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Calibration of calculation models of wooden guardrails with Operational Modal Analysis

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***Abstract*— This study analyses the differences between two calculation models for guardrails on building sites that use wooden boards and tubular steel posts. Wood was considered an isotropic material in one model and an orthotropic material in a second model. The elastic constants of the wood were obtained with ultrasound. Frequencies and vibration modes were obtained for both models through linear analysis using the finite element method. The two models were experimentally calibrated through operational modal analysis. The results obtained show that for the three types of wood under analysis, the model which considered them as an orthotropic material fitted the experimental results better than the model which considered them as an isotropic material.**

***Index Terms*— Finite Element Method, Guardrails, Operational Modal Analysis, Safety, Ultrasound.**

I. INTRODUCTION

One of the greatest difficulties in the analysis of Collective Protection (CP) and Auxiliary Construction Practices (ACP) is the preparation of a calculation model that reflects the real situation as faithfully as possible [1]. In the case of Temporary Edge Protection Systems (TEPS), the various options for post joints used in the structure to which the TEPS is anchored produces significantly different results [2], [3]. Models normally used in the analytical assessment of even the most elementary case of anchoring through the introduction of a post in a plastic sleeve embedded in the frame fail to offer safe solutions, as they predict significantly less movement than is obtained through experimental analysis [4], [5].

Operational Modal Analysis (OMA) is a non-destructive experimental assessment procedure that calculates the vibration modes of a structure and their associated frequencies [6], [7]. The use of this technique in mechanical engineering has spread significantly. It is used at present to analyze the dynamic performance of civil engineering structures and buildings such as bridges [8], [9], pedestrian walkways [10] , football stadiums [11], [12], flue gas stacks [13], reinforced concrete buildings [14] and housing stock [15]–[17]. Once the vibration modes of the structure and their associated frequencies are obtained with OMA, the same information can be obtained through an analytical assessment. The comparison of experimental and analytical results allows the analytical model to be calibrated. If the results differ, the analytical model should be modified until the degree of approximation of the results from both procedures are sufficiently similar.

One of the most commonly used techniques in the analytical assessment of structures is the Finite Element Method, or FEM. The development of an analytical assessment model requires the inclusion of the elastic properties of the materials in question (elasticity modules and the Poisson ratio). In the case of steel, the material can be modeled as isotropic. Wood is a material that is characterized by the great variability of its elastic constants, even among pieces with the same resistance class and from the same source. Wood can also be modeled as an orthotropic material, with different elastic characteristics for each of the spatial [18]–[20]. Among the non-destructive techniques most commonly used to obtain the properties of wooden elements are those based on the use of ultrasound, on which extensive information is available [21]–[25].

In this study, the real dynamic behavior of the TEPS, obtained with OMA, was compared with analytical prediction from FEM-based mathematical model simulations. The elastic characteristics of the wood were obtained using ultrasound for the development of the FEM. Whenever the results do not coincide, in terms of vibration frequencies or the geometry of vibration modes, the model should be reconsidered and improved. The OMA study may therefore be used as a guide to model calibration or correction.

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II. MATERIALS AND TECHNIQUES USED

Three TEPS made with guardrail pine boards of varying quality and thickness posts made of circular tubular S235 steel (40 mm x 1.5 mm) were analyzed. In the three cases, the posts were 2400 mm apart, the board section was 150 mm high with a thickness of 30 and 40 mm. System 1 (S1) was assembled using 30 mm-thick boards and ME 1 visual classification as per UNE Standard 56544 (Association Española de Normalización 2007), corresponding to a C27 resistance class. System 2 (S2) was assembled using 30 mm-thick boards and Rejected visual classification. Finally, System 3 (S3) was assembled using 40 mm-thick boards and Rejected visual classification. Fig. 1 shows the general geometry of Systems S1, S2 and S3. Fig. 2 shows a detailed view of the connection between the timber frame and the steel past.

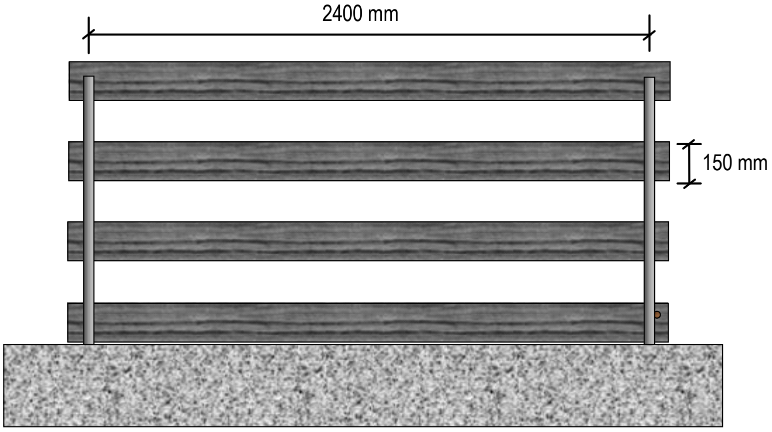

Fig. 1: General geometry of Systems S1, S2 and S3.

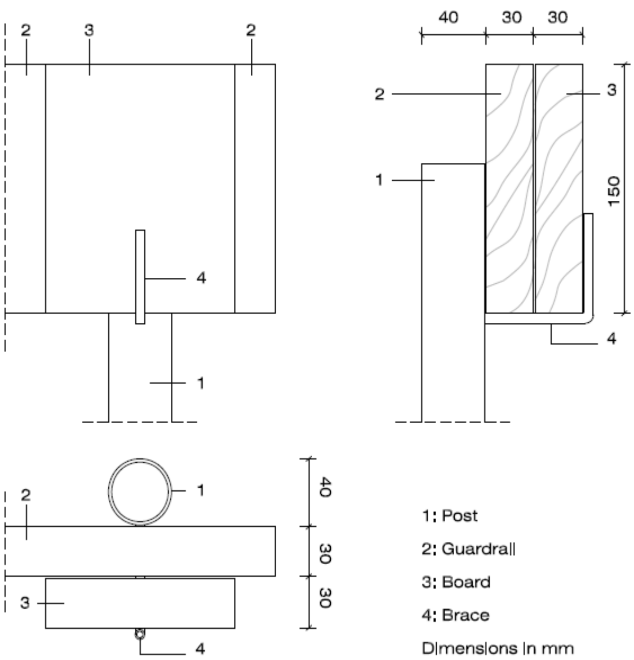

Fig. 2: Detail of the bracket holding the timber board to the steel post.

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III. EXPERIMENTAL AND ANALYTICAL WORK

A. *Experimental Work. OMA*

Dynamic experimental analysis was performed using OMA. This technique consists of reproducing all elements and conditions of the shape of the structure and subjecting it to minor controlled impacts, in order to identify its specific vibration modes.

The propagation of mechanical waves generated through blows generates specific vibration modes within the structure. These modes correspond to the predominant propagation of a mechanical wave with a specific pulse frequency, which may be recorded with a suitable mechanical vibration detection system.

A number of measurement points were established to perform OMA, in this case ICY acceleration sensors, distributed at different points of the structure. A number of acceleration readings were taken, with random and environmental excitation, including factors such as wind, traffic, or, in the case of this study, two people with hammers striking the provisional edge protection system, producing random excitations.

Subsequent analysis through modal identification techniques of these readings obtained from the accelerometers, particularly the ICPs, yielded the vibration modes of the structure and their associated frequencies. The identification of vibration modes through Operational Modal Analysis was performed with 7 accelerometers arranged in 4 measurement sets, forming a total of 28 positions. Two fixed accelerometers were left in place and the rest were moved around different measurement sets. A time of around 60 seconds was measured for each of the measurement sets followed by a series of blows with a hammer. The diagram in Fig. 3 shows the position of the accelerometers. The Frequency Response Functions (FRF) were calculated from the readings of each accelerometer channel. Algorithms were used that added these FRFs and their application in specific bands. Thus, a spectral response graph was obtained showing frequencies of interest positioned in the abscissa corresponding to certain peaks. However, as this was a spectral diagram calculated from various measurement sets, all frequencies did not need to correspond to intrinsic vibration modes, meaning that another algorithm family could be applied to analyze the stability and the confidence level of these frequencies.

The algorithm allows us to observe the degree of scattering or fluctuation of the value for each frequency. Therefore, peaks with a greater number of "s" and which presented greater peak-to-peak amplitude represented the correspondence of that frequency to a specific vibration mode.

Based on the frequency of the movements calculated at each point for that frequency, it was possible to reproduce the schematic movement of the whole system recorded with accelerometers, in this case, the TEPS. Here, we may stress the importance of being able to obtain the modes experimentally, and therefore, of having real results without having to make assumptions concerning the mechanical properties of the materials and elements which constitute the system, in this case, the vertical steel posts and wooden boards.

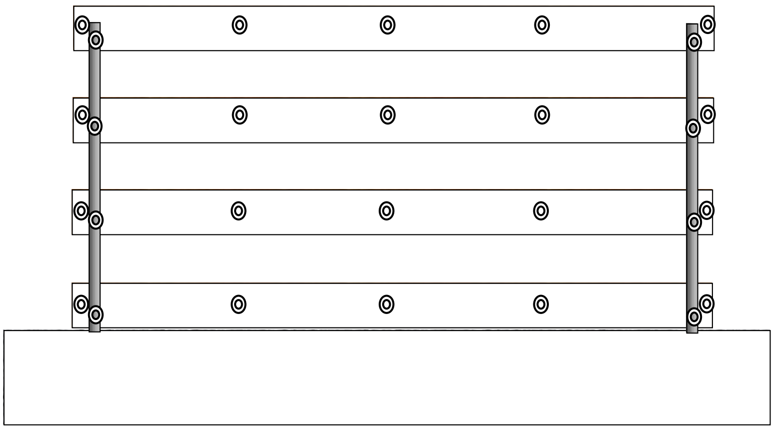

Fig. 3: Positioning of accelerometers.

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B. Obtaining the elastic characteristics using ultrasound

Ultrasound inspections were performed with a DPR300 ultrasonic pulser/receiver and Tektronics TDS3012 digital oscilloscope. 250 kHz Broadband PANAMETRICS V1012 and V150 transducers were used, some of which were unpolarized and others transverse wave polarized. This implies the capacity to discriminate these waves through different orientations or dimensions of the boards. Thus, 3 radial (R) measurements were made, 3 transversal (T) measurements and 3 longitudinal (L) measurements. Readings based on digitalized 1 MHz sample signals were obtained that permitted the calculation of propagation time.

Based on the propagation time of each longitudinal (tp), and transversal (ts) wave and the apparent density (ρ), equations were applied that related longitudinal (Vp) and transversal (Vs) propagation speeds and density (ρ) to elastic constants, in order to obtain longitudinal (E) and transversal (G) elasticity modules and the Poisson ratio (ν) which, along with the density, modeled integral TEPS elements, on the assumption that these are isotropic (1) (2) and (3).

$$v = \frac{1 - 2 \cdot \left(\frac{V_s}{V_p} \right)^2}{2 \cdot \left[1 - \left(\frac{V_s}{V_p} \right)^2 \right]} \quad (1)$$

$$G = \rho \cdot V_s^2 \quad (2)$$

$$E = V_p^{\,2} \cdot \rho \cdot \frac{(1+v)\cdot(1-2v)}{1-v} \quad (3)$$

Three dimensional measurements of the wooden boards were used to determine the constants for each dimension, so that the material could be considered orthotropic. By introducing each data group (E, ρ, ν) corresponding to the dimension (longitudinal, transversal and radial) as modeling parameters of the material for the simulations, a study can be made of those parameters which allow greater similarity between the experimental OMA measurements and the numerical simulation for each dimension.

C. FEM analytical assessment

The fact that the posts were inserted into an element with a far greater mass was considered in the numerical simulation of the TEPS, on the assumption that there is no movement on the Z axis (the vertical axis) and that movement on the X axis (perpendicular to the TEPS) and the Y axis (contained within the TEPS) is more or less negligible at the height where the post starts. Fig. 4 and 5 show a TEPS diagram that is reproduced here for each of the three test configurations. Board thickness and/or resistance class was altered in each case.

Fig. 4: Front view of the TEPS.

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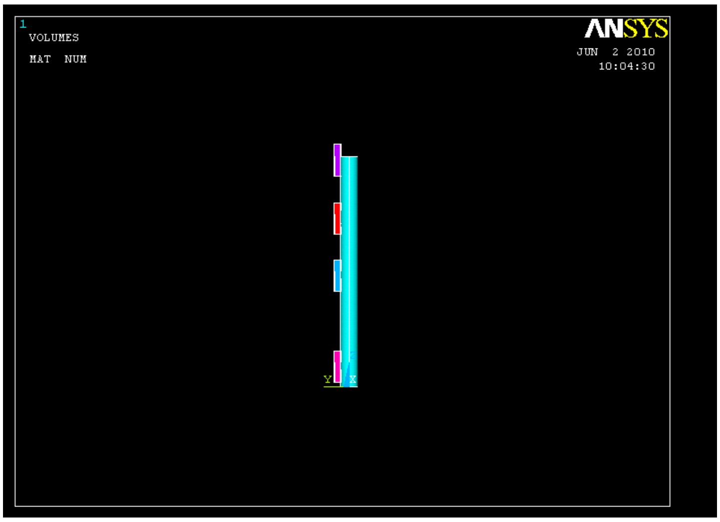

Fig. 5: Side view of the TEPS.

It was assumed, in the finite element analysis model, that the posts were embedded in the concrete beam and that the guardrails were loosely retained in brackets fixed to the posts (Fig. 2). The characteristics were obtained from measurements made directly through ultrasound inspection of the boards used in the testing.

The type of mesh consisted of discretization via solid tetrahedrons, both on the wooden boards and the steel posts. The mesh motor was standard. Analysis was lineal.

Once the mesh process had been completed and dimensioned in order to ensure a good spatial resolution with capacity for computation, analysis of specific TEPS modes was performed. Specific frequencies were obtained for each vibration mode and the unit displacements, in other words, the displacements of the system based on unit and flat excitement across the analysis band. These modes (in frequency and displacement forms) were compared with the values and modes obtained experimentally.

IV. RESULTS

A. Experimental results from vibration modes

The dynamic analysis performed with OMA identified specific experimental modes. The same process was followed in all three systems. The following outlines the work undertaken on the S1 system. Fig. 6 shows the process of recording vibrations on the S1 system, randomly striking it with two hammers.

Fig. 6: The process of recording vibrations through random blows with plastic hammers.

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Following application of the dynamic identification algorithm, the peaks in the spectral diagram were selected that might have corresponded to a natural vibration mode for the whole TEPS system and not to mathematical or natural modes (Fig. 7). A column of letters (s, f, v, d, o) was assigned to each peak that appeared in the response spectrum, which indicate the frequencies, from among those identified, that correspond to the stable modes of the structure. The letter “s” indicates that the frequency, the damping, and the vector of the pole are stable; the letter “f” indicates that the frequency of the pole is stable, the letter “v” indicates that the vector of the pole is stable; the letter “d” indicates that the damping and the frequency of the pole are stable; the letter “o” means that the pole is not stable. Values assigned a greater number of the letter “s” correspond to stable modal forms of the frequency.

The analysis band was selected for the three TEPS analyzed to 250 Hz. It should be understood that above these frequencies, the resulting modes were not the simplest and, in any event, represented separate elements or harmonic modes greater than the simplest movements. Fig. 8 shows the 5 first vibration modes obtained by OMA for the S1 system.

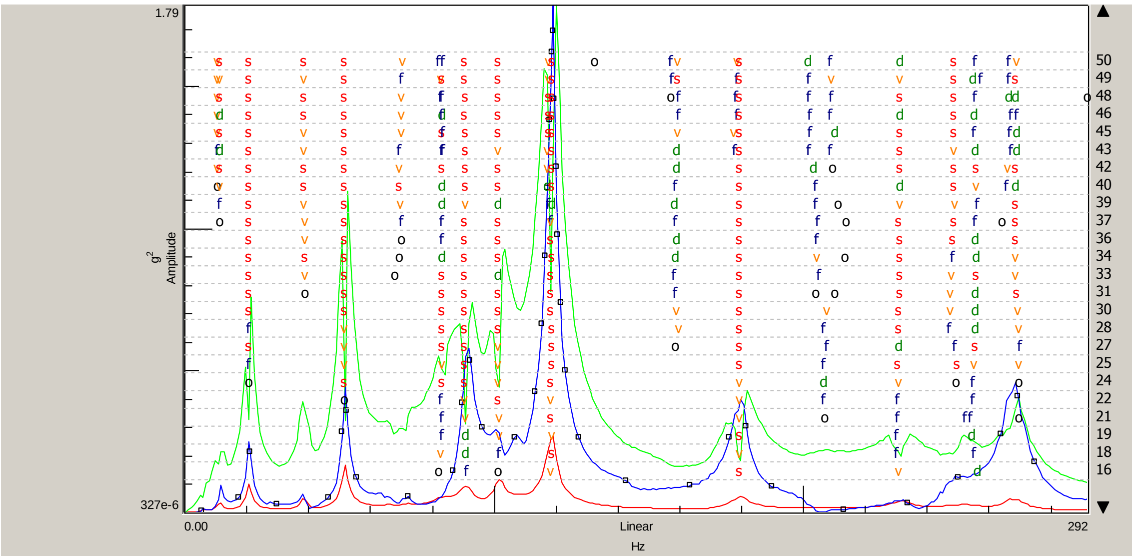
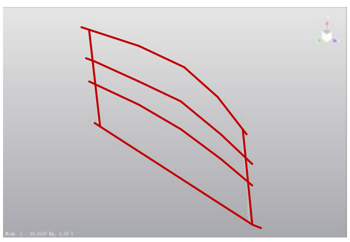
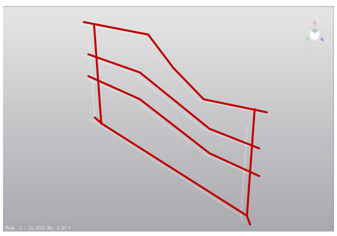


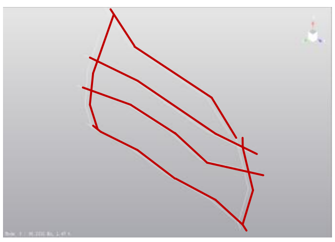
Fig. 7: Statistical analysis and stabilization for the S1 system.



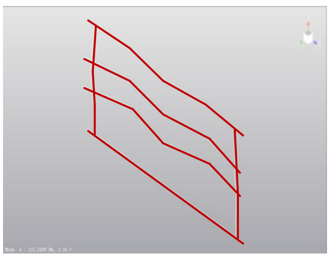
(a) Mode 1: f = 20.62 Hz



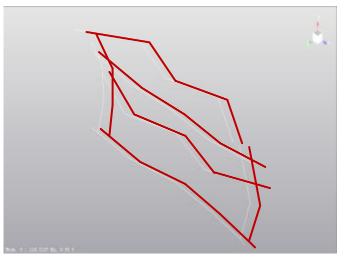
(b) Mode 2: f = 51.67 Hz



(c) Mode 3: f = 90.25 Hz



(d) Mode 4: f = 101.25 Hz



(e) Mode 5: f = 118.31 Hz

Fig. 8: Vibration modes obtained by OMA for the S1 system, considering wood as an isotropic material.

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The fundamental frequency or Mode 1 (frequency 20.62 Hz) corresponded to a bending movement where vertical posts were in phase, in terms of their movement with respect to each other, whilst the boards also moved in phase with respect to each other (Fig. 8a). Mode 2 (frequency 51.67 Hz) corresponded to a twisting movement where vertical posts were in counter phase, in terms of their movement with respect to each other whilst the boards showed a central node half way along their 2400 mm length (Fig. 8b). Mode 3 (frequency 90.25 Hz) corresponded to a double twisting movement for vertical posts and boards (Fig. 8c). Modes 4 (frequency 101.25 Hz) and 5 (frequency 118.31 Hz) corresponded to a bending movement where the vertical posts were in phase although the boards showed a single node, although one of the boards might vibrate in counter phase with respect to the others (Fig. 8d and Fig. 8e).

The experimental assessment performed using OMA on the S2 and S3 systems offered the same vibration mode formats although with associated frequencies that differed from the values obtained from the S1 system. Section 5 of this study shows the corresponding numerical values.

B. *The elastic properties of wood*

Based on the propagation speeds of the ultrasound waves and the apparent densities, the values of elastic constants were obtained. Table I shows the values obtained for the main guardrails of the three systems under study. The orthotropic nature of the wood became evident on observing the huge variation in its mechanical characteristics depending on the spatial dimension in which it was obtained. The elasticity modules obtained were greater on the longitudinal dimension; the other two dimensions showed considerably lower values. It could also be seen that there was no relationship between elasticity module values for the transversal and radial dimensions, as they varied for each set of analyzed boards. Each measurement represented the average of at least three ultrasound inspection measurements on the board.

C. *Analytical results from specific vibration modes*

Numerical simulations based on finite element analysis were performed on the three TEPS studied with OMA. Three independent calculations were made for each of the TEPS, considering the mechanical characteristics obtained through ultrasound for each dimension (Table I). Fig. 9 shows the 5 first vibration modes obtained with FEM for system S1, considering wood as an isotropic material, which employs the characteristics obtained in the longitudinal dimension (L) as the mechanical characteristics of the boards.

Table I. Ultrasound characterization and elastic constants values

Board	Dimension	Propagation length (m)	t_p (s)	t_s (s)	V_p (m/s)	V_s (m/s)	E (N/mm^2)	G (N/mm^2)	ρ (kg/m^3)	υ
S1	Length	2.591	495	884	4905	2930	9660	3950	470	0.223
	Radial	0.030	16.6	26.8	1868	1142	1460	610		0.195
	Transversal	0.142	97.6	163	1469	871	850	350		0.221
S2	Length	2.600	492	948	5266	2733	9240	3510	460	0.316
	Radial	0.030	15.2	37.4	1959	783	790	280		0.402
	Transversal	0.142	90.4	153	1625	921	1000	400		0.246
S3	Length	2.580	568	956	4577	2720	8350	3400	460	0.227
	Radial	0.040	19.2	31.0	2084	1314	1920	820		0.177
	Transversal	0.145	96.0	158	1577	921	940	390		0.207

t_p propagation time longitudinal, t_s propagation time transversal, V_p propagation speed longitudinal, V_s propagation speed transversal, E module elasticity longitudinal, G module elasticity transversal, ρ density, υ: Poisson ratio
Mode 1 (frequency 26.87 Hz) corresponded to the first experimental mode, focusing on the observed deflections in direction Y (Fig. 9a). The vertical posts moved little, with a maximum elongation on the central point of the upper board. No displacement nodes were observed in direction Y on the boards. Mode 2 (frequency 65.49 Hz) corresponded to the second experimental mode, focusing on the observed deflections in direction Y (Fig. 9b). The vertical posts moved in counter phase, with considerable displacement. The upper board showed the greatest displacements. A displacement node was observed in direction Y in the central part of the boards. Mode 3

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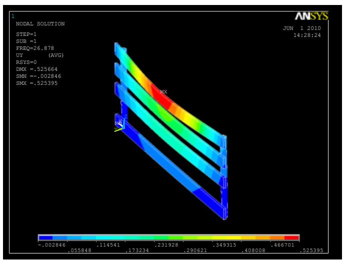
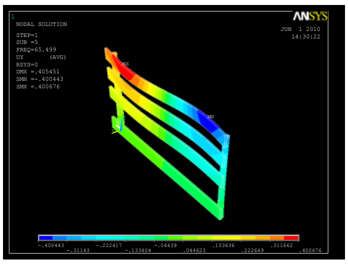
(frequency 100.84 Hz) corresponded to the third experimental mode, focusing on the observed deflections in direction Y (Fig. 9c).

The vertical posts moved in counter phase, although no node is observed in their movement. The boards moved in counter phase. A displacement node was observed in direction Y in the central part of boards. Mode 4 (frequency 130.25 Hz) corresponded to the second experimental mode, focusing on the observed deflections in direction Y (Fig. 9d). The vertical posts moved in counter phase, with considerable displacement. Maximum displacement was observed on the upper board. A displacement node was observed in direction Y in the central part of boards. Mode 5 (frequency 205.93 Hz) corresponded to the fifth experimental mode, focusing on the observed deflections in direction Y (Fig. 9e). The vertical posts showed slight displacement. Maximum displacement was observed on the upper board, with displacement Y produced in counter phase with respect to the two intermediate boards. Two displacement nodes were observed in direction Y on the boards.

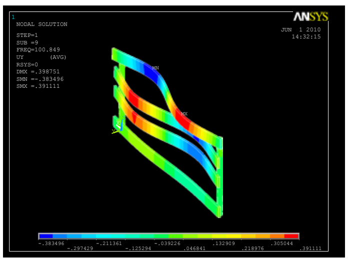
A summary of the results obtained from systems S2 and S3 for the radial and tangential dimensions is shown in Section 5 of this study.



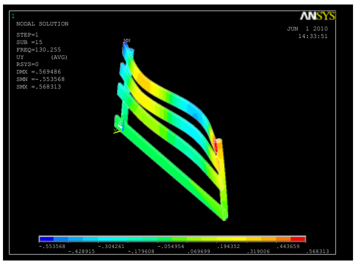
(a) Mode 1: f = 26.87 Hz



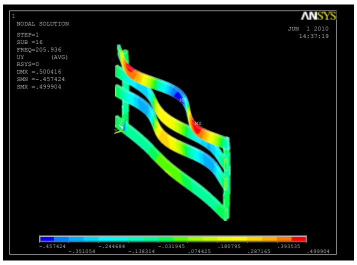
(b) Mode 2: f = 65.49 Hz



(c) Mode 3: f = 100.84 Hz



(d) Mode 4: f = 130.25 Hz



(e) Mode 5: f = 205.93 Hz

Fig. 9: S1 System vibration modes obtained with FEM. Wood as an isotropic material.

IV. ANALYSIS AND DISCUSSION OF RESULTS

The results obtained with OMA and numerical simulation techniques considering the isotropic materials did not coincide. Significant differences between the experimental and analytical assessment may be noted for the TEPS types and the different characteristics employed. The vegetative anatomy and fibrous structure of the wood mean it is an anisotropic material [26]. Usually, the simplified classification linear anisotropic or orthotropic is used [27], allowing the constitutive equation for the material to be expressed as follows (4):

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \qquad (4)$$

Where, σ_{ij} represents the stress tensor, and ε_{kl} the strain tensor. The rigidity tensor, C_{ijkl}, represents the matrix expression of the elastic constants obtained through experimental measurement.

The following simplifications were assumed, in order to develop the model:

- Wood was characterised as a homogenous, orthotropic material across the three spatial dimensions.

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- Wood is a continuous material.
- There were no defects and the fibres were oriented in a parallel direction to the axis of the piece [28].

In previous hypotheses, the rigidity matrix in the area of elastic and linear performance was considered symmetrical. Applying a mathematical development [27], an expression for each matrix was obtained based solely on 12 values with respect to the initial configuration of a 6 x 6 matrix (5).

$$\underline{\underline{C}} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad (5)$$

Applying the relationship between modules, the Poisson ratio for each position of the conformity tensor S, the following expression is obtained (6):

$$\underline{\underline{S}} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{12}}{E_1} & -\frac{\nu_{13}}{E_1} & 0 & 0 & 0 \\ -\frac{\nu_{21}}{E_2} & \frac{1}{E_2} & -\frac{\nu_{23}}{E_2} & 0 & 0 & 0 \\ -\frac{\nu_{31}}{E_3} & -\frac{\nu_{32}}{E_3} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \quad (6)$$

The relationships between the terms of the conformity matrix S, the rigidity matrix C and the speed of the ultrasound wave were known and could be calculated for the Christoffel equation (7):

$$\left[G_{ik} - \rho V^2 \delta_{ik}\right] = 0 \quad (7)$$

where, G_{ik} is the Christoffel tensor related to rigidity, V_p = speed, ρ = density and δ_{ik} the Kronnecker delta. Thus, assuming 1, 2, 3 as the indices for dimensions x, y, and z, the values obtained in the ultrasound characterisation can be used for longitudinal, radial and transversal dimensions x, z and y.

Fig. 10 shows the 5 first vibration modes obtained with FEM for the S1 system, considering wood as an orthotropic material, with the displacement values similar to the experimental modes obtained with OMA.

Table II sets out the results obtained using the experimental OMA technique for the identification of specific modes that characterise the dynamic behaviour of TEPS and their comparison with the results obtained through the numeric simulation realised using the Finite Element Method (FEM), considering the wooden boards as either an isotropic or an orthotropic material. Four FEM simulations were performed on each of the systems. In three

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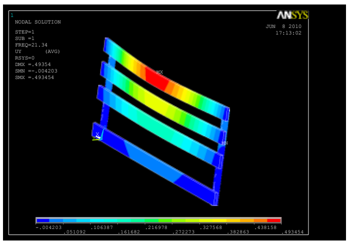
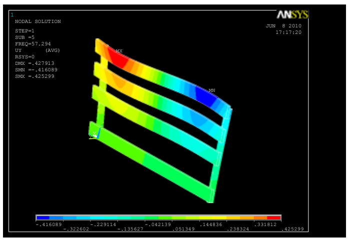
simulations, the wood was considered isotropic, taking the elastic constants of the longitudinal (L), radial (R), and transversal (T) dimensions. In the fourth simulation, the wood was considered orthotropic (LRT).

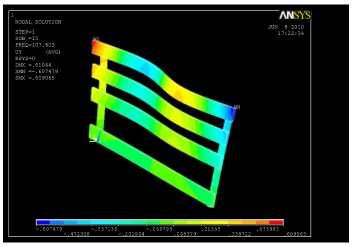
Fig. 10: Vibration modes obtained for the S1 system through FEM. Wood as an orthotropic material.



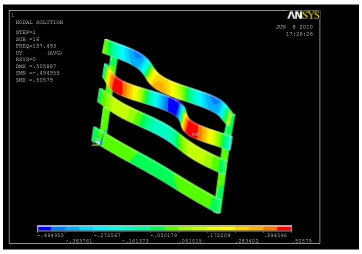
(a) Mode 1: f = 21.34 Hz



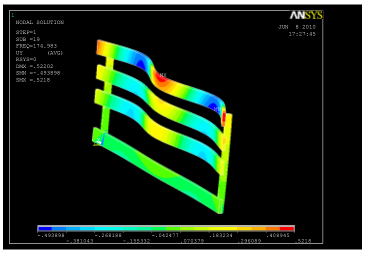
(b) Mode 2: f = 60.92 Hz



c) Mode 3: f = 107.80 Hz



(d) Mode 4: f = 157.49 Hz



(e) Mode 5: f = 174.98 Hz

Table II. Summary of frequency values (Hz) obtained in TEPS

				MODE 1	MODE 2	MODE 3	MODE 4	MODE 5
S1		OMA		20.619	51.67	90.25	101.25	118.31
	FEM	ISOTROPIC	L	26.87	65.49	100.84	130.25	205.93
			H	11.64	31.90		58.49	68.50
			W	14.52	39.30	44.56	67.04	
		ORTHOTROPIC	LHW	21.34	60.92	107.80	157.49	174.98
S2		OMA		19.272	47.53	66.68	67.90	96.65
	FEM	ISOTROPIC	L	26.65	64.60			
			H	12.34	33.78			60.75
			W	12.03	32.69			
		ORTHOTROPIC	LHW	21.51	56.65	107.33	156.56	173.27
S3		OMA		20.15	53.53	58.47	79.83	103.87
	FEM	ISOTROPIC	L	27.63	66.61	89.98		150.50
			H	18.14	47.25	71.17		146.07
			W	14.17	38.46	44.48	64.44	111.01
		ORTHOTROPIC	LHW	24.28	59.20	94.90	127.86	227.09

There are other modes derived from numerical simulation that correspond to vibrations specific to isolated elements or boards, although these were not considered as they do not represent a TEPS mode either as a whole or as single element.

The first modes 1 and 2, which are fundamental simple flexural modes, were clearly obtained in all simulations. Modes 3, 4 and 5 represent a combination of movements between the vertical steel posts and the wooden boards, vibrating either in phase or in counter phase, both in terms of the posts with respect to the wood and the wooden boards with respect to each other. These upper modes are not always identified, at least in terms of a simulation of wooden boards that takes wood to be an isotropic material.

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The results indicate that the greatest similarity was found when applying the orthotropic model to each of the boards. The results showed a clear similarity between the first two modes although their frequency values do not exactly coincide.

As may be expected, the analytical results, which consider wood as an isotropic material, although with mechanical characteristics that correspond to its transversal or radial dimensions, differed considerably from the experimental results.

V. CONCLUSIONS

One of the greatest difficulties when analytically assessing TEPS is that of obtaining a calculation model for analysis. The calibration of calculation models through non-destructive techniques may, in many cases, result in an interesting alternative to standard practices which proves most useful when carrying out the mechanical testing of prototypes.

This study has examined the possibility of using OMA as a non-destructive experimental technique for calibrating TEPS calculation models. Thus, vibration modes for TEPS, consisting of wooden boards and tubular steel posts, were obtained with OMA. The same information was analytically obtained, through FEM, presupposing elastic and linear material behaviour and rigid joints between the guardrail boards and the post, and between the posts and the frame structure.

The maximum correspondence between modes was obtained by using the values relating to the orthotropic model for wooden boards, for each TEPS type.

The efficiency of the method to calibrate TEPS models is evident in the similarity of results for the first specific vibration modes (1 and 2), which correspond to the bending behaviour of the wooden elements of the TEPS. These results were obtained experimentally, by performing a dynamic characterisation with OMA, and analytically, through a numerical simulation that performed finite element analysis modelling and analysis of the TEPS.

One of the greatest difficulties in the analysis of TEPS is the preparation of a calculation model that reflects the real situation. One of the most commonly used techniques in the analytical assessment of structures is the FEM. In this research, the real dynamic behaviour of the TEPS, obtained with OMA, was compared with analytical prediction from FEM. The OMA study may therefore be used as a guide to model calibration or correction.

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