The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W15, 2019
27th CIPA International Symposium “Documenting the past for a better future”, 1–5 September 2019, Ávila, Spain

STRUCTURAL ANALYSIS OF WOOD BEAMS BY NON-DESTRUCTIVE METHODS IN RESTORATION WORKS OF THE CATHEDRAL OF MORELIA, MEXICO

M. I. Carrillo Gómez[1*], J. R. Sotomayor Castellanos [1], D. Raya González[1]

[1] Universidad Michoacana de San Nicolás de Hidalgo, Morelia, México - (mayrairery, rayadavid)@gmail.com, - madera999@yahoo.com

Commission II, WG II / 8

KEY WORDS: Humidity content, density, wave velocity, stress waves, dynamic modulus, structural rigidity (stiffness)

ABSTRACT:

In the ceiling framework of the capitular hall of the Cathedral of Morelia, the overall state of the beams of the ceiling framework of the capitular hall of the Cathedral of Morelia was diagnosed as deplorable, for which a replacement was put underway for more recently sawed beams. The focus of this investigation was to determine the humidity content of the wood, its density, the wave velocity, the dynamic modulus and the quality factor of a sample of five new beams. These parameters were compared to the medium of five old beams. For the density, wave velocity, dynamic modulus and rigidness, there were no differences found between the old and new beams. The results suggest that the mechanical and physical properties of the new wood beams are equivalent to those of the older ones. Consequently, the strategy of substituting old and deteriorated wood beams for recently sawed ones was successful and complies with the requirements of the International Council of Monuments and Sites as referred to in the principles for the preservation of historical wooden structures.

1. INTRODUCTION

One strategy in the restoration works of wood ceilings in historical edifications is the substitution of antique wood beams for equivalent structural elements, for recently sawed wood of the same species, which has the mechanical quality and resistance of the wood beams to be substituted (Croatto and Turrini, 2014). This reconstruction of a technical character, requires the convenient rigor to guarantee the safety of the user and the stability of the edification while respecting the aesthetic and environmental aspects of the timber (Worthing and Dann, 2000).

Among the buildings which integrate the artistic heritage of the city of Morelia, the Metropolitan Cathedral of Morelia stands out, located in the capital of the state of Michoacan, Mexico (1660 – 1744). It was designed by the Italian architect Vicencio Barroso de la Escayola, in a style typified by the experts as Baroque. It is dedicated to the Transfiguration of the Lord, the vice regal administration and the New Spanish ecclesiastical hierarchy considered it as the most ambitious project of the colonial territory for that century (Gonzalez, 2006).

The bishop and the Michoacan capitulars foresaw towards 1765, integrated to the southern wall of the temple, the building in which all administrative activity related to diocesan regulation would take place. This construction, known as The Mitra, would house the offices of the secretary of ecclesiastic government, the treasure hall and the agencies related to archives; within its solid walls, its elliptical dome, which crowns the staircase and the two-level archery that defines the façade (Aguilera, 2016).

In this area of the Cathedral known as The Mitra, during the restoration works, the state of the wood beams holding the framework of the roof of one of the office rooms of the capitular hall was diagnosed as deplorable. Consequently, they were replaced by recently sawn wood beams (Figure 1).From a holistic point of view, the requirement for structural resistance must be met; that is to say, the characteristics of the new wood beams must be equivalent to those of the beams which have been taken down (Sousa *et al*., 2016).

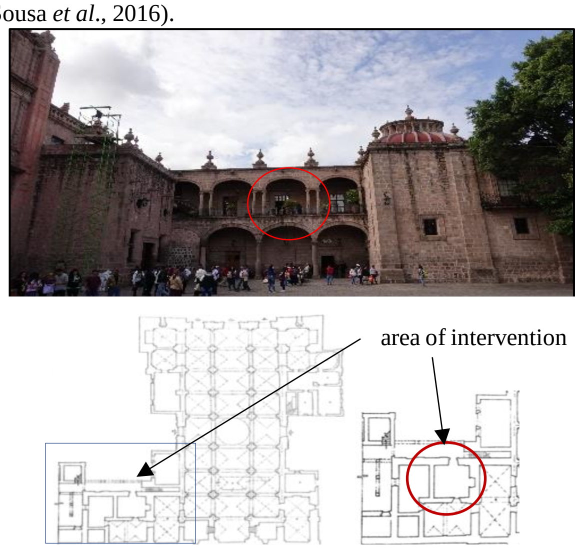


Figure 1. Facade and architectural plan of the Metropolitan Cathedral of Morelia and the building of La Mitra. Taken from the file sent to UNESCO to register the Historic Center of Morelia in the List of Cultural Heritage of Humanity, 1990. Copy protected by the Municipal Historical Archive of Morelia. (Aguilera, 2016)

The current investigation proposes as a work hypothesis, that the physical and mechanical characteristics of the new beams are similar to those of the old beams, by which the exchange of the new beams for the older ones assures the structural stability of the new roof. The technology used in this investigation is that of stress waves, a non-destructive method which has proved its efficiency for the mechanical characterization of structural elements of wood (Li *et al*., 2015; Dahle *et al*., 2016; Kloiber *et al*., 2016; Chen and Guo, 2017). This focus is complementary to other techniques and methods to assure the structural reliability of wood edifications with historical and cultural value (Machado

M. I. Carrillo Gómez[1*]

et al., 2011; Kránitz *et al*., 2014; Arangjelovski *et al*., 2015; Feio and Machado, 2015; Henriques and Neves, 2015; Kloiber *et al*., 2015; Sousa *et al*., 2015; Zhang *et al*., 2015; Cavalli *et al*., 2016a; Cavalli *et al*., 2016b; Milch *et al*., 2016; Sousa *et al*., 2017; Barozzi *et al*., 2018; Walsh-Korb and Avérous. 2018).

The objective of the investigation was to determine the humidity content of the wood, its density, the wave velocity, the dynamic modulus and the quality factor of a representative sample of the old beams in order to compare these parameters to the medium in the old beams.The investigation aims to assess the technique of non-destructive character of stress waves in the evaluation of the mechanical strength in old and new beams (Íñiguez-González *et al*., 2015). In order to achieve this, we propose modeling the wood as an elastic material, macroscopically homogeneous with a material and elastic orthotropy.

2. METHODOLOGY

The experimental strategy of this investigation consisted of analyzing a representative beam by beam sample of the roof framework (Cestari *et al*., 2010; Branco *et al*., 2017). In this case study, the variability factor is limited to the genus Pinus and to the comparison of two representative samples of sawn wood from trees originating from ecologically similar regions. To simplify the analysis, the influence of weathering and the conditions of service to which the old wood was exposed, is considered minimal.

On the other hand, the influence of the characteristics of tree growth is considered minimal, from which the two sets of beams in their technological properties come. Thus, for the group of old beams, the segment of the beam that does not indicate severe deterioration was studied, corresponding to the segment of the beam exposed in the room that does not show deterioration, and the two segments embedded in the walls were eliminated.

Similarly, during experimentation, the temperature and humidity in the wood were kept constant and evenly distributed spatially. In the same context, in order to simplify the phenomenon and to interpret the measurements of the wave velocity, the effect of the damping of the mechanical wave was excluded and idealized as if it were traveling in a single and unique direction.

2.1 Material. Five new beams (NB) and five old beams (OB) of genus Pinus were analyzed. The genus of wood was identified at the macroscopic level in the Laboratory of Wood Mechanics, of the Faculty of Engineering in Wood Technology, of the Michoacán University of San Nicolás de Hidalgo. The old beams were selected from a set of twenty beams extracted during the restoration works of the roof of the chapter house of the Cathedral of Morelia (Figure 2). The new beams were acquired in sawmills from the state of Michoacán, Mexico.

Figure 2. Old beams of the roof framework

The old beams were exposed on three sides to the environment of an interior ceiling and it is estimated that their service period was 50 years. Significant deterioration was visible in the ends that were embedded (Figure 3), therefore, the observations were made in the central segment with wood free of deterioration.

Figure 3. Deterioration in the ends of the beams

The sampling plan for the measurements of moisture content and wave velocity is presented in Figure 4. Subsequently, the subscripts R, T and L refer to the radial, tangential and longitudinal directions. The dimensions of the beams studied are detailed in Table 1.

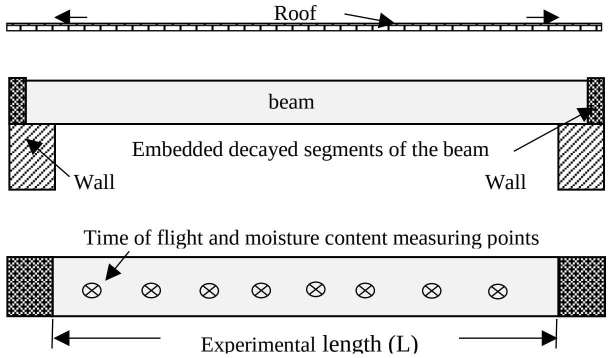


Figure 4. Sampling strategy for measurements of wave speed and moisture content

New beams				
No.	b	h	L	I
	(m)	(m)	(m)	(m^4)
1	0.17	0.22	7.14	0.000151
2	0.18	0.22	7.05	0.000160
3	0.18	0.23	7.11	0.000183
4	0.17	0.22	7.18	0.000151
5	0.18	0.23	6.86	0.000183
$\bar{x}$	0.18	0.22	7.07	0.000165
σ	0.01	0.01	0.13	0.000016
CV	3.1	2.4	1.8	9.8
Old beams				
No.	b	h	L	I
	(m)	(m)	(m)	(m^4)
1	0.16	0.24	6.78	0.000184
2	0.15	0.25	6.83	0.000195
3	0.17	0.24	6.84	0.000196

4	0.17	0.24	6.93	0.000196
5	0.15	0.23	6.92	0.000152
x	0.16	0.24	6.86	0.000185
σ	0.01	0.01	0.06	0.000019
CV	6.3	2.9	0.9	10.2

b = Base; h = High; L = Length; I = Modulus of inertia of the section; x = Mean; σ = Standard deviation; CV = Coefficient of variation.

Table 1. Geometrical properties of the beams

2.2 Density and humidity content. The apparent density of the wood was determined with the weight / volume ratio of 35 specimens with dimensions of 0.02 m x 0.02 m x 0.02 m (Raposo *et al*., 2017), cut out of the ten beams under study. To lighten the text, subsequently, the "apparent density" of the wood will be written as "density". The moisture content of the wood was measured with an electric hygrometer (Dietsch *et al*., 2015) at the same sites where the wave transmission times were measured (Figure 5).

2.3 Stress waves tests. The wave transmission times were measured with a Fakopp © device in transverse (seven measurements in h / 2) and longitudinal directions (two measurements in L / 3) of the beams (Figure 5).

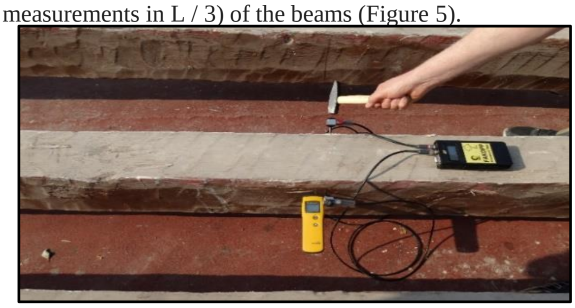


Figure 5. Measurements of the humidity content and wave velocity.

The wave velocity was calculated with the distance / transmission time ratio (Dackermann *et al*., 2014; Sasaki *et al*., 2014). The averages of the measurements on a beam were considered for the analysis. The dynamic modulus of the beams was determined by adapting the protocols reported by Kloiber *et al*. (2016) as well as Morales and Machado (2017) and equation number (1) was used:

$$E = \rho_H \times v^2 \quad (1)$$

Where: E = Dynamic Modulus (N m^{-2})
ρ_H = Density (kg m^{-3})
v = Wave velocity (m s^{-1})

2.4 Experimental design. The two groups of five new beams and five old beams were considered two independent samples. The response variables of each sample were the moisture content (H), the density (ρH) and the wave velocity (v) in the radial-transverse (RT) and longitudinal (L) directions. The dynamic modulus (E) and the rigidity of the beams (EI) were considered as derived variables. Normality tests were carried out, as well as verification and analysis of variance. The demarcation criteria to accept a statistically significant difference for a confidence level of 95% were values of P (α = 0.05) <0.05.

3. RESULTS AND ANALYSYS

Table 2 presents the mean values, the standard deviations and the coefficients of variation of the measurements made in the new beams and old beams. Table 3 shows the results of the statistical analysis proposed by the experimental design.

New beams						
No.	H	ρ_H	v_{RT}	E_{RT}	v_L	E_L
	(%)	(kg m^{-3})	(m s^{-1})	(MN m^{-2})	(m s^{-3})	(MN m^{-2})
1	11.1	706	1221	1052	5001	17653
2	10.9	541	1349	985	5296	15171
3	11.2	444	1430	909	4712	9869
4	10.6	556	1256	876	5057	14213
5	9.7	562	1627	1488	5256	15519
x	10.7	562	1377	1062	5064	14485
σ	0.60	94	162	248	234	2871
CV	5.6	16.6	11.8	23.3	4.6	19.8
Old Beams						
No.	H	ρ_H	v_{RT}	E_{RT}	v_L	E_L
	(%)	(kg m^{-3})	(m s^{-1})	(%)	(kg m^{-3})	(m s^{-1})
1	9.2	487	1512	1113	4816	11301
2	9.0	505	1416	1012	5548	15533
3	10.1	476	1605	1226	4098	7988
4	9.1	479	1339	858	4698	10564
5	10.1	436	1703	1265	4199	7688
x	9.5	476	1515	1095	4672	10615
σ	0.55	25	145	165	579	3168
CV	5.8	5.3	9.6	15.1	12.4	29.8

H = Moisture content; ρ_H = Density; v = Ultrasound speed; E = Dynamic modulus; RT = Radial-tangential; L = Longitudinal: x = Mean; σ = Standard deviation; CV = Coefficient of variation (%).

Table 2. Measurement results

New beams		
Distribution tests	Skewness	Kurtosis
H	-1.387	1.016
ρ_H	0.626	0.971
v_{RT}	0.611	-0.465
E_{RT}	1.672	1.606
EI_{RT}	1.740	1.842
v_L	0.746	0.141
E_L	-1.048	1.022
EI_L	-0.421	-0.441
Old beams		
Distribution tests	Skewness	Kurtosis
H	0.488	-1.472
ρ_H	-1.002	1.022
v_{RT}	-1.102	1.194
E_{RT}	-0.559	-0.354
EI_{RT}	1.255	0.948
v_L	-0.731	0.105
E_L	0.911	0.353
EI_L	0.604	0.360

https://doi.org/10.5194/isprs-archives-XLII-2-W15-263-2019 | © Authors 2019. CC BY 4.0 License.

Hypothesis tests	Vervar $P_{(\alpha = 0.05)}$	Anova $P_{(\alpha = 0.05)}$
H NB *vs.* H OB	0.946	0.011*
ρ_{CH} NB *vs.* ρ_{CH} OB	0.242	0.085
v_{RT} NB *vs.* v_{RT} OB	0.793	0.812
E_{RT} NB *vs.* EI_{RT} OB	0.185	0.198
EI_{RT} NB *vs.* EI_{RT} OB	0.512	0.005*
v_L NB *vs.* v_L OB	0.175	0.759
E_L NB *vs.* E_L OB	0.174	0.759
EI_L NB *vs.* EI_L OB	0.491	0.316

H = Moisture content; ρ_H = Density; v = Ultrasound speed; E = Dynamic modulus; EI = Rigidity of beam; RT = Radial-tangential; L = Longitudinal; Vervar = Verification of variance; Anova = Analysis of variance; * Statistical difference at 95% of confidence.

Table 3. Statistical analysis results

3.1 Statistical analysis. For all the variables (H, ρH, vRT, ERT, vL, EL, EIRT and EIL) corresponding to the two samples studied (new beams and old beams) the values of skewness and kurtosis indicate that the distributions were statistically normal. Likewise, the verifications of the variance and its analysis allow us to conclude that there is no statistically significant difference between the magnitudes of the parameters studied in the two samples, except for the moisture content and the rigidity in the radial-tangential directions (Table 3).

3.2 Humidity content. The results of the statistical analysis indicate that there is a statistically significant difference between the moisture contents of the new and old beams. Arithmetically, the moisture content of the new beams was 1.6% higher than that of the old beams. The coefficients of variation of the two groups of beams were similar (Table 2).

The moisture content of the new beams was reached by drying treatment. In contrast, the moisture content of the old beams represents the equilibrium moisture content achieved during the service time of the structure in the interior ceiling. Once installed, the new beams will reach the moisture content in equilibrium for the wood exposed to the interior of a room in the Cathedral of Morelia.

According to Unterwieser and Schickhofer (2010), the impact of variation of moisture content on the density of new beams would be a factor of 0.67% decrease and on wave velocity a factor of 0.96% increase.

In this way, once the newly installed beams stabilize, the decrease in their density and the increase in the wave velocity will result in the increase of the dynamic modulus, which minimizes the risk of replacement of the beams. In short, the wood of the new beams is in a dry state and its moisture content is equivalent to that of the old beams. This corollary satisfies the recommendation to install structural elements of dry wood in restoration works (Riggio et al., 2018).

3.3 Density. The results of the statistical analysis indicate that there are no statistically significant differences between the wood densities of the new and old beams. The magnitudes of the densities are comparable with those reported for wooden beams of Pinus spp. endemic to the state of Michoacán (Sotomayor and Ramírez, 2013). The density of the new beams is 18.1% greater than the density of the old beams.

Even if we consider the decrease in density caused by the new equilibrium moisture content of the beams already installed, the density of the new beams ensures a magnitude equivalent to that of the old beams.

It is important to mention that the measurements of the density in the new and old beams were made with small specimens extracted from the central segments of the beams that did not contain visible deterioration. According to the hypothesis of the material homogeneity in the macroscopic scale of the wood, that is to say, with density distributed evenly throughout the volume of a piece under study, the differences between beams and between groups of new and old beams refers to the value average of the measurements without considering the variations in the anatomical structure of the wood.

Consequently, the density of the wood of the new beams, being greater than that of the old beams, satisfies the requirement of equivalent density in the reinstallation of old wooden beams in old buildings proposed by Cavalli et al. (2016b).

On the other hand, the coefficient of variation of the density of the new beams is 11.3% greater than the corresponding to that of the old beams. In effect, the coefficient of variation of the new beams differs from the coefficients of 8% reported for beams of Pinus spp. (Sotomayor et al., 2009) and 14% for beams of the same gender (Sotomayor and Ramírez, 2013).

Quite possibly, the group of new beams is formed by different species, a conjecture that goes against the principle of substitution of material recommended by the International Council on Monuments and Sites. This particularity derives from the need to identify the species of the new wood and trying to make it, at least, of the same kind as that of the old wood.

If substitution with wood of the same species cannot be ensured, then the density and rigidity of the beams are the criteria that can ensure a substitution of equivalent resistance characteristics.

3.4 Wave velocity. The results of the statistical analysis show that there are no significant differences between the wave velocities of the new and old beams for both the radial-tangential direction and the longitudinal direction. The wave velocities in the radial-tangential direction of the new beams were lower than the measurements in the old beams by 9% and their coefficient of variation increased 23%. The wave velocities in the longitudinal direction of the new beams were greater than those corresponding to the old beams by 8.4%, but their coefficient of variation decreased by 63%.

The results in the radial-tangential direction indicate that the measurements of the wave velocity in the cross sections of the beams are more sensitive to local variations in the structure and apparent quality of the wood. However, measurements in the longitudinal direction of the beams are more homogeneous compared to those in the radial-tangential direction.

The wave velocities in the longitudinal direction were greater with respect to those of the radial-tangential direction by a factor of 3.7 for the new beams and 3.1 for the old beams. These results are similar to the anisotropy radii measured in wood of different wood species reported by Dackermann et al. (2014).
The wave velocity is used as an indicator of the dynamic modulus in a given wood piece (Yamasaki et al., 2010). In such a way that, if the magnitudes of the wave velocities of the old wood do not differ considerably in comparison with another piece of freshly

sawn wood, both of the same species and with similar moisture contents, it can be proposed that their mechanical resistance is equivalent (Morales and Machado, 2017).

Figure 6 presents, in the form of maps, the variation of the wave velocities in the radial-tangential direction. The five beams studied are considered as a structural system. From the observation of these maps, it is deduced that there is no knot moving away from the layer indicating the existence of a material discontinuity caused by the deterioration of the wood.

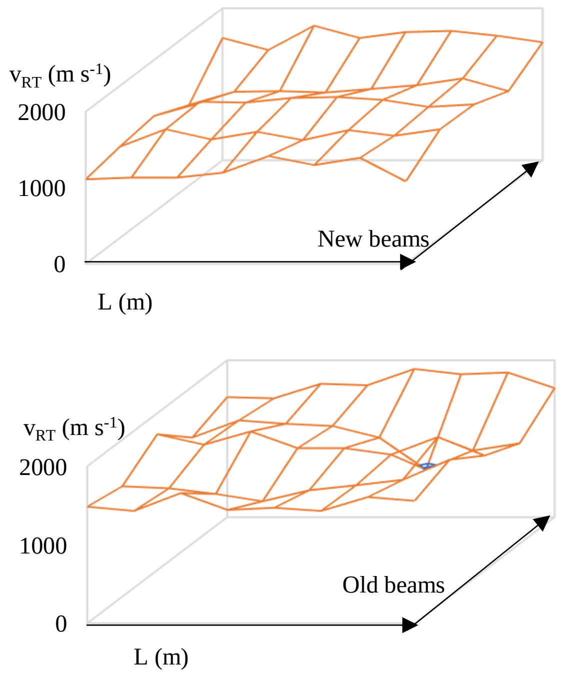


Figure 6. Map of the wave velocities measured in the radial-tangential direction of the beams.

The magnitudes of the wave speeds determined in this investigation (2019) are comparable with those reported in the literature for beams of the genus Pinus (Sotomayor et al., 2009). Thus, the results of this research suggest that, although there is a variability at the local level, as a whole the differences are not significant.

3.5 Dynamic modulus. The average value of the dynamic modulus in the radial-tangential direction of the new beams is 3% less than that corresponding to the average value of the old beams. The coefficient of variation of the new beams increases 51% with respect to that of the old beams. The dynamic moduli in the longitudinal direction of the new beams is 36% larger than those of the old beams. Likewise, the coefficient of variation of the new beams is 33.5% less than that of the old ones.

The dynamic modulus results from the calculation made with equation (1) where the density and the wave velocity are implicit. In this way, the variation of these parameters influences the magnitude of the dynamic modulus as a derived parameter (Yu et al., 2017). From here, it can be proposed that the density of the wood and the wave speed, measured directly on the beams, are descriptive indicators of the technological state of the wood.
This argument is explained graphically in Figure 6 where, for the two types of beams of this investigation (2019), the dispersions of the velocities in the radial-tangential directions are represented and compared with the wave velocities for new Pinus beams spp. reported by Sotomayor et al. (2009). From the point of view of the beam-by-beam comparison, the clouds intersect around the average values. However, particular values can be observed for each one of them.

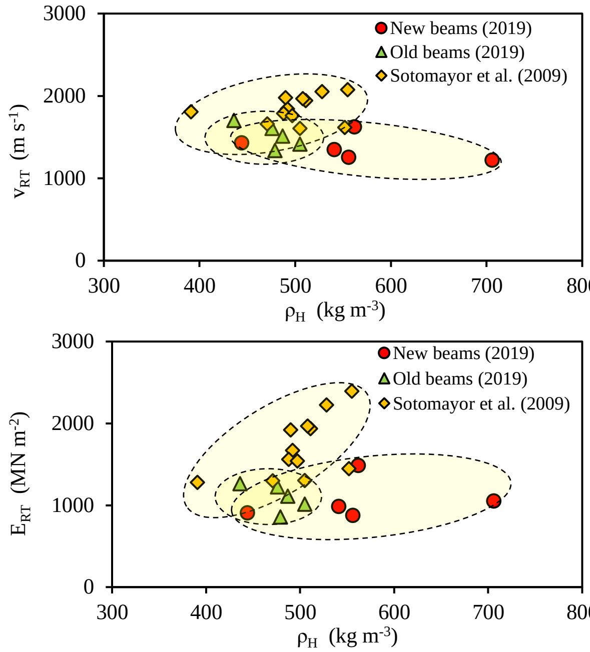


Figure 7. Dispersions of wave velocities and dynamic modulus in the radial-tangential direction

The density of the wood is considered as evenly distributed in the beam, and the wave velocity is idealized in a single and unique direction of the wood. However, the dynamic module represents an intensive parameter of the material that is representative and valid for a beam. This peculiarity in the methodology used in this case study suggests that, in as much as possible, a sufficient number of copies is necessary in order to ensure a statistically representative sample size.

3.6 Rigidity of the beams. To have a better perspective of the use of the dynamic module, it is advisable to introduce the concept of rigidity of the beam defined by the product of the dynamic modulus of the wood (E), weighted by the geometry properties of the beam, in this case, the moment of inertia I of its cross section.

Table 4 lists the stiffness values of the new and old beams, calculated with the results of Table 1 and 2.

	New beams	
No.	EI_{RT} (MN m^2)	EI_L (MN m^2)
1	0.159	2.663
2	0.157	2.423
3	0.166	1.801
4	0.132	2.144
5	0.271	2.832
$\bar{x}$	0.177	2.373
σ	0.054	0.411
CV	30.6	17.3

	Old beams	
No.	EI_{RT} (MN m^2)	EI_L (MN m^2)
1	0.279	2.083
2	0.277	3.034
3	0.314	1.564
4	0.262	2.069
5	0.259	1.169
$\bar{x}$	0.278	1.984
σ	0.022	0.700
CV	7.9	35.3

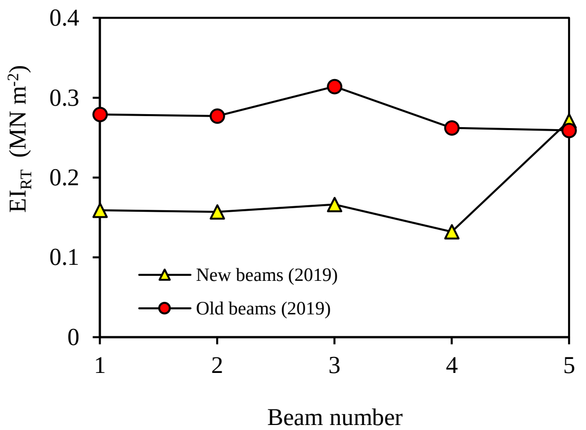
EI = Stiffness; RT = Radial-tangential; L = Longitudinal; $\bar{x}$ = Mean; σ = Standard deviation; CV = Coefficient of variation (%).

Table 4. Stiffness of the beams

The stiffness calculated using the dynamic modulus in both the radial and tangential directions and the dimensions of the cross sections of the new beams is 36% less than that corresponding to the rigidity of the old beams; the coefficient of variation of the new beams increases 28.7% compared to that of the old beams.

The stiffness calculated using the dynamic module in the longitudinal direction and the dimensions of the cross sections of the new beams is 19.6% greater than that corresponding to the old beams. In addition, the coefficient of determination of the new beams decreases 51%.

Figure 8 contrasts stiffness (EI) values between both types of beams. By observing beam by beam, it is deduced that the stiffness (EIRT) of the new beams, calculated using the value corresponding to the radial-tangential dynamic modulus, is lower in comparison with those of the old beams. In contrast, the stiffness values (EIL) of the new beams, calculated using the longitudinal dynamic modules, become confused with those of the old ones.



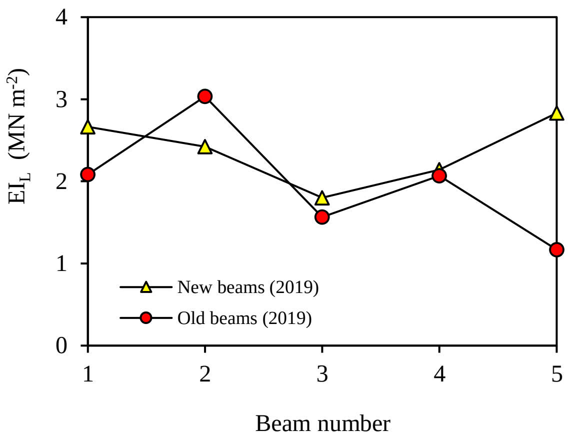


Figure 8. Stiffness dispersions

These results complement the criteria proposed in the bibliography (Munafò et al., 2015; Kránitz et al., 2016), which establish that the magnitudes of the elasticity modulus of the structural elements that replace old beams must be equivalent. However, they do not specify the analysis of EI stiffness, as a more specific parameter to ensure resistance, at least, equivalent to new beams in restoration work in buildings in service.

The EI stiffness of the beams is the combination of an intensive characteristic of the material, in this case, of the dynamic modulus of the wood and of the geometry of the structural element, in this case, of the transversal section corresponding to the radial and tangential directions. In effect, the average dimension of the base (b) of the new beams was greater than that corresponding to the old beams. In contrast, the average dimension of the height (h) of the new beams was lower than that corresponding to the old beams. These characteristics of the beams influenced the stiffness given that the height of the beams is the dimension that controls the magnitude of the moment of inertia. As a result, the moment of inertia of the new beams was 10.8% less than that of the old beams.

The international trend is to apply principles, standards and methodological proposals to ensure, after interventions, the safety and integrity of old wood structures (Kasal and Tannert, 2010, Koehl et al., 2013, Morales et al., 2014; Cruz et al., 2015, Feio and Machado, 2015, Tampone and Ruggieri, 2016, Ongaretto et al., 2016, Uzun et al., 2017, Clemente, 2018, Salonikios et al., 2018).

Considering that in Mexico restoration practices are not regulated, for practical purposes in this case study, possibly in the restoration work other criteria were considered for a better adaptation of the new roof beams.

4.CONCLUSIONS

The results of the structural analysis of wooden beams by non-destructive methods in restoration works of the Cathedral of Morelia, Mexico, suggest that the physical and mechanical characteristics of the new beams are equivalent to those of the old beams. Consequently, the strategy of replacing old and deteriorated beams with recently sawn beams was successful and satisfies the requirements of the International Council on Monuments and Sites with respect to the principles for the preservation of historic wooden structures.

ACKNOWLEDGEMENTS

The research was sponsored by the Doctoral Program in Wood Science and Technology, from the Faculty of Engineering in Wood Technology, from the Michoacán University of San Nicolás de Hidalgo, in Morelia, Michoacán, Mexico. We appreciate the support provided for this research by the National Institute of Anthropology and History (INAH), regional delegation of Michoacán and the authorities of the Metropolitan Cathedral of Morelia (Father Humberto González Correa Custodian of the Santa Mitra Building of the Metropolitan Cathedral of Morelia) and the department of Sacred Art, for the support and recommendations for this investigation.

REFERENCES

Arangjelovski, T., Gramatikov, K., and Docevska, M. 2015. Assessment of damaged timber structures using proof load test. Experience from case studies. *Construction and Building Materials*, 101, pp. 1271-1277.

Aguilera, R. S., E. 2016. La Catedral de Morelia. Serie Cantera Rosa. Textos Archivísticos Colección V. H. Ayuntamiento de Morelia 2016, Dirección de Asuntos Interinstitucionales y Cabildo, Archivo Histórico Municipal de Morelia. 7-42 pp. 1-56.

Barozzi, G., Cosentino, N., Lanzoni, L., and Tarantino, A. M. 2018. Safety assessment of historic timber structural elements. *Case Studies in Construction Materials*, 8, pp. 530-541.

Branco, J. M., Sousa, H. S., and Tsakanika, E. 2017. Non-destructive assessment, full-scale load-carrying tests and local interventions on two historic timber collar roof trusses. *Engineering Structures*, 140, pp. 209-224.

Cavalli, A., Bevilacqua, L., Capecchi, G., Cibecchini, D., Fioravanti, M., Goli, G., Togni, M., and Uzielli, L. 2016a. MOE and MOR assessment of in service and dismantled old structural timber. *Engineering Structures*, 125, pp. 294-299.

Cavalli, A., Cibecchini, D., Togni, M., and Sousa H. S. 2016b. A review on the mechanical properties of aged wood and salvaged timber. *Construction and Building Materials*, 114, pp. 681-687.

Cestari, C. B., Cestari, L., Corradino, G., Crivellano, A., Marzi, T., and Panosch, P. 2010. Hidden architecture. Restoration of historic timber structures: the great roof structures of the Cathedral of Vercelli. Structural Faults & Repair 2010. 13th International Conference, Edinburgh, United Kingdom. pp. 1-12.

Chen, Y., and Guo, W. 2017. Nondestructive Evaluation and Reliability Analysis for Determining the Mechanical Properties of Old Wood of Ancient Timber Structure. *BioResources*, 12(2), pp. 2310-2325.Clemente, P. 2018. Extending the life-span of cultural heritage structures. *Journal of Civil Structural Health Monitoring*, 8(2), pp. 171-179.

Croatto, G., and Turrini, U. 2014. Restoration of historical timber structures. Criteria, innovative solutions and case studies. In: Seminário *Intervir em construções existentes de madeira*. P. B. Lourenço, J. M. Branco e H. S. Sousa (eds.). Gimaraes, Portugal. pp. 119-136.

Cruz, H., Yeomans, D., Tsakanika, E., Macchioni, N., Jorissen, A., Touza, M., Mannucci, M., and Lourenço, P. B. 2015. Guidelines for On-Site Assessment of Historic Timber Structures. *International Journal of Architectural Heritage*, 9, pp. 277-289.

Dackermann, U., Crews, K., Kasal, B., Li, J., Riggio, M., Frank Rinn, F., and Tannert, T. 2014. In situ assessment of structural timber using stress-wave measurements. *Materials and Structures*, 47, pp. 787-803.

Dahle, G., Carpenter, A., and DeVallance, D. 2016. Non-Destructive Measurement of the Modulus of Elasticity of Wood Using Acoustical Stress Waves. *Arboriculture & Urban Forestry*, 42(4), pp. 227-233.

Dietsch, P., Franke, S., Franke, B., Gamper, A., and Winter, S. 2015. Methods to determine wood moisture content and their applicability in monitoring concepts. *Journal of Civil Structural Health Monitoring*, 5(2), pp. 115-127.

Feio, A., and Machado, J. S. 2015. In-situ assessment of timber structural members: Combining information from visual strength grading and NDT/SDT methods. A review. *Construction and Building Materials*, 101, pp. 1157-1165.

González, M. E. 2006. Estudio y proyecto para la Plaza Mayor de Morelia, Trazo, proporción y símbolo en el arte virreinal Morelia, UNAM Gobierno del Estado de Michoacán, pp. 375.

Henriques, D. F., and Neves, A. S. 2015. Semi-destructive in situ tests as support to the assessment of a conservation process. *Construction and Building Materials*, 101, pp. 1253-1258.

International Council on Monuments and Sites (ICOMOS). 1999. *Principles for the Preservation of Historic Timber Structures*, ICOMOS International Wood Committee, Mexico. 3 pp.

Íñiguez-González, G., Arriaga, F., Esteban, M., and Llana, D. F. 2015. Reference conditions and modification factors for the standardization of nondestructive variables used in the evaluation of existing timber structures. *Construction and Building Materials*, 101, pp. 1166-1171.

Kasal, B., and Tannert, T. 2010. *In Situ Assessment of Structural Timber*. State of the Art Report of the RILEM. Technical Committee 215-AST. Springer, Heidelberg, Germany.

Kloiber, M., Drdácký, M., Machado, J. S., Piazza, M., and Yamaguchi, N. 2015. Prediction of mechanical properties by means of semi-destructive methods: A review. *Construction and Building Materials*, 101, pp. 1215-1234.

Kloiber, M., Reinprecht, L., Hrivnák, J., and Tippner, J. 2016. Comparative evaluation of acoustic techniques for detection of damages in historical wood. *Journal of Cultural Heritage*, 20, pp. 622-631.

Koehl, M., Viale, A., and Reeb, S. 2013. A historical timber frame model for diagnosis and documentation before building restoration. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume II-2/W1, ISPRS 8th 3D GeoInfo Conference & WG II/2 Workshop, Istanbul, Turkey. pp. 201-212.

Kránitz, K., Deublein, M., and Niemz, P. 2014. Determination of dynamic elastic moduli and shear moduli of aged wood by means of ultrasonic devices. *Materials and Structures*, 47, pp. 925-936.

Kránitz, K., Sonderegger, W., Bues, C. T., and Niemz, P. 2016. Effects of aging on wood: a literature review. *Wood Science and Technology*, 50(1), pp. 7-22.

Li, X., Dai, J., Qian, W., and Chang, L. 2015. Prediction of Internal Defect Area in Wooden Components by Stress Wave Velocity Analysis. *BioResources*, 10(3), pp. 4167-4177.

Machado, J. S., Lourenço, P. B., and Palma, P. 2011. Assessment of the structural properties of timber members in situ. A probabilistic approach. SHATIS'11 International Conference on Structural Health Assessment of Timber Structures. Lisbon, Portugal. pp. 1-12.

Munafò, P., Stazi, F., Tassi, C., and Davì, F. 2015. Experimentation on historic timber trusses to identify repair techniques compliant with the original structural–constructive conception. *Construction and Building Materials*, 87, pp. 54-66.

Milch, J., Tippner, J., Sebera, V., Kunecký, J., Kloiberb, M., and Navrátila, M. 2016. The numerical assessment of a full-scale historical truss structure reconstructed with use of traditional all-wooden joints. *Journal of Cultural Heritage*, 21, pp. 759-766.

Morales Conde, M. J., and Machado, J. S. 2017. Evaluation of cross-sectional variation of timber bending modulus of elasticity by stress waves. *Construction and Building Materials*, 134, pp. 617-625.

Morales Conde, M. J., Rodríguez Liñán, C., and Rubio de Hita, P. 2014. Use of ultrasound as a nondestructive evaluation technique for sustainable interventions on wooden structures. *Building and Environment*, 82, pp. 247-257.

Ongaretto, E., Pozza, L., and Savoia, M. 2016. Wood-based solutions to improve quality and safety against seismic events in conservation of historical buildings. *International Journal for Quality Research*, 10(1), pp. 17-46.

Raposo, P. C., Correia, J. A. F. O., Sousa, D., Salavessa, M. E. Reis, C., Oliveira, C., and De Jesus, A. 2017. Mechanical Properties of Wood Construction Materials from a Building from the 19th Century. *Procedia Structural Integrity*, 5, pp. 1097-1101.

Riggio, M., D'Ayala, D., Parisi, M. A., and Tardini, C. 2018. Assessment of heritage timber structures: Review of standards, guidelines and procedures. *Journal of Cultural Heritage*, 31, pp. 220-235.

Sasaki, Y., Yamasaki, M., Uchida, M., And Torichigai, T. 2014. Non-destructive Stress Evaluation of Wood Members in Japanese Traditional Building. 11th European Conference on Non-Destructive Testing, Prague, Czech Republic, pp. 1-8.

Salonikios, T., Theodoulidis, N., Morfidis, K., Zacharopoulou, G., and Raptis, K. 2018. Efficiency investigation of structural interventions based on in situ ambient vibration measurements onAcheiropoietos Early Byzantine basilica, Thessaloniki, Greece. *Journal of Civil Structural Health Monitoring*, 8(1), pp. 135-149.

Sotomayor Castellanos J. R., and Ramírez Pérez, M. 2013. Velocidad de onda y módulos de elasticidad por ultrasonido y ondas de esfuerzo de vigas de madera de *Pinus* spp. *Investigación e Ingeniería de la Madera*, 9(1), pp. 21-33.

Sotomayor Castellanos, J. R., Bernabé Santiago, R., Hernández Maldonado, S. A., Sarmiento Bustos, D., Fernández García, G., and Alfaro Trujillo, I. 2009. Caracterización no destructiva de vigas de madera de *Pinus* spp. utilizando ultrasonido y ondas de esfuerzo. *Investigación e Ingeniería de la Madera*, 5(1), pp. 3-22.

Sousa, H. S., Branco, J. M., and Lourenço, P. B. 2016. A holistic methodology for probabilistic safety assessment of timber elements combining onsite and laboratory data. *International Journal of Architectural Heritage*, 10(5), pp. 526-538.

Sousa, H. S., Branco, J. M., Machado, J. S., and Lourenço, P. B. 2017. Predicting mechanical properties of timber elements by regression analysis considering multicollinearity of non-destructive test results. SHATIS'17 International Conference on Structural Health Assessment of Timber Structures. Istanbul, Turkey. pp. 1-9.

Sousa, H. S., Machado, J. S., Branco, J. M., and Lourenço, P. B. 2015. Onsite assessment of structural timber by means of hierarchical models and probabilistic methods, *Construction and Building Materials*, 101(2), pp. 1188-1196.

Tampone, G., and Ruggieri, N. 2016. State-of-the-art technology on conservation of ancient roofs with timber structure. *Journal of Cultural Heritage*, 22, pp. 1019-1027.

Unterwieser, H., and Schickhofer, G. 2010. Influence of moisture content of wood on sound velocity and dynamic MOE of natural frequency and ultrasonic runtime measurement. *European Journal of Forest Products*, 69(2), pp. 171-181.

Uzun, Z., Köse, C., and Köse, N. 2017. A multidisciplinary study to reveal the historical value of wooden structures and to develop a conservation approach: Dere and Karlı Mosques in Samsun, Turkey. *Journal of Cultural Heritage*, In Press.

Walsh-Korb, Z., Avérous, L. 2018. Recent developments in the conservation of materials properties of historical wood. *Progress in Materials Science*, In press.

Worthing, D., and Dann, N. 2000. Approaches to the repair of traditional timber-framed buildings: the application of conservation philosophy into practice. *Structural Survey*, 18(4), pp. 136-147.

Yamasaki, M., Sasaki, Y. and Iijima, Y. J. 2010. Determining Young's modulus of timber on the basis of a strength database and stress wave propagation velocity II: effect of the reference distribution database on the determination. *Journal of Wood Science*, 56(5), pp. 380-386.

Yu, Y., Liu, Y., Gong, M., Xu, Z., and Fang, Y. 2017. R&R study of using a stress wave timer to measure the elastic modulus of structural dimension lumber. *Measurement*, 95, pp. 293-296.

Zhang, J., Xu, Q., Xu, Y., and Zhang, M. 2015. Research on residual bending capacities of used wood members based on the correlation between non-destructive testing results and the mechanical properties of wood. *Journal of Zhejiang University-SCIENCE A* (*Applied Physics & Engineering*), 16(7), pp. 541-550.