Study, diagnosis and rehabilitation of the wooden slabs of two palace houses in Seville

C. Rodríguez Liñan, P. Rubio de Hita, J.C. Gómez de Cózar
University of Seville, Technical School of Architecture, Department of Architectonic Constructions, Seville, Spain

ABSTRACT: In this paper, we present and apply the results of a research that has developed a methodology to evaluate the degree of damage and resistance of structural wood in rehabilitation works. This technique of study and diagnosis is a non destructive technique which use ultrasonics and the type of wood called *Pino Sylvestris* (wild pine). The buildings where this technique has been applied are palace houses built in the period between the 17th and 18th centuries in Seville. The wood of the rafters of these buildings has undergone the attack of different xylophagous destructive agents.

The research performed let us know the degree of residual resistance of the wooden beams and slabs depending on their degree of damage and, according to this resistance, the rehabilitation is projected. Rehabilitation solutions are defined by making use of the maximum resistance of the wood with the use of collaborative flagstones made of reinforced concrete.

1 METHODOLOGY APPLIED

1.1 Description of the methodology applied

A methodology based on trials, specific for the inspection in situ of wooden slabs has been applied. 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 correlation obtained between the measures of speed of transmission 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 speeds of transmission 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 is here studied.

1.2 Correlation of measures of ultrasonics with resistant parameters

The correlation between measures of speed of transmission with resistant parameters have been obtained by means of statistics from a database with the experimental results developed on over 300 test tubes of ultrasonic measures and trials of breakage by force of static flexion. Measures of normal speed and loss of density in damaged wood have also been correlated.

1.3 Estimation of the damage to the wood

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

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

A specific criterion for high density wood with values of normal speed 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) and corresponds to a start of damage. Using the correlation of density and normal speed, a start of damage is established for a drop of normal speed over 300 m/s.

1.4 Obtaining basic and allowable tensions

Eurocode 5 "Regulations of project for wooden structures"states that the system to calculate structures of that material is based on the basic tensions of the species (σb).

By basic tension we mean that which flaw-free wood can resist permanently and safely enough in a degree of humidity of 12 %. This tension is obtained in an experimental way, from the characteristic value of tension of breakage (σr) of the trial of static flexion divided into a coefficient of safety which takes into account the size of the test tube and the means of developing the trial. This coefficient, according to the regulations is of 3.43.

$$\sigma b = \sigma r/3{,}43 \qquad (1)$$

The allowable tension (σadm.) is obtained from the basic tension divided into a coefficient of safety F=3.

$$\sigma adm = \sigma b/3 \qquad (2)$$

When using the method of limit states, the tension of calculation is obtained by dividing the basic tension into a coefficient of safety of 1.5 and overpondering the loads by multiplying by a coefficient of 1.6.

In the method here applied, we have obtained the statistical correlation which let us obtain the tension of breakage by means of the speed of transmission.

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

$$\sigma r = 0{,}173\ V_l - 74{,}54 \qquad (3)$$

- If we use the maximum crossed longitudinal speed which does not take into account the flaws of the piece, we will obtain the basic tension when dividing into the coefficient of safety.
- If we use the medium crossed longitudinal speed, which includes the flaws of the beam, we will obtain the allowable tension when dividing into the coefficient of safety.

In the case of damaged wood, the estimation of the tension of breakage is made from the normal average speed of the section which takes into account the flaws and damages of this section but not of the whole beam and, for this reason, the tension obtained from this value will be a basic tension.

$$\sigma r = 0{,}747\ V n - 956 \qquad (4)$$

The results of applying this methodology to obtain the resistance to flexion of the wooden beams has been checked through a comparative study with the results obtained in breakage in real beams, and we obtained excellent results. (Rguez Liñan C, Rubio P. and Gómez de Cózar J.C. Estocolmo 1999)

2 THE BUILDINGS

The methodology developed to study the condition of damage of the beams and frameworks of wood of *Pino Sylvestris* in the rafters and covers has been applied in the study carried out prior to the rehabilitation of two palace houses of the city of Seville: *the house of Las Águilas* and *the palace house of Viejos Street*.

Figure 1: House of Águilas

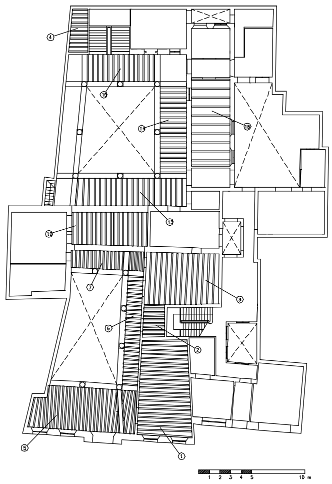


Figure 2: House of Águilas (First floor)

Figure 3: House of Viejos St.

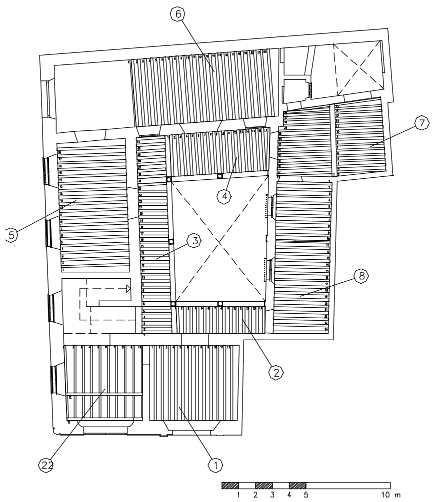


Figure 4: House of Viejos (First floor)

The house of Las Águilas (Fig.1) located in the old quarter of the city of Seville in the parish of San Esteban, is nowadays a building that has undergone many alterations and transformations throughout its history though it preserves most of the wooden slabs of its original structure. Its ground plan (Fig.2) adapts to the neighbouring party walls by arranging all the rooms around two main patios. It has two floors for noblemen and the third one for servants at the flat roof level.

The House of Viejos Street (Fig.3) is an old palace of the 17^{th} century also located in the old quarter of the city of Seville. This three storeys building arranged around a main patio preserves almost entirely the wooden rafters of its slabs and covers. The turret, which crowns the building with an angle, was completely ruined as well as some of the covers formed by rafters and collar joints which were in the last floor of the building. Its ground plan is arranged following the characteristic model of sevillian house around a main patio. (Fig.4).

3 THE WOODEN SLABS

The beams of the wooden slabs have been represented in the ground plan (Fig. 2 and 4) with the rooms numbered. The beams that have been studied are in bold. There are four types of wooden slabs.

Formed by wooden beams with or without carved surfaces, wooden sheathing with blocks or strips perpendicular to the beams as a second order. In most cases there are friezes and contact elements such as mouldings and vergeboards and, just in one case, the beam filling is made of brick.

Formed by two orders of beams, with coffers covered with square soffits framed by a moulding.

Formed by three orders of superimposed beams that lead to a set of two soffits between the main beams. These are squares surrounded by a moulding and with an ornamental golden pineapple in the centre. (Fig.5).

Figure 5: Coffered ceiling pineapple (Águilas)

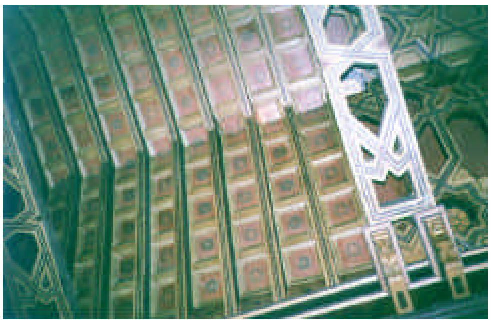


Figure 6: Cover of rafters and collar joints

In the house of Viejos street there are several spaces in the second floor assigned to storage and servants covered with wooden structures of rafters and collar joints with *almizate* (plane formed by the collar beams), with bracing every three metres by means of tie beams. The rafters, tie beams and strips are decorated with its surface carved like the rest of the beams of the building.

A filling of mortar made of lime and sand is laid completely dispersed over the slabs and, the marble flooring is laid onto it. The thickness of the filling is for an average of 10 cm. The beams spans range between 1,6 m and 4,45 m in the case of Viejos street and between 2 m and 6,35 m in the house of Águilas. In the cover of rafters and collar joints, the sheathing is made of wood and, a cover of roof tiles is situated onto it.

4 THE CONDITION OF THE WOOD

The wood used for the beams and sheathing is of a conifer of the botanical species of *Pino Sylvestris* (wild pine). In most cases and, after visualisation, xilophagous agents were detected: fungi which caused rotting, attack of insects: termites, regular woodworm and big woodworm specific of beams.

5 STUDIED ZONES

In order to test and diagnose the wood of the slabs, we chose those rooms which had the slabs we intended to preserve and, among the ones in each room, we chose the beams (approximately between the 10 and 20% of the total) which showed more traces of damage. These beams are in bold in the ground plans (Fig. 2 and 4) and all the slabs studied are also numbered to be easily spotted.

6 TESTS MADE

The following non destructive tests have been made to each and every beam selected: determining the humidity content by means of the Protimeter sounding, determining the speeds of transmission transversely to the beams by means of ultrasonics. The sections studied are located the way they appear in figure 7 and three spots were studied in each section. This test is called *section homogeneity test.*

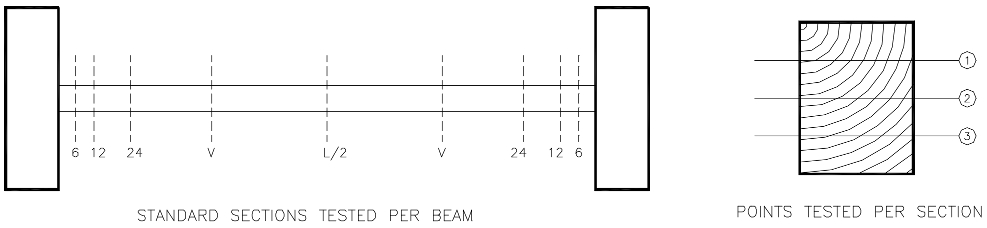


Figure 7: Section Homogeneity test layout

7 RESULTS OF THE TESTS

The results of the test obtained in situ were recorded in record cards to be later processed by the program Ultramad 1. The data are processed in this program in order to be corrected following the correcting coefficients of the direction of the fibre as well as the correction relative to humidity (all the values refer to normal speed, fibre and humidity of 12%) and an individual record card is obtained for each beam studied (Fig. 8) in order to study the degree of damage and loss of density per section by comparison of the values of normal speed obtained with the reference values of sound wood.

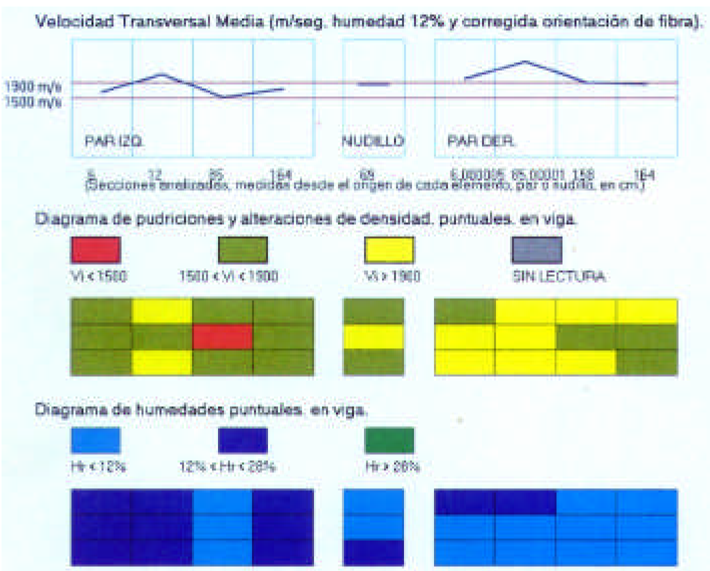


Figure 8: Record card of a beam (Águilas)

And last, by applying the equations obtained which relate the normal speed of wood to the resistance to flexion of the same wood, the resistance of the wood in the different sections of the beam studied is obtained. The analysis of the group of sections in relation to the momentum gained for a uniformly distributed and continuous load on a beam with two supporting elements allows us to determine the following values: the maximum continuous load for each beam and the maximum superficial load the slab is able to bear. These results are depicted by means of maps where the different values obtained are represented by colour codes: humidity content, degree of damage per sections of each beam, and maximum load. One of these maps is represented in figure 9 that corresponds to the maximum load obtained for the beams studied in the house of Viejos street.

Figure 9: Ground plan with maximum loads (Viejos)

8 THE DIAGNOSE

Whether the capacity of load of the wooden slabs is enough or needs some kind of reinforcement for the new use of the buildings is deduced by comparison with the necessities of resistance of the slabs from the analysis of the results.

The zone with higher loss of density because of the attack of xylophagous agents can also be diagnosed for each of the beams in order to substitute part of them. No beam has been partially treated in the buildings here studied. The elements highly damaged by termite attack were eliminated and substituted.

9 THE REHABILITATION

In view of the diagnose obtained after the analysis of the results of the tests and depending both on the degree of damage of the beams and their carrying capacity, two different solutions may be chosen for the slabs and frameworks here studied.

- When it is possible to reuse the wooden structure analysed safely enough for the new use planned for the building. In this case, we propose constructing a small concrete flagstone onto the slab that will act as a topping by means of timber connectors with the beams.
- When it is not possible to reuse the wooden structure of the slab of the room because it does not guarantee enough safety for the state of the loads provided for in the new use of the building. Building thin flagstones of reinforced concrete in the space occupied by the already existing filling is proposed for these cases. This solution allows leaving the present slab exposed and collaborating on bearing its own weight and part of the operating load equal to the maximum load value per unit of length that this slab is capable of bearing. The wooden slab is hanging on the flagstone to provide for the isolated possibility of failure of some element due to the loss of local resistance in some fixed connection (Fig.10).
- A complementary fungicide and antixylophagous treatment is highly recommended on the beams to stop the xylophagous agents from acting and destroying the wood.

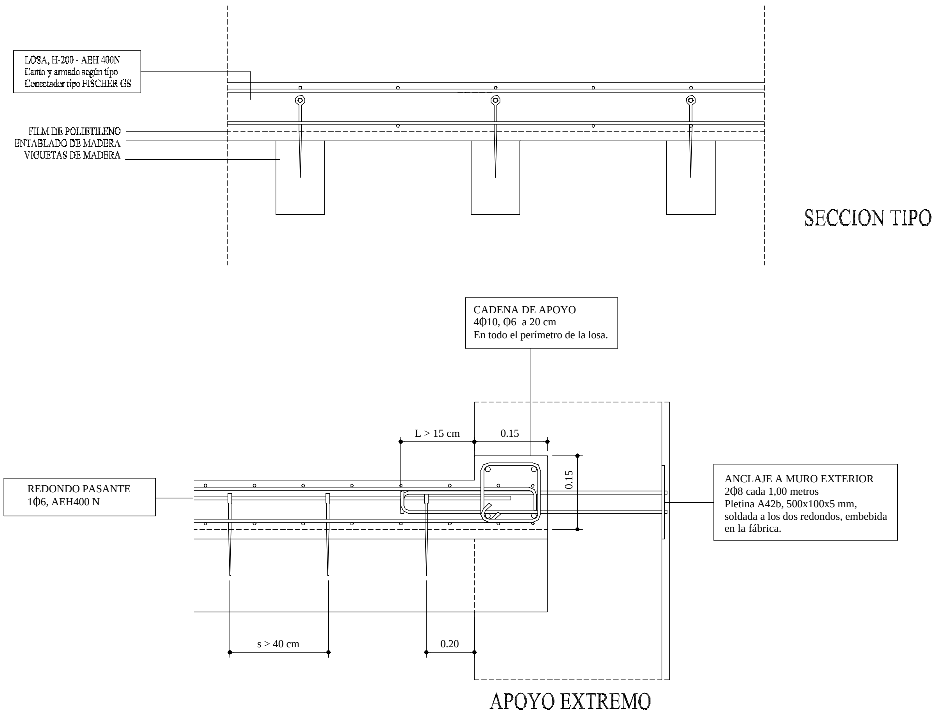


Figure 10: Sections and details of the flagstones

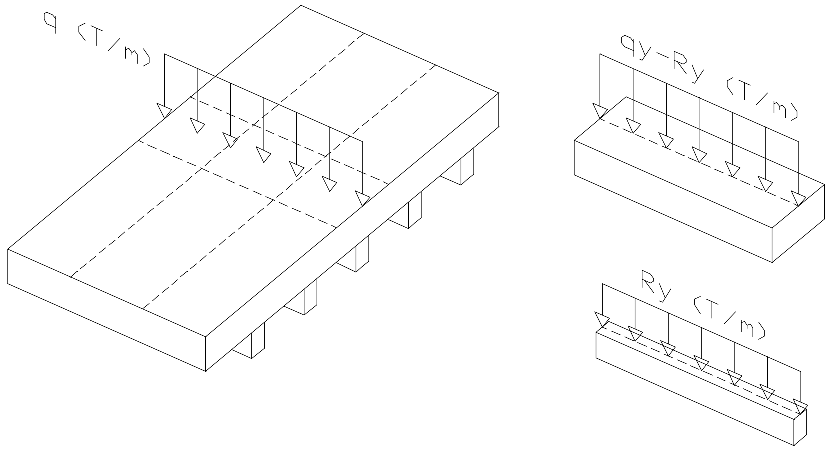
10 THE MEASURING OF THE FLAGSTONES

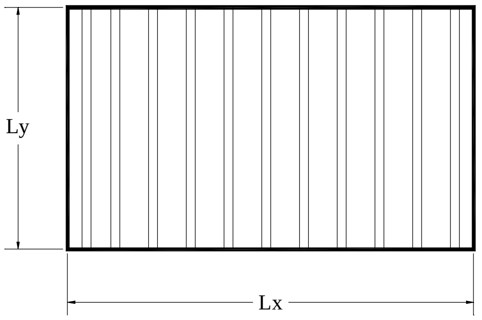
The measuring and building of the flagstones has been made through the simplified method of MARCUS for the following hypothesis.

- Flagstone supported in all its edges.
- Equal deformation of the flagstone and the wooden slab, imposing the condition that the load supported by the wooden slab does not exceed the allowable load deduced by the tests.

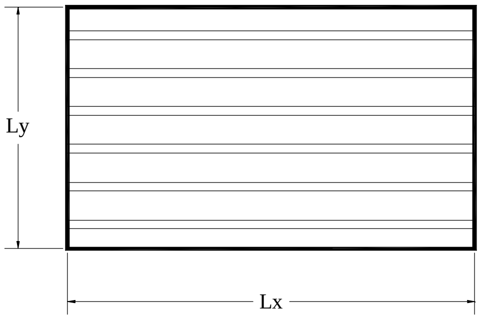
- The possibility of a total failure of the wooden slab has been provided for in the building of the flagstone.

The equations used are stated below (Fig 11) and the two situations provided for are specified: direction of the wooden beams parallel to the minor direction, direction of the wooden beams parallel to the major direction.





$$R_y = q_y(1-k)$$
$$q_y = q\frac{a^4}{k+a^4}$$
$$q_x = q\frac{k}{k+a^4}$$



$$R_x = q_x(1-k)$$
$$q_y = q\frac{ka^4}{1+ka^4}$$
$$q_x = q\frac{1}{1+ka^4}$$

Figure 11: Layout of calculation of flagstones and equations

We have designed flagstones of between 8 and 15 cms of thick for concrete HA20 with steel B400 with a minimal amount higher to the ones established by the Spanish regulations that must be complied with: rule EHE-98. The flagstone that will be necessary to set for each slab is obtained by means of a computer program and depending on its allowable load. The table 1 was made for the flagstones that were projected for the building of the house in Viejos street.

Table 1: Features of flagstones (Viejos)

Forjado actual (Madera Pino Flandes)				Losa propuesta (HA-20, B-400)					
Hab	Luz m	ent. cm	q_{adm} Kp/m	H cm	qm Kp/m	f cm	fmax cm	Ai (#)	As (#)
1	4,45	41	86	11	51,92	0,85	1,04	N10 a 20	N8 a 20
2	1,60	39	532	8	90,77	0,03	0,06	N8 a 20	N8 a 20
3	1,70	37	210	8	86,72	0,05	0,07	N8 a 20	N8 a 20
4	2,50	36	118	8	84,38	0.22	0,35	N10 a 20	N8 a 20
5	4,05	40	94	11	57,70	0,80	1,00	N10 a 10	N10 a 20

11 THE MEASURING OF THE RIBBED FLAGSTONES

Ribbed flagstones of reinforced concrete for those wooden slabs with no carrying capacity for the loads (deadloads+overloads) provided for in the project; in this way, the wooden beams would hang from the flagstone by means of some bolts and would not support any load. Three types of flagstones are projected depending on the width of the rib and the distance between the axes (Fig. 12). The edge and beam filling of the flagstone is determined by the limitation of its deflection. (Fig. 13)

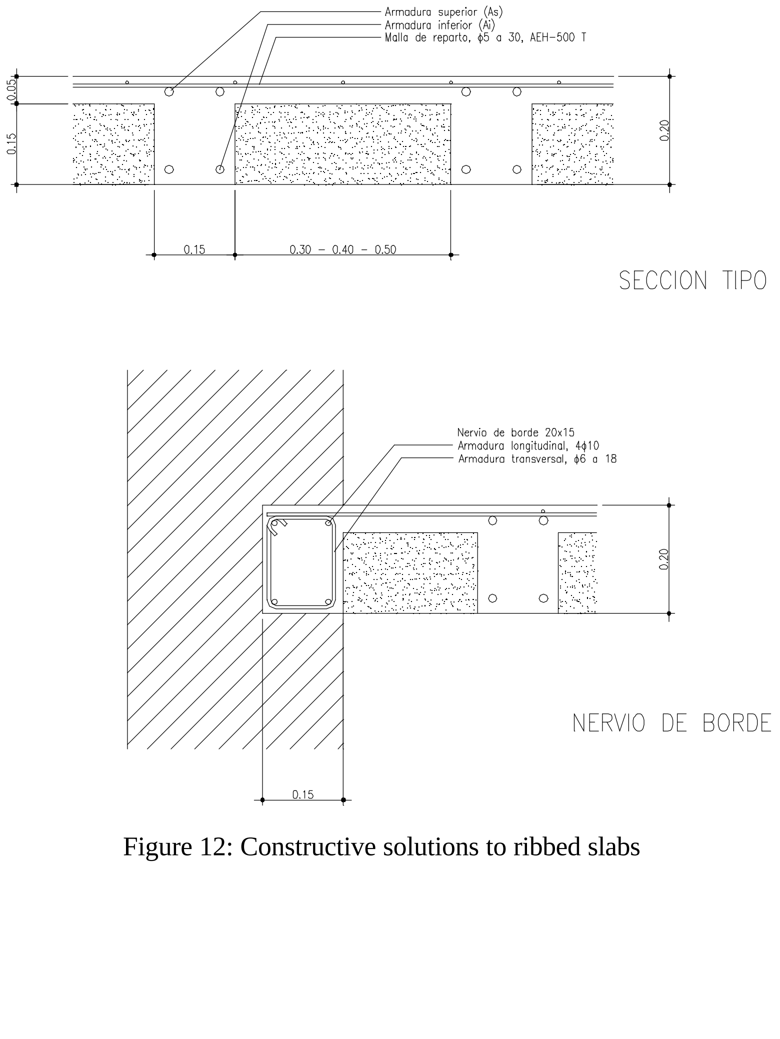


Figure 12: Constructive solutions to ribbed slabs

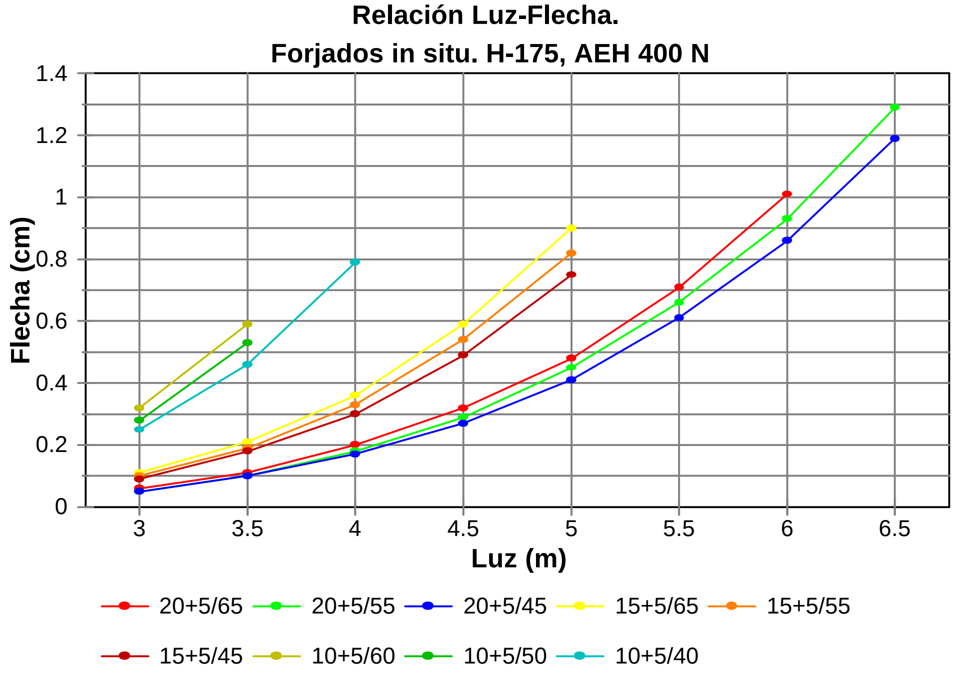


Figure 13: Ribbed slabs, relationship between span/deflection

12 CONCLUSIONS

A method of evaluation in situ of the wood of *pino sylvestris* has been developed by means of non destructive techniques based on ultrasonics which allows obtaining an estimation of the degree of damage and resistance of the wood used in frameworks of historic buildings. Through this method of testing in situ and the application of equations deduced in an experimental way, the condition of the wooden slab studied is diagnosed. The maximum resistance capacity and the individual degree of damage is obtained for each and every element of the slabs here studied. In view of the results obtained, the use of thin reinforced concrete slabs supported onto the perimeter load wall are proposed as a solution which allows preserving the wooden slabs even when their capacity of resistance is reduced. A computer program allows determining the flagstone that would be required for each slab.

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