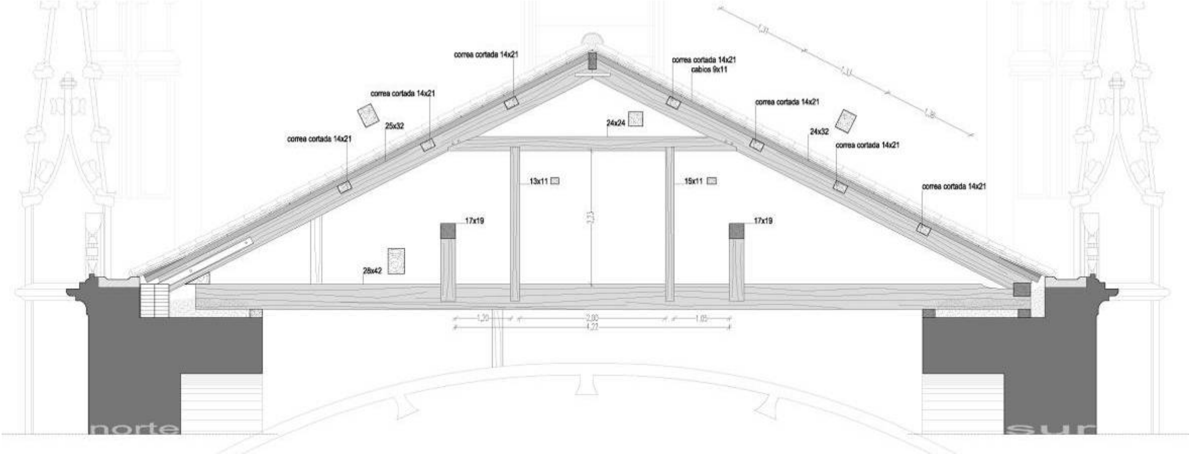

Figure 7. Typical section of main trusses.

As the walls flare at the top to almost 2 m it allows for an effective system of increasing support for the trusses, with two favourable consequences: trusses can rely on a double sill plate, with the consequent sharing of the bearing load, and the free span is reduced from 14,30 to 11,10 m (Figure 7).

3.1 Peculiarities

The defects most frequently encountered are knots and wane. These are found mainly in the rafter ties due to their large section. The knots are of great importance for the timbers mechanical strength, while the waning simply constitutes a reduction in the overall section of the timber. It is also quite common to find splitting that took place in the drying process and may appear down the entire length of the timber.

Figure 8. Longitudinal splitting in the rafter.

Figure 9. Waning on rafter tie.

3.2 Structural damage

With the visual inspection initial data are obtained concerning any structural damage of biological and non biological origin, and areas for further instrumental inspections are proposed. The results from this inspection are represented in plans through a series of icons and colour codes that the research group has developed (Ramon-Cueto, 2007) with the intention that these will become standard practice in the near future. The most important types of damage we have identified are:

- A general inclination or slope of the trusses towards the east. There has been an attempt to resolve this tendency by placing a cross brace between the collar brace and the rafters ties. This solution is inadequate and pushes down on the collar braces causing torsion and horizontal bending.
- Deformed or broken rafter ties.
- Accumulation of debris in the area where the rafter and rafter ties are supported on the sill plates. In many cases, this debris completely covers the entire length of the sill plates, which in conditions of high humidity and a lack of ventilation has initiated the decay of the timber and allowed for the formation of fungus with severe crushing in the cell structure of the timber and in some cases its virtual disappearance. As well as preventing the ventilation of the timber, the accumulation of debris has made a detailed inspection impossible allowing for the possible discovery of more severe damage than the one initially identified.
- Opening of structural joints. The traditional joints used in the timber structure have opened and completely separated from each other in some cases. In this state the joints do not function as theoretically intended and allow for further deformation in the truss structure.
- Discontinuity and degradation in the planks covering the roof surface. With the passing of time, the movement and or deformation of the structure, the damage caused by weather conditions and damage initiated by birds has caused movement in the roof tiles allowing rain water to enter.

3.3 Biological and non-biological pathologies

It should be noted that, in general, the state of the timbers in the roof structure is quite good. There appears to be limited biological pathologies with practically an absence of insect attacks except in small areas that were found to be, in most cases, of little depth. The biological pathologies present were in the form of wood destroying fungus, which only in exceptional cases has caused damage to some truss elements.

Moreover, debris accumulated in the area of the sill plates and where the rafter ties are supported, which was not accessible in the visual inspection, may hide serious structural decay in some other timber elements, and that may be discovered during the restoration process.

The non-biological pathologies are due mainly to the humidity caused by leaks usually found on the north facing side of the roof. In the most affected areas, the moisture has passed through the planking to the rafters and down through to the sill plate and walls.

In the area where the trusses come into contact with the wall there are also humid areas but, because access was not possible, a quantitative determination was not possible to be made with the xilohigrometer. In these areas, an infrared thermographic camera was used in order to get images that can be very useful to quantify the areas that had moisture present at the time of the inspection.

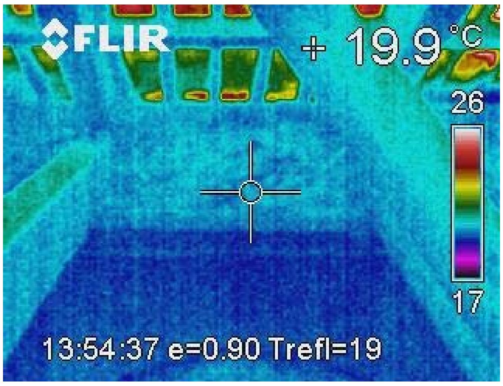

Figure 10. Uniform temperature detected in dry zones.

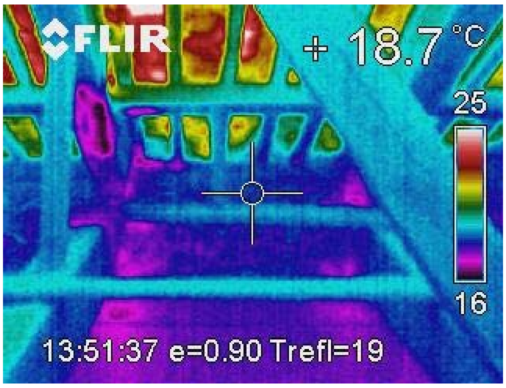

Figure 11. Localizing humidity by infrared thermography.

Figure 12. Advanced fungi decay.

Figure 13. Deep damage caused by insects in the rafter ties.

4. INSTRUMENTAL INSPECTION

4.1 Identification of the wood species. Micro photography.

The identification of the wood species allows us a ver useful approach to the physical-mechanical characteristics, its natural resistance to insect attacks and impregnability for possible preservation or curative treatments. The first macroscopic visual analysis indicates that the timbers belong to the general group of “conifers”. To reach a positive identification of the species a microscopic analysis of the timbers was collected on site, and then cut into parts between 25 to 50 µm thick with a special device. After the samples are tinted, they are mounted onto slides, and then examined under the electron microscope.

In this case, all samples collected from each of the structural elements of the roof correspond to the species of Pinus sylvestris. This is corroborated in the historic report we mentioned before, as there are references to the wood coming from the region of Mount Valsaín and that historically Pinus sylvestris had been the characteristic species in the region.

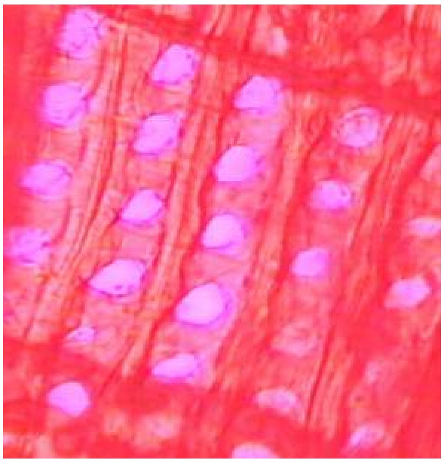

Figure 14. Microscopic image of rafter

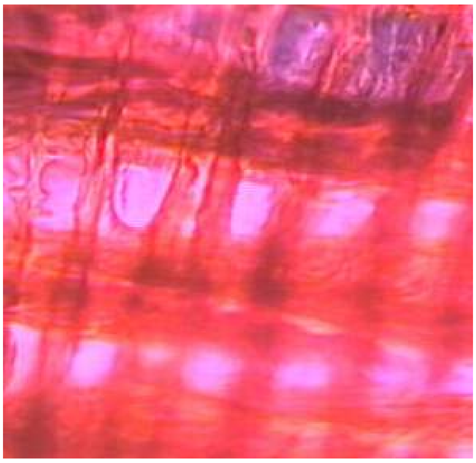

Figure 15. Microscopic image of rafter 8-South.

4.2 Assessment of moisture using the electric xilohigrometer

Moisture and density are the primary properties of wood related to its mechanical characteristics, and today it is well known that when the moisture content increases the strength is decreased and the timbers elasticity is affected. A Xilohigrometer measures the electrical conductivity between two electrodes that are spiked into the timber member to be tested. It provides an average direct reading of the timbers surface moisture in the specific point where the reading is taken at a depth of up to 1 cm and based on the linear relationship between moisture content and the logarithm of the ohmic resistance.

In our case, the moisture content of the wood tested had an average humidity value of between 10 and 15%, which is considered normal for timber in a roof structure. However, there are areas where, due to rainwater leaks, high moisture content, in excess of 17%, was found. These high readings can be compared directly with the thermographic images taken, which reflect the distribution of humidity in each timber element.

Table 1: Moisture value averages in the timber types,

	RAFTER TIES		**RAFTERS**		**CROSS RAFTERS**	
	Nº Elem.	Media	Nº Elem.	Media	Nº Elem.	Media
MOISTURE %	17	12,5	17	12,1	12	12,5

Figure 16. Humidity reading with electric xilohigrometer.

Figure 17. Measuring ultrasonic speed.

4.3 Non-destructive ultrasonic test

Measurement of the ultrasound propagation speed through wood is a non-destructive technique which is widely used in the field of forestry and on which there are abundant studies (Acuña 2007, 2000 Rodriguez, among others). It is based on the presence of cavities, knots, resin pockets or internal degradations that alter the transmission speed of generated waves. The application of this technique has the advantage that it can be used in situ for the evaluation of wood used in the structure.

The equipment used for this study was made by Sylvatest which employs a frequency of 30 kHz. Knowing the species (density), the length of the timber member and its geometry, the time (μs) used for the ultrasonic wave to reach from transmitter to receiver is measured, which allows us to determine the Module of Dynamic Elasticity using the following direct link between them:

$$v = L/t \qquad\qquad MOE_d = v^2 \cdot \rho \qquad (1)$$

Where: v = speed of propagation of the longitudinal ultrasonic waves through the wood (m / s), L = Distance between probes or length of the test piece (m), t = time it takes to receive the probe-wave receiver emitted by the probe-issuer (s), MOE = Dynamic Modulus of Elasticity (N/mm^2), ρ = tested beam density (kg/m^3).

In timbers situated in an existing structure, it is difficult to have access to end grain, and that is why an indirect assessment is usually made. In this tarticular case, ultrasonic speed measurements were made from the face of the timber near its termination to the opposite face. This indirect method (face to face) creates a 45 degree axis through the timber between transmitter and receiver. In order to put in relation the speed obtained using the indirect method with measurements taken in a direct line, our research group has published (Acuña et al. 2007) some correction factors, by the distance and by the angle between the longitudinal direction and the joining line of transmitter and receiver, which makes it possible to correlate both numbers.

Table 2: Summary results from ultrasonic tests.

VARIABLES	Rafters	
	Nº Elements	**Media (Standard Des.)**
CORRECTED WAVE SPEED (m/s)	9	**5.008 (579)**
ESTIMATED DENSITY (kg/m^3) (By resistograph)	44	**470,3**
DYNAMIC MOE (1) N/mm^2	9	**11.935**

The dynamic modulus of elasticity obtained with formula (1) in relation to the indirect speed corrected for the distance and angle of the transmitter and receiver (5,008 m/s) and the average density estimated with resistograph (470.3 kg/m^3) gives a value of 11,935 N/mm^2. Based on this parameter it was estimated that timber members have class strength in the range of **C24**. However, this initial assumption, which may be considered appropriate in terms of elasticity, because it had been obtained from a global measurement of timbers, should not be extended -for logical security reasons- to bending strength features since other local defects may influence on this, such as the existence of knots in tensile sensitive areas, and which are not properly evaluated by the ultrasonic propagation test.

4.4 Resistograph

Resistography is a pseudo-non-destructive technique that is based on a drilling kit which drills wood timbers with a very fine drill bit, and at the same time records by means of a potentiometer the force necessary for the bit or needle to advance at a constant speed through the timber. The resistance to the drilling is directly proportional to the timbers density, and therefore the higher the density, the greater the opposition or resistance presented by the wood.

Figure 18. Resistograph used in study.

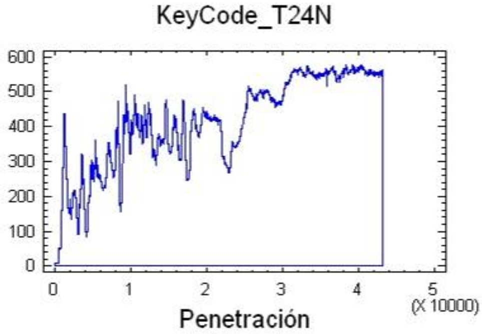

Figure 19. Resistogram data.

The drilling kit used in these tests was the German made RINN-TECH RESISTOGRAPH® XB-3450-S Professional model. Data were recorded graphically in its memory, and a small printer was used, which printed the resistographic profiles at 1:1 scale. Relating graphically employed force (% amplitude) per length unit. Analyses were carried out only in areas inaccessible by other techniques.

The resistogram analysis methodology to evaluate the state of conservation of the structural elements was based on the visual analysis, and a methodology of numerical analysis developed by our research team (Acuña 2007). Values obtained in the timber elements of the cathedral were compared and contrasted with the data bank of healthy pine wood available in our laboratory. The resistographic variables used as a comparison pattern together with the admitted limits of population tolerance for each of these elements are listed in the table. Tolerance analysis of 6σ of these elements allows the elimination of those timbers which breach any of the bounding established conditions.

Table 3: Results from resistographic analysis.

Variables	Key of the variable	Resistographic range	Population tolerance limits		
			Lower limit	Middle value	Upper limit
Total average	1	A	141,825	228,224	314,596
Angle 1000	2	A	7,42184	11,3979	15,374
Population devi.	3	B	24,9363	54,7435	85,3507
Maximum	4	B	134,949	331,182	527,415
Minimum	5	B	115,282	179,727	244,172
Maximum average	6	B	158,606	254,65	350,694
Minimum average	7	B	120,376	233,362	346,348

5. SUMMARY AND CONCLUSIONS

This piece of research has been carried out taking into consideration the theoretical foundations established by the ICOMOS' Committee named ISCARSAH at its 2001 meeting in Paris, and more specifically the principles ratified by the 12th General Assembly of ICOMOS in Mexico, 1999.

5.1 Strength classes estimate

The conclusion of these findings is based on the use of these specific criteria of visual and instrumental inspection carried out, which resulted in the following strength and class assignation being proposed:

Table 4: Assignation of proposed strength class values.

	Bending strength f_m (N/mm^2)	**Mod. Elast. parallel $E_{0,med}$ (N/mm^2)**	**Medium density (Kg/m^3)**
STRENGTH CLASS	**C16**	**C24**	**C30**

5.2 Elaborated Results

This piece of research has used an original sýstem for coding and integrating heterogeneous graphs and document formats concerning the diagnosis and subsequent results of the non-destructive testings carried out on site (Ramon-Cueto 2007).

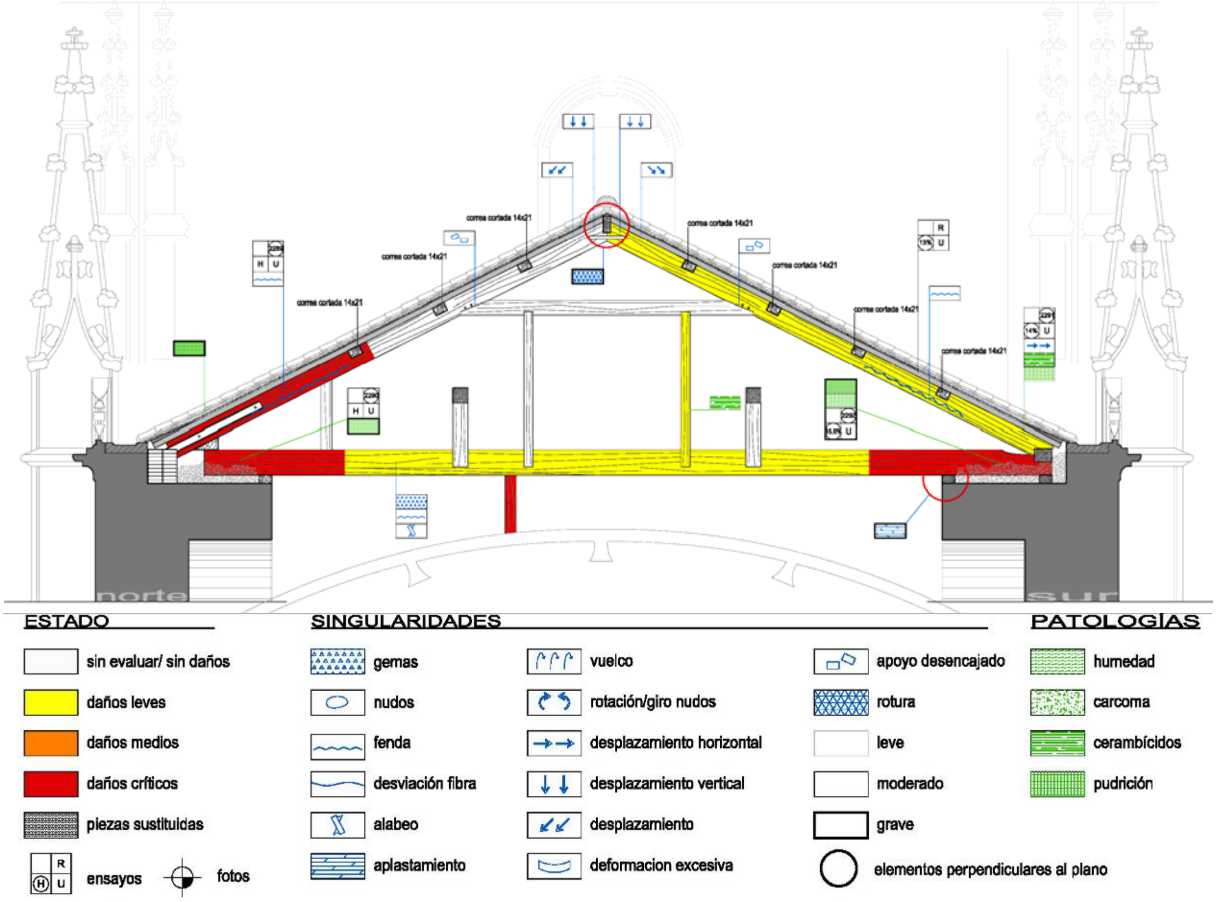

Figure 11: Graphic representation of results.

As we can see, Figure 11 consists of a hyper textual document based on a series of icons that assist in navigating through photographs and results of the trials and tests conducted. In addition colours are used to indicate in an immediate way the severity of the damage that has been discovered.

5.3. Summary of proposals for intervention

Before the intervention on this structure, special attention should be paid to the general inclination of the main trusses, which may worsen over time due to the rheological behaviour of wood materials.

For the repair and consolidation of the areas identified, in whole or in part, the **same species or type** of wood -with similar natural characteristics to the ones this study has contributed to characterize- should be used. Original techniques and methods of building equal to those originally used should be employed, documenting and discreetly marking the pieces or the new parts with a knife or engraver.

As a general rule, all humid or wet areas should be eliminated. The accumulated debris, which makes adequate ventilation impossible, should also be removed.

Nothing makes us suspect that the generous dimensions of the timber pieces studied will not be able to continue fulfilling their primary structural function, once the deficiencies and damages detailed in this study are corrected, especially when the permanent loads supported get lighter. However, during the project phase, a structural evaluation, based on the limit states method, should be performed in accordance with safety and aptitude to the service requirements established by the Spanish norms CTE DB-SE M, but taking into account the fact that there is not any uncertainty associated to the construction process that determines the safety coefficients to be used in project. In this case, models must be used which adequately reflect the current condition of the building, in accordance with the principles of the structural safety analysis, and which take into account the processes of deterioration that may prove relevant.

6. ACKNOWLEDGEMENTS

This work has been made possible through the collaboration of the Directorate General for Heritage and Cultural Property of the Ministry of Culture and Tourism of the “Junta de Castilla y León” (regional government).

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