Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

# Analysis, Intervention and Repair of Timber Structures

C. Rodríguez Liñán, P. Rubio de Hita, J.C. Gómez de Cózar and F. Pérez Gálvez
*University of Seville, Technical School of Architecture, Department of Architectonic Constructions, Seville, Spai*

ABSTRACT: Ultrasonic tests are an effective technique of getting a diagnosis of timber structures in historical buildings. This technique is quite valuable to undertake a restoration job. A new methodology of analysis and diagnosis of timber roofs through this non destructive technique is presented.

The aim of this paper is to get the state of damage and the bending strength capacity of the timber roof of the Monastery of Santa Clara's dining room in Carmona (Seville) by using this technology.

From the results obtained about the bending strength capacity of the studied beams, it can be affirmed that the timber roof is not able to support safely enough the new use proposed.

Considering the historic and artistic importance of this timber roof, we propose as a restoration methodology based on hanging the roof through bolts from a reinforced concrete platform built-in the perimeter walls. This solution guarantees that the timber roof does not work, just adjusting the distance between the bolts.

## 1 INTRODUCTION

Nowadays ultrasonic techniques are turning out to be an useful and effective tool to diagnose timber structures. Works (2) (3) (4) (5) made by the research group PAI TEP-205 "Analysis and evaluation of construction and structural systems in Architecture" of Junta de Andalucía (composed by teachers of the Department of Architectonic Constructions of Technical School of Architecture, Seville) confirm this.

The work of timber roofs' diagnosis of several buildings in the historical city centre of Sevilla and the validity of the results obtained makes it evident, giving in all cases a worthy and strict information about the state of damage and the bending strength capacity of these structural elements. These data have been essentials to approach successfully the restoration works of these buildings.

The methodology used in first cases is being enriched by solving singular aspects for every case according to the diagnosis' requirements.

Anyhow, works made not only conclude with diagnosis works but also bring, at sight of results and taking into account every singular project's requirements, the constructive solution suitable to roofs restoration.

The diagnosis of the timber roof of the Monastery of Santa Clara's dining room in Carmona (Seville) was sought by the works management, as part of the previous studies that were used for determine the restoration works.

## 2 DESCRIPTION OF THE ULTRASONIC METHODOLOGY APPLIED

A methodology based on trials, specific for the inspection in situ of wooden slabs has been applied (1). This method is based in the characteristics of spreading of the ultrasonic waves in the wood of the wild pine. The application of this methodology let us have an idea of the degree of damage of the wood we study. The experimental relationships obtained between the measures of velocity of ultrasonics and the loss of density and resistance of the material are here used. An estimation of the value of resistance to flexion of the wood here studied can be obtained from the velocity of transmissions of the ultrasonics and its correlation with the values of tension of breakage. These correlations have been performed for samples of wood of the same type as the one that has been here studied.

### *2.1 Estimation of the damage of the wood*

The following three intervals for the diagnosis of wood have been established from the correlation obtained associating values of normal velocity of ultrasonics to values of loss of density and resistance:

- Normal velocity (Vn) > 1900 m/s. → Sound wood. (Loss of density under 20%. )
- 1500 m/s ≤ Normal velocity (Vn) < 1900 m/s. → Wood with start of damage. ( Loss of density between 20% and 30% )
- Normal velocity (Vn) < 1500 m/s → Damaged wood.

A specific criterion for high density wood with values of normal velocity over 3000 m/s must be applied to sound wood apart from the general criterion stated above. This criterion is good to detect variations of density higher than the natural variation inside the trunk (10 % maximum) (8) and corresponds to a start of damage. Using the correlation of density and normal velocity, a start of damage is established for a drop of normal velocity over 300 m/s.

In order to get results below, it is necessary that all normal velocity values should be comparable between them. So it has been taken into account the influence of moisture content and grain direction of wood, rectifying all values for the same moisture and orientation.

### *2.2 Obtaining of estimated values of wood behaviour*

Nowadays, wooden structures' calculus is based in norm UNE EN 338 and its review in the European Normative project, pr EN 338. This norm assigns the properties of resistance, stiffness and density according to wooden resistance classification.

In order to determine old wood resistance (instead of assigning a resistance type with its characteristic value of tension of breakage (XK) by default) we assign the characteristic value of tension of breakage obtained trough ultrasonic values, without establishing resistance type at first.

Several tests have been made in order to obtain XK value based on the characteristic value of tension of breakage (σr) of the trial of static bending divided into a coefficient of safety which takes into account the size of the test tube (2x2x30 cm) and the means of developing the trial. This coefficient is 3.43.

Trough this tests we have obtained the statistical correlation which let us obtain the tension of breakage by means of the velocity of ultrasonic transmission.

$$X_d = \frac{\Phi r}{3.43} \tag{1}$$

The calculus value is obtained from the characteristic value ($X_K$) onwards trough the expression:

$$X_d = K \bmod \frac{X_k}{\gamma_M} \tag{2}$$

where $X_K$ = characteristic value of bending strength, $\gamma_M$ = Partial safety coefficient (When using the method of limit states, we use 1.3.) and $k_{mod}$ = Modification factor that takes into account the load duration effect and the humidity contents for every resistance states.(Load duration corresponds to the combination hypotheses which belongs to different classes of charging duration (permanent and overload). As for service Class, it is used Class 1, that represents 12% of medium humidity contents of hygroscopic equilibrium. Under roof and closed structures belongs to this service class. According to this considerations, we obtain $k_{mod} = 0.80$)

In the method here applied, we have obtained the statistical correlations between tension of bending breakage in test tubes and velocity of ultrasonic transmission, which allows to obtain tension of breakage by means of the velocity of transmission.(1)

In the case of sound wood, the estimation is carried out from the longitudinal velocity (V1) with two possible cases:

$$\sigma_r = 0.173V1 - 74.54 \tag{3}$$

Vl will be determinated in beams in situ from following values onwards: $V\ L_{\text{maximum cross}}$ which does not take into account the flaws of the piece and $V_{\text{L medium cross}}$, which includes the flaws of the beam.

In the case of damaged wood, the estimation of the tension of breakage is made from the normal average velocity of the section through the expression:

$$\sigma_r = 0.747V_n - 956 \tag{4}$$

Characteristic value ($X_K$) is obtained according to equation (1).

Calculus value ($X_d$) is obtained according to equation (2), Characteristic value ($X_K$) and all we have say before.

### *2.3 Obtaining maximum loads for beams supported at both ends.*

If we analyse the bending diagram of a beam, we can say that working tensions which are required to each section are different. In the case of a material with the same resistance in all of its sections, sound wood, it will be enough checking working tension at the middle point of the beam, because in this point is where maximum normal tensions are produced.

However, in damaged wood, it will be necessary to compare working tensions of each section with calculus tension, because breakage could be produced in any section depending on its damage conditions.

Maximum load allowed by the beam is obtained by means of calculus tension ($X_d$) of each section, using the equation:

$$\gamma_{F1}Q_s + \gamma_{F2}Q_c = \frac{X_d bh^2}{3e\left(Lx - x^2\right)} \tag{5}$$

where *Qs* = uniformly distributed overload, *Qc* = deadload (structure weight plus filling and pavement), *γF1* = variable actions (= 1,50), *γF2* = permanent actions (= 1,35), $X_d$ = bending resistance, *b* = width of the beam, *h* = Height of the beam, *L* = Free distance between supports, *e* = distance between beams axes and *x* = co-ordinate of studied section.

If the values of x-co-ordinate and calculus tension ($X_d$) are replaced in this equation, we can obtain maximum load ( $\gamma_{F1}$ $Q_s$+ $\gamma_{F2}$ $Q_c$ ) for each section of the beam.

The lowest maximum load of all studied sections will be the one which limits the maximum allowable load for the beam.

We also could say that the beam which has the lowest maximum load will limit maximum load for the timber roof.

This work shows the results of maximum load for each studied beam in Kp/m and maximum allowable loads for timber roofs in Kp/m2.

Maximum loads will be estimated taking into account beam deflection limit by means of the following equation:

$$Q' / Q = (384\ E\ h / 80\ X_d\ L)\ 1/\alpha \tag{6}$$

where Q' = maximum load by means of blending criterion, $Q = (Q_s + Q_c)$ = maximum load by means of breakage criterion, $E$ = material elastic modulus (In this case E = 105.940 Kp/cm$^2$ obtained by breakage tests ), $h$ = height of the beam, $L$ = distance between support axes, $X_d$= calculus resistance, α = factor of deflection limitation (f < L/ α . = 500)

Shear force tests have not been considered in order to determine maximum loads.

For sound wood, the most unfavourable maximum tension is produced in the centre where there are no shear forces. For damaged wood, when damage is located at the edges ( Vn. 1500 m/s ) is recommended cleaning and reinforcing them, so shear force tests are not necessary. However, shear force tests could be done using shear characteristic resistance $f_{vk}$ obtained from a table of the normative (7) according to resistance classification which is determined by characteristic value $X_K$ (in the table is named $f_{mk}$).

## 3 DESCRIPTION OF THE TIMBER ROOF STUDIED

### *3.1 Historical aspects*

According to references (9) Santa Clara's monastery was founded at the last third of 15$^{th}$ century. Part of the present church belongs to this period. Mudejar cloister with two floors was built at the beginning of 16$^{th}$ century (Fig.1).

Dining room, of which roof is studied, is located at the ground floor and it has an entry from the cloister gallery. Starting from the date of cloister building and the coffered ceiling decoration, we can say the dining room was also built at the beginning of 16$^{th}$ century

Apart from the historical worth of this room and its coffered ceiling, there is an added artistic value because of its polychromy (Fig. 2).

Figure 1 : Monastery's cloister

Figure 2 : General view of dining room's timber roof

### *3.2 Constructive description*

The dining room is located at the ground floor of the building and the entry is made trough the monastery's cloister. Over it first floor has tile roof as it is shown in the constructive section. (Fig.3). Timber roof has 27 beams with section of 10 cm x 20 cm, 4,40 m length and 70 cm of distance between axes. They support *zoquetes* of 6cm x 4 cm. Over them, there are bricks of 20 x 30 x 4 cm which are decorated in the underside (Fig. 4).

Roof weight (just only beam + *zoquetes* + bricks, without filling and pavement) is 1,0 KN/ml over each beam or 1,428 KN/m$^2$ as superficial load uniformly distributed on the roof.

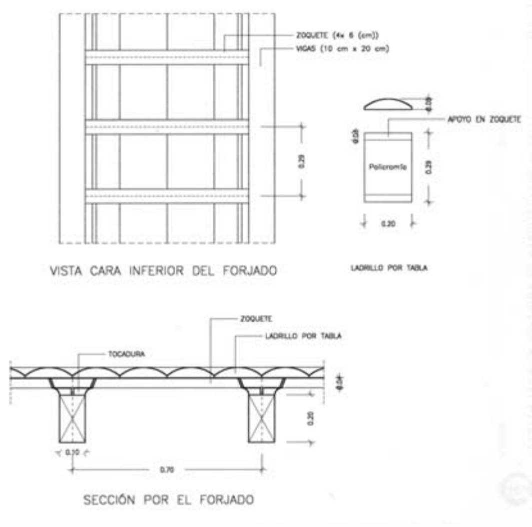



Figure 3 : Dining room's section

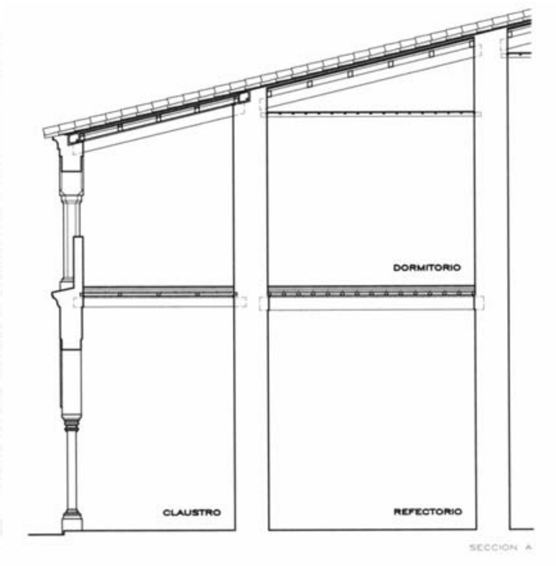



Figure 4 : Timber roof's constructive section.

### 3.2 *Visual inspection of damages*

First visit showed the roof's bad conditions. It had big deflection and several beams had been strengthened by inserting thin metal sheets (Fig. 5).

Half of the roof was propped up.

Damages in this area have been produced by water filtrations coming from upper floor of which roof was in bad conditions. Because of deflection, water is accumulated in the centre of the roof so wood damages by humidity have produced the attack of xilophagous agents. Mechanic capacity of the material has been reduced so some beams had cracks caused by blending breakage in the centre of the beam. (Fig. 6)

After the visual inspection, we could say that damages were: first, all beams had deflection visible to the naked eye and longitudinal cracks. Regarding to xilophagous agents, there was a generalized attack of little woodworms in all beams plus and brown rotting (Fig.7).

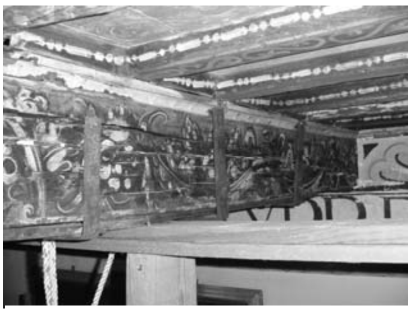


Figure 5 : Beams strengthened by metal sheets

Figure 6 : Deflection breakage

Figure 7 : Woodworms attack and brown rotting

On the other side, brown rotting attack strengthen little woodworm (Anobium Punctatum) action because if these ones, at first, only attack wood perimetral whiteness, rotting fungi make easy woodworm's *duramen* digestion so depth of penetration of woodworms' attack is higher. It stands to reason that these facts had produced loss of material and density that deeply affected beam's carrying capacity which caused blending breakage in some cases.

## 4 ULTRASONIC TESTS

Five beams from the timber roof have been tested. They appear in the ground plan numbered as 1-2, 1-6, 1-8, 1-20, y 1-25 (Fig. 8).

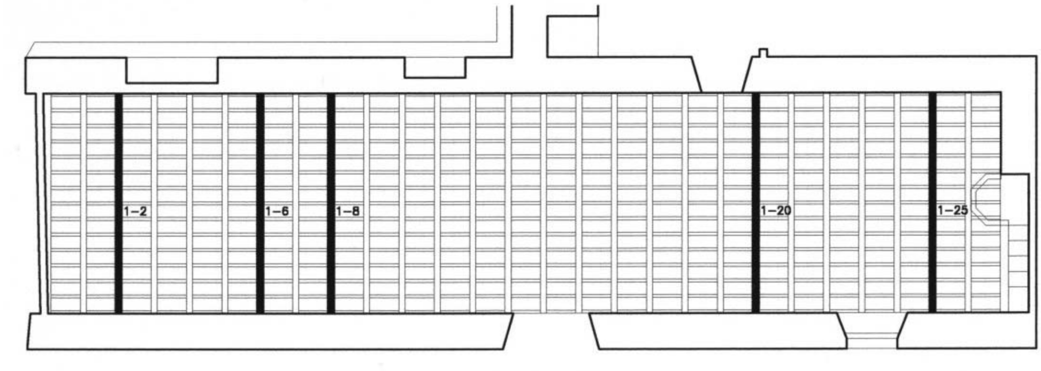



Figure 8 : Studied beams

Selection criterion has been obtaining data from some beams apparently in better conditions and data from those which are apparently more damaged. Two areas have been tested, the most damaged (the one propped up) to which beams number 2, 6 and 8 belong to and the least apparently damaged area to which beams number 20 and 25 belong to.

From each beam 13 sections have been tested. Four of them were next to edges and five in the centre area. Reference sections' position is shown in Fig. 9.


Figure 9 : Studied sections

## 5 RESULTS AND DISCUSSION OF ULTRASONIC TESTS

Tests' results are shown in maps where values' intervals are represented in colour codes for the different parameters that have been took into account: degree of damage, degree of humidity and maximum load.

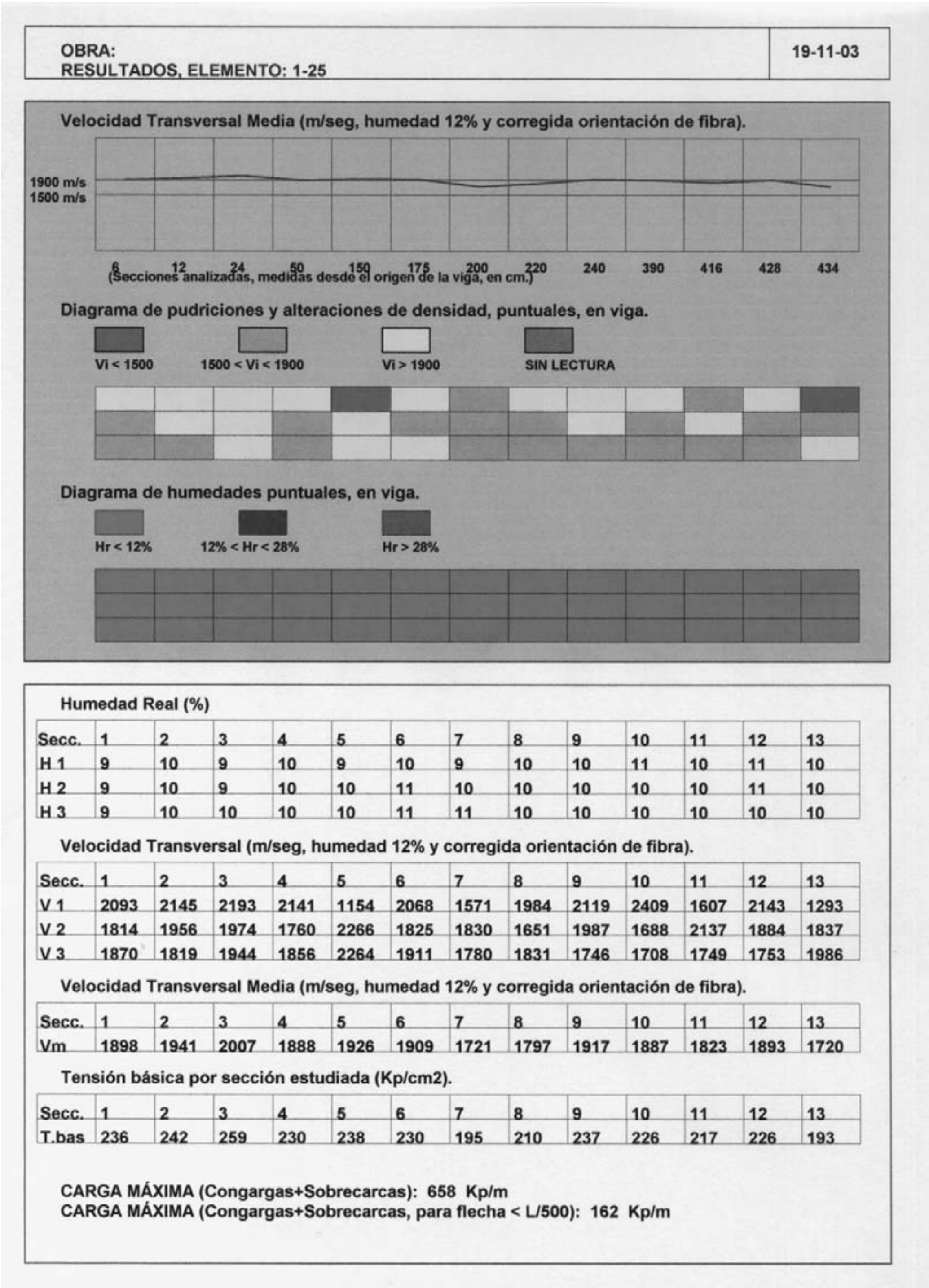
For each beam, some results cards are obtained where are represented the measuring that have been made: ultrasonic velocity, humidity content and maximum load's values (Fig. 10).

The map of degree of damage (Fig. 11) shows loss of density of wood. It is generated by interpreting ultrasonic velocity by means of the criterion of section 2.1.

For the studied roof we obtained the following results: 1-2, 1-6 and 1-8 beams (which are located in the propped up area) are in blue or red colour. This means that none has sound wood as blue colour means beginning of damage and red colour big damage. 1-20 and 1-25 beams (in no propped up area) are softly damaged, less than previous beams where some areas appear without damage so are in yellow colour.

The map of humidity content (Fig. 12) shows data obtained by means of resistance hygrometer are low values in general for all beams (≤ 12%) except for 1-8 beam, where soft high value is obtained.

These results are not compatibles with conditions needed to reach the degree of damage saw in the wood. They are justified taking into account when doing tests, some interventions were done in the building to avoid water filtrations trough the roof. So this damage were produced before, degree of humidity was higher than the ones obtained in tests.



OBRA:
RESULTADOS, ELEMENTO: 1-25 | 19-11-03

Velocidad Transversal Media (m/seg, humedad 12% y corregida orientación de fibra).



Diagrama de pudriciones y alteraciones de densidad, puntuales, en viga.



Diagrama de humedades puntuales, en viga.



Humedad Real (%)

| Secc. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H 1 | 9 | 10 | 9 | 10 | 9 | 10 | 9 | 10 | 10 | 11 | 10 | 11 | 10 |
| H 2 | 9 | 10 | 9 | 10 | 10 | 11 | 10 | 10 | 10 | 10 | 10 | 11 | 10 |
| H 3 | 9 | 10 | 10 | 10 | 10 | 11 | 11 | 10 | 10 | 10 | 10 | 10 | 10 |

Velocidad Transversal (m/seg, humedad 12% y corregida orientación de fibra).

| Secc. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| V 1 | 2093 | 2145 | 2193 | 2141 | 1154 | 2068 | 1571 | 1984 | 2119 | 2409 | 1607 | 2143 | 1293 |
| V 2 | 1814 | 1956 | 1974 | 1760 | 2266 | 1825 | 1830 | 1651 | 1987 | 1688 | 2137 | 1884 | 1837 |
| V 3 | 1870 | 1819 | 1944 | 1856 | 2264 | 1911 | 1780 | 1831 | 1746 | 1708 | 1749 | 1753 | 1986 |

Velocidad Transversal Media (m/seg, humedad 12% y corregida orientación de fibra).

| Secc. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vm | 1898 | 1941 | 2007 | 1888 | 1926 | 1909 | 1721 | 1797 | 1917 | 1887 | 1823 | 1893 | 1720 |

Tensión básica por sección estudiada (Kp/cm2).

| Secc. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T.bas | 236 | 242 | 259 | 230 | 238 | 230 | 195 | 210 | 237 | 226 | 217 | 226 | 193 |

CARGA MÁXIMA (Congargas+Sobrecarcas): 658 Kp/m
CARGA MÁXIMA (Congargas+Sobrecarcas, para flecha < L/500): 162 Kp/m

Figure 10 : Photo of one beam's results card

The map of maximum load (Fig. 13) shows maximum allowable loads for each beam obtained by means of ultrasonic tests we use section 2.3 equations.

Results are represented by colour codes in the map distinguishing three intervals for the studied beams.

Although some beams can support load values higher than 7 $KN/m^2$, maximum load of the roof is determined by the most damaged beam's values (2.2 $KN/m^2$).

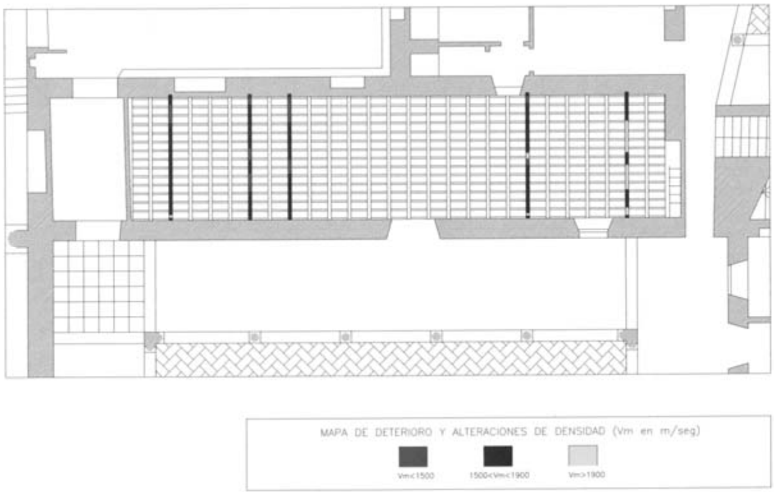



Figure 11 : Map of degree of damage

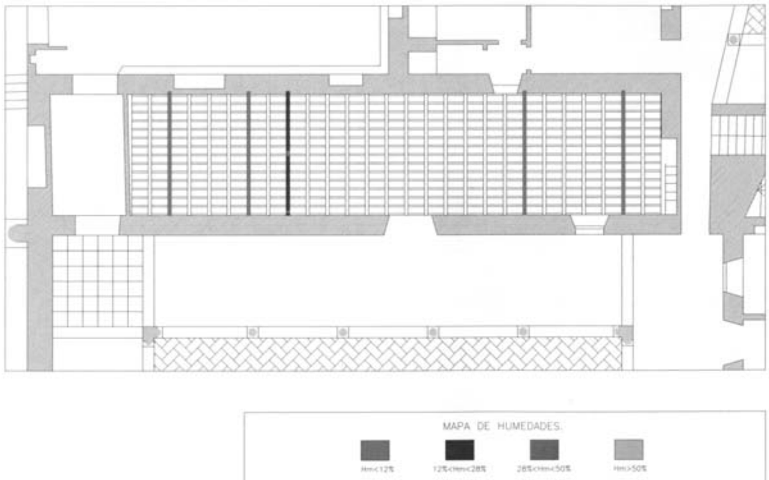



Figure 12 : Map of humidity content

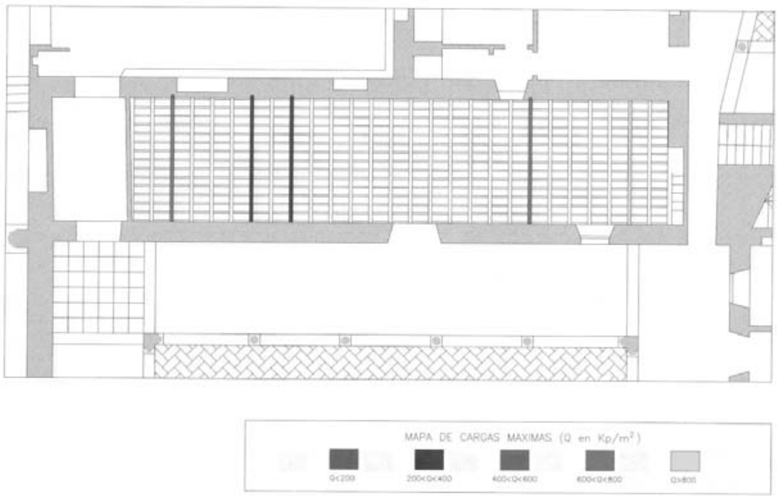



Figure 13 : Map of maximum loads

## 6 CONCLUSIONS

The results confirm the following thing: There are some beams which can not support overloads produced by using the room for temporary public exhibition (3-4 KN/$m^2$), other beams could not support its own weight so even less could support new pavement.

Now, it is possible to say the timber roof can not support with enough security the new use that has been proposed.

## 7 INTERVENTION PLAN

This situation is frequent in rehabilitation works: there is a timber roof with good artistic qualities but with such as degree of damage whose original conditions are impossible to keep up. On the other hand, we can not substitute the most damaged elements because of its decoration. So we should look for a structural supplement solution.

One of the most widespread repairs is using flagstones supported in its perimeter (stonework wall) and fixed to the timber roof. This solution must not be mistaken with a mixed roof concrete-wood. Usually it is not possible to put the concrete flagstone on the existing roof because on the roof there are secondary elements (*rastreles*, *tocaduras*, bricks, etc.) that make a gap between beams and the flagstone. (Fig. 2)

Apart from these geometric conditions, we have to take into account wood damage that puts limits when using high traction values in a mixed solution.

So, the best solution is hanging existent roof by means of some bolts (we will determine the specific distance between them) on the reinforced concrete flagstone supported on its perimeter (walls). Wooden beams will not support any load. This solution is the one we have used and it is shown in Fig. 14.

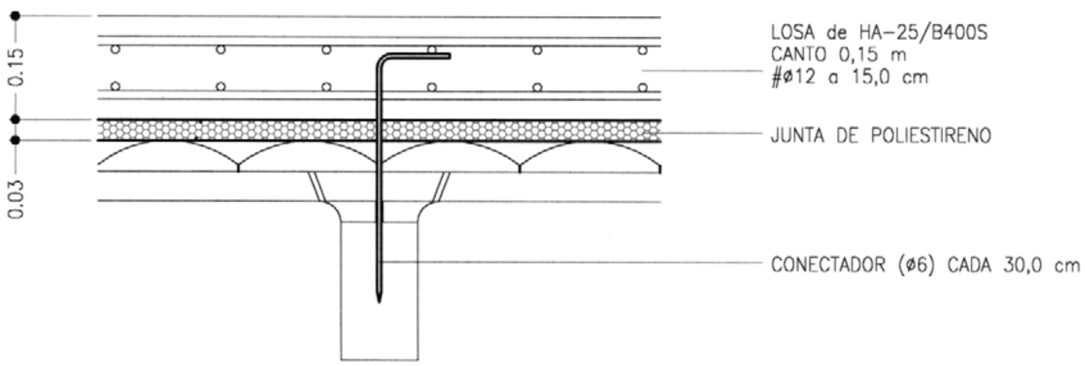



Figure 14: Roof rehabilitation's solution

Mathematical expansion of this solution, admitting that vertical deformation of concrete flagstone and wooden beam hanged on it is similar, allow us to determine (for foreseen overloads) maximum load over beams and bolt's maximum traction.

Making the structural analysis of this case, we obtain the following results:

- Reinforced concrete flagstone: HA-25 with 0.15 m of thickness, upper and lower steel framework of # $\phi$12 a 15.0 cm. In this solution timber roof only supports 10% of total load and in any case the load that is transmitted to each beam (0.62 KN/m) is lower than the one which can support any of them.
- Bolts: They are under traction or compression stress depending on cases. Its load does not exceed 0.72 KN/m. It was recommended to place them every 30 cm so they will support 0.22 KN of maximum load.

While concrete flagstone construction and to avoid timber roof receiving more loads than foreseen, in necessary not to take propping-ups off until concrete flagstone will had reached appropriate resistance to support its own weight and all of the other loads, even it is recommended to prop up areas which are not propped up yet. Figs. 15-17 show the construction process.

Figure 15 : Bolt

Figure 16 : Roof with bolts and extruded polyester sheet.

Figure 17 : Steel framework of concrete flagstone.

## REFERENCES


Arguelles Alvarez R., Arriaga Martitegui F. *Normas de cálculo de estructuras de madera*. A.I.T.M. 1987.

Arriaga et al. Evaluación de la capacidad portante de forjados antiguos con vigas de madera . Rev, AITIM N1161 Nov Madrid 1992.

Bucur V.. La vitesse des ultrasons el la qualite du bois. Communication au colloque du groupe Francais de Réhologie Paris 1984.

Gutierrez Oliva A., Baonza Merino V., Fernandez-Golfin Seco J.I. *Variaciones de la densidad de la madera de pino silvestre de los sistemas Central e Ibérico*. Congreso Forestal "IBATI-97" Navarra. Abril .1997.

Misztal ,B et al. *Reconstrucción of old wooden floors by used of the componed elements* 5 Wolrd Conference on Timber Engineering . Montreaux ( Swizerland ) 1998

*Norma UNE EN 338 y su revisión en el borrador, proyecto de Norma europea*, pr EN 338.

Hernández Díaz J. et al. *Catálogo monumental arqueológico y artístico de la provincia de Sevilla*. TII. Ed. Diputación Provincial de Sevilla. 1953.

Rodriguez Liñan C., Rubio De Hita, P. *Evaluación del estado de la madera, en obras de rehabilitación mediante técnicas de ultrasonidos*. Universidad de Sevilla. Secretariado de Publicaciones. Instituto Universitario de Ciencias de la Construcción. Sevilla. 2000.

Rodríguez Liñán C., Rubio De hita P. *Evaluación del estado de la madera en obras de rehabilitación mediante técnicas de ultrasonidos y obtención de parámetros resistentes*. Informes De La Construcción. Vol 47.nº 440. Instituto Eduardo Torroja. Consejo Superior de Investigaciones Científicas. Noviembre / Diciembre.1995.

Rodríguez Liñán C., Rubio De Hita P., Gómez De cózar J.C. *Aplicación de la técnica de los ultrasonidos en la evaluación del estado de la madera en el Palacio de los Marqueses de la Algaba de Sevilla*. Neutra nª3. COOAAO.1998.

Rodríguez Liñán C., Rubio De Hita P., Gómez De Cózar J.C. *Study, diagnosis and rehabilitation of the wooden ceilig of two palace houses in Seville*. 3er Seminario Internacional sobre construcciones Históricas. Ed. Paulo B. Lourenco Pere Roca. Guimaraes. Portugal. Septiembre. 2001.

Rubio De Hita P. *Evaluación del estado de la madera, en obras de rehabilitación mediante técnicas de ultrasonidos*. Tesis Doctoral. Universidad de Sevilla. Sevilla. 1997.

Wayne W., Wilcox W. Detection of early stages of Word decay with ultrasonic pulse velocity " Forest Products Journal XXXXVIII 15 1998