CMMoST 2021

6TH INTERNATIONAL CONFERENCE ON

Mechanical Models in Structural Engineering

01 – 03 December 2021

Escuela de Ingenierías Industriales
Universidad de Valladolid

Book of Abstracts

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BOOK OF ABSTRACTS

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Abstracts

A METHODOLOGY TO ESTIMATE THE PROPERTIES OF A TUNED MASS DAMPER INSTALLED ON A SLENDER STRUCTURE

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Keywords: Tuned Mass Damper, system identification, structural dynamics, experimental modal analysis

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ABSTRACT

A Tuned Mass Damper (TMD) is a device that is installed on a structure in order to reduce its response level when it is subjected to dynamic loads [1,2]. It can be assimilated to a single-degree-of-freedom (SDOF) system, as shown in Figure 1, with its own values for the moving mass m_t, stiffness constant k_t and damping coefficient c_t, which confers them a certain natural frequency ω_t and damping ratio ζ_t. For it to be effective, its natural frequency must be close to the natural frequency of a specific structural mode [3]. The TMD is placed on a certain point of the structure and, thanks to the mechanical coupling that occurs between it and the structure, the contribution of the mode to which it is tuned is heavily reduced. However, if the TMD is mis-tuned, its efficiency may be drastically reduced, so great care must be taken when deciding its final modal properties.

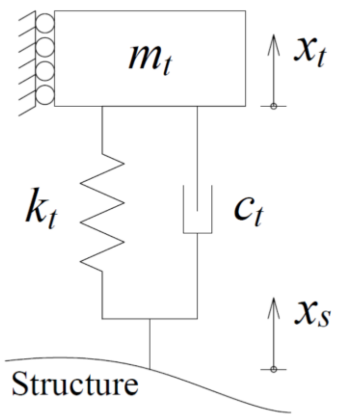

Figure 1. *Schema of a SDOF system attached to a certain point of a structure.*

Before installing it, it is relatively easy to estimate the modal properties of the TMD. However, once installed on the structure, where it is coupled to the structural response, this estimation is quite more challenging [4]. In this work, a methodology to estimate the natural frequency, damping ratio and moving mass of a TMD installed on a lively structure. It requires very little experimental equipment: two accelerometers and a device to induce a controlled force on its moving mass (e.g., an impact hammer). By simultaneously measuring the applied force and the acceleration response of the moving mass and the point of the structure to which it is attached, the three parameters can be accurately estimated. To show the performance of the methodology, a real TMD has been crafted (Figure 2) and installed on a laboratory-scaled structure to perform the required tests. The TMD is also placed on a rigid floor to directly estimate its properties for comparison purposes. Results show that, with the proposed methodology, the modal properties of the installed TMD are accurately estimated with a low amount of equipment and time to perform the tests [5].

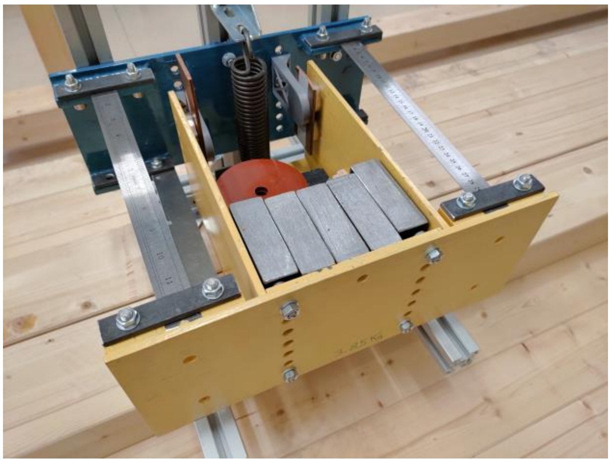

Figure 2. *Experimental realization of the TMD used to validate the methodology.*

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ON THE DESIGN OF SEVERAL TUNED MASS DAMPERS FOR A MULTI-DEGREE-OF-FREEDOM MODEL OF A SHEAR BUILDING

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Keywords: tuned mass damper, multi-objective optimization, genetic algorithm, ultimate limit state, serviceability.

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ABSTRACT

Some slender structures may require mechanical system to reduce the dynamic response of one of its vibration modes. In this case, it is easy to decide which system to install, generally a TMD tuned to that mode, and where to place it (generally in a position where the modal coordinate is a maximum). However, when there are several modes with high dynamic responses or there are several criteria to be satisfied by the TMD device, the problem becomes more challenging.

Any engineering structure must fulfil the building standards or prescriptions of security (Ultimate Limit State, ULS) and functionality (Serviceability Limit State, SLS). In the case of slender buildings, low intense earthquakes or wind action cause oscillations that can affect the comfortability of the occupants (SLS) whereas severe earthquakes could cause excessive stresses and therefore member damage or even structure collapse (ULS).

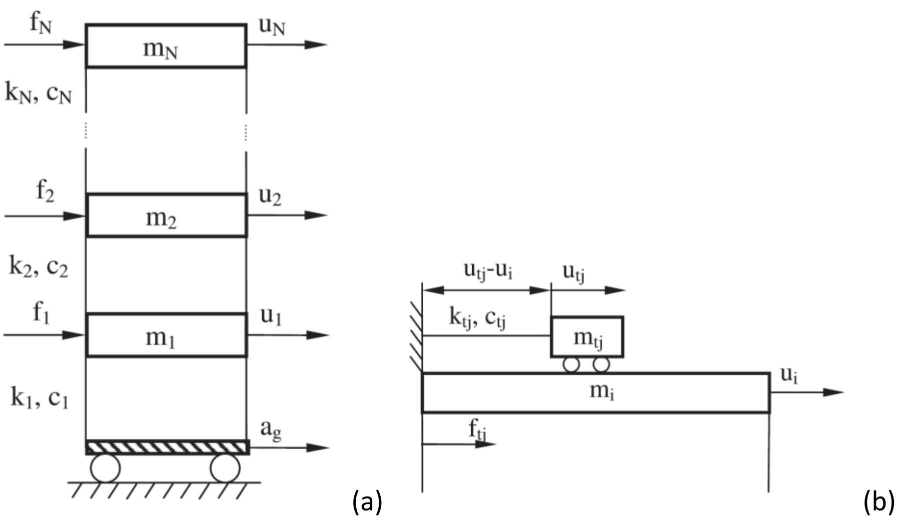

Figure 1. *Conceptual N-storey building (a) and TMD models (b)*

One way to reduce the dynamic response of slender buildings is by installing passive vibration mitigation devices known as tuned mass dampers (TMD). The effectiveness of these devices depends on their size (mass), their mechanical properties (frequency and damping) and their location in the building (some of its floors). Mass, frequency and damping are variables with continuous distribution. However, they must be placed is in a particular floor, which is a discrete factor. Obviously, several devices can be installed, each with different parameters and in different placements. In this case, a reasonable comparison will require that the total mass be the same. Given the total mass but not its distribution among the multiple devices complicates even more the design problem. The large number of factors and their different nature leads to an intricate problem which can only be addressed by the appropriate numerical techniques.

The study case is a simple N-story building, and its response is analysed in terms of both objectives and the total added mass of the devices. Figure 1.a shows the conceptual modelling of the building where a proper TMD (figure 1.b) can be installed in any of its floor.

The dynamic loadings affect usually to the serviceability of the building, i.e., the comfort of their occupants and functionality of the facilities, but, less often, to the structural integrity (in the case of earthquakes or hurricanes). It is desirable that the structure could be comfortable, functional and secure at the same time, regardless the loading condition. For this end, some standards provide guidelines in terms of limit values to some physical magnitudes such as stresses or accelerations. In this sense, those standards make the difference between SLS and ULS. The former usually defines threshold values for acceleration response taking into consideration the perception of the occupants of the structure. The latter focuses on the highest stresses the material can eventually develop when the structure is subjected to the worst loading scenario. These two criteria will be used as segmented objective functions for articulating the multi objective approach under study.

Note that the effectiveness of the device depends on the mass, also its price, being desirable to achieve the required protection with the minimum mass. To address the problem, a multi-objective algorithm driven by genetic algorithms are selected among other approaches. The first objective (SLS) is evaluated in terms of the Frequency Response Functions (FRF) and for the second one (ULS) the assembly is under an earthquake and the maximum drift between floors are considered.

The results obtained for the case of 2 and 5 storey building are analyzed.

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EXPERIMENTAL CHARACTERIZATION OF PISTON-LIKE MAGNETIC DAMPERS

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Keywords: Eddy current damper, tuned mass damper, frictionless damper.

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ABSTRACT

The vibration mitigation devices known as tuned mass dampers (TMD) comprises basically a frame that houses a mass suspended on elastic elements and dampers. Ideally all mechanical components are linear so that the whole device is an ideal SDOF system. For that, the damper must exert a force proportional to the velocity, behaving as a viscous damper. The traditional way of manufacturing such a damper is by means of pistons that transfer oil from one chamber to another (Figure 1.a). This mechanical arrangement inevitably adds friction (because of the oil seals) so that the force in the damper depends not only on velocity but also on friction.


(a)
(b)
(c)

Figure 1. *Different types of dampers. (a) viscous damper. (b) axial magnetic device. (c) radial piston-like magnetic damper.*

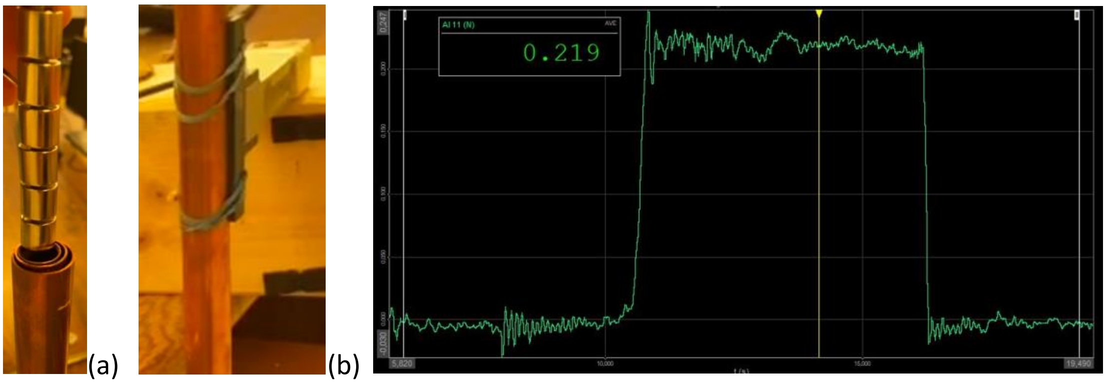
Since friction leads to a non-linear behavior, the actual operation of the TMD is impaired. Note that the TMD is installed in the vibrating structure and that it is the movements of this structure that cause the TMD to move and dissipate energy. For small oscillations, friction causes the TMD does not start up, conditioning the efficiency of the assembly.

It is known that the interaction, without contact, between permanent magnets and non-ferromagnetic metallic materials such as aluminium or copper behaves as a viscous damper by the effect known as Eddy currents [1-5]. The dissipation depends on the relative arrangement between the magnets and

the metallic materials. Assuming that the magnets are disks, they can be arranged axially (figure 1.b) or radially (figure 1.c). Figure 1.b shows a battery of magnetic disks axially arranged with the corresponding copper plate, tested and characterized in previous laboratory TMD prototypes.

However, in order to be able to replace viscous oil dampers by others based on these magnetic principles, it would be interesting to radially arrange the magnetic disks with respect to the metallic part in such a way that the assembly would adopt the shape of a piston. The simplest way would be to stack several disks and introduce them into a tube. It is known that the most favourable arrangement to maximize the damping capacity is to place the different disks in repulsion, with some separation between them, but there are no analytical formulas for the estimation of the damping capacity.

The aim of this work is to evaluate the damping capacity as a function of different variables, among which the following are worth mentioning: Magnet disk size and its magnetization Number of stacked magnet disks, Separation between disks, Separation of the pile from the containing tube and Material of the tube and its thickness. The experimental setup that has been carried out is shown in figure 2. It shows a pile of magnets which is dropped inside a copper tube (a). The copper tube is held in a load cell (b) which records the force and time (c). After the modelling and post processing, the damping capacity is obtained and some practical conclusions are drawn.



(a) (b)

(c)

Figure 2. *Experimental layout. Pile of magnets (a) load cell (b) and force.vs.time records (c)*

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SCALABLE AND LOW-COST MEMS-BASED STRUCTURAL HEALTH MONITORING SYSTEM

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Keywords: Scalable, low-cost, SHM, MEMS accelerometers, Experimental Modal Analysis

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ABSTRACT

One of the most popular options in the Structural Health Monitoring field is the tracking of the modal parameters, which are estimated through the frequency response functions of the structure, usually in the form of accelerances, which are computed as the ratio between the measured accelerations and the applied forces. This requires the use of devices capable of synchronously recording accelerations at several points of the structure at high sampling rates and the subsequent computational analysis using the recorded data.

To this end, this paper presents the design and development of a scalable low-cost Structural Health Monitoring (SHM) system based on multiple myRIO platforms and digital MEMS (Micro Electro-Mechanical Systems) triaxial accelerometers. The system, managed by a specifically developed software, acquires the accelerations and also computes the corresponding frequency response functions for the subsequent modal analysis.

This proposed SHM system using only a single board with some accelerometers was validated by comparing the data measured by this set-up with a conventional SHM system based on piezoelectric accelerometers, as can be observed in Figure 1. After carrying out some validation tests, a high correlation can be appreciated in the behaviour of both systems in time and frequency domains. So, from this validation test, it can be concluded that the proposed system is sufficiently accurate and sensitive for operative purposes, apart from being significantly more affordable than the traditional one. This system and the corresponding validation results were presented by the authors in a previous work [1].

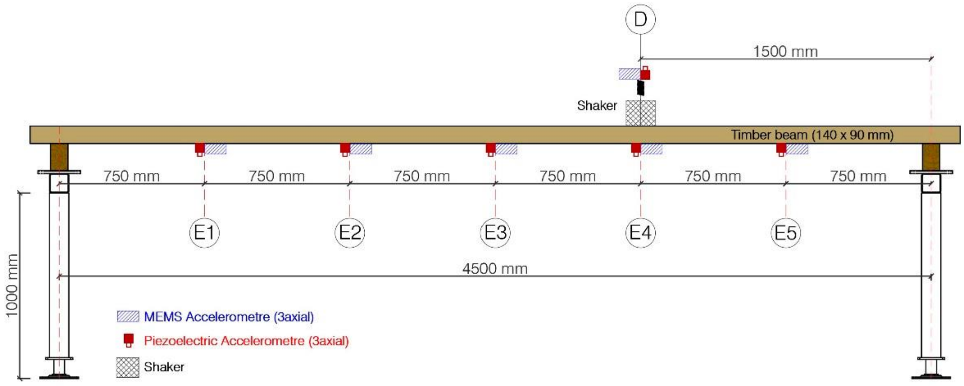

Figure 1. *Validation test for a simple version of the system*

After this validation test, a larger system composed by several slave boards connected and synchronized to a master one was tested. In this new scenario, the devices were deployed on a timber platform to estimate its modal properties. The obtained results were compared with the ones provided by the same commercial system that were used in the first validation test. This comparison showed that similar results were obtained with both systems, but using the proposed systems means having a significantly lower cost. This enlarged system and the corresponding validations results were also presented by the authors in another previous work [2].

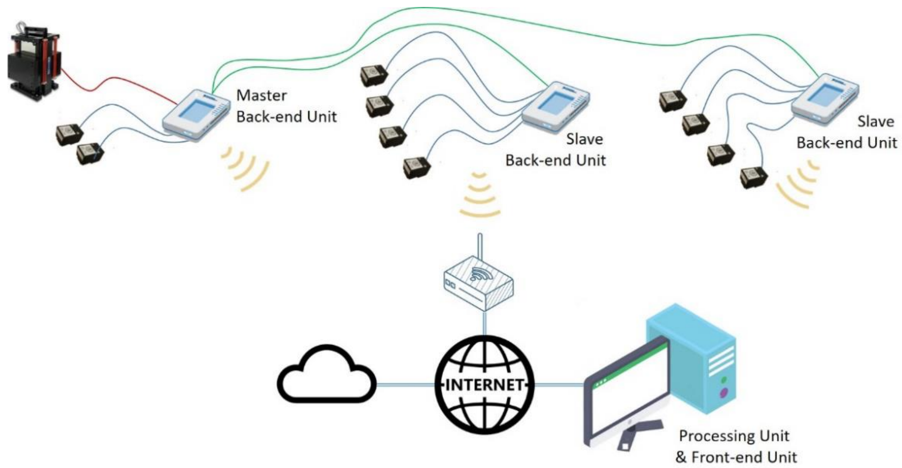

Figure 2. *Configuration of the monitoring system*

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INFLUENCE OF THE BOUNDARY CONDITIONS ON THE MODAL PROPERTIES OF A WALKABLE TIMBER PLATFORM

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Keywords: Timber bridge, Dynamic test, Boundary conditions, MEMS accelerometer

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ABSTRACT

Timber structures as a rule have timber supports between their main body and the ground or secondary structure [1]. However, under poor designs, these timber pieces can reach higher humidity level than main structure due to accumulation of rainwater or direct contact with earth. And for that, decay damages, both fungi and insect types, are usually common. In other cases, a good design can improve this timber supports selecting more durable wood species, placing intermediate elastomeric materials, or even using specific metal fittings [2]. All these variables, many not provided in the initial design (as decay for example), cause that the timber supports designed for timber structures do not always correspond to the theoretical limitations considered in the structural design [3-5]. The timber supports from different wood specie, density, size, or even the section loss by decay, affects the dynamic response of this kind of structural elements. This research has two main objectives. Firstly, this work is focus on analysing the influence of different timber support boundary conditions on the dynamic response of a full-scale pedestrian timber bridge, mainly on the natural frequencies, modal forms and on the damping properties. Secondly, tests are used to validate a new low-cost structural monitoring system, designed and developed by our research group [6], compared to a commercial analogy measurement system.

Dynamic vibration tests were performed on a full-scale pedestrian bridge with a size of 140 x 1000 x 13500 mm. It was built on structures laboratory with 9 fir wood (*Picea abies*) glulam beams of section 100 x 140 mm and resistant class GL24h, mechanically connected. Both measurement systems, 10 commercial piezoelectric accelerometers and 10 MEMS digital accelerometers, were placed at the same time and positions on a 5x2 grid, to measure pedestrian bridge dynamic response [7]. During test campaign a lineal shaker was fixed on the pedestrian bridge to excite the structure (Fig. 1a).

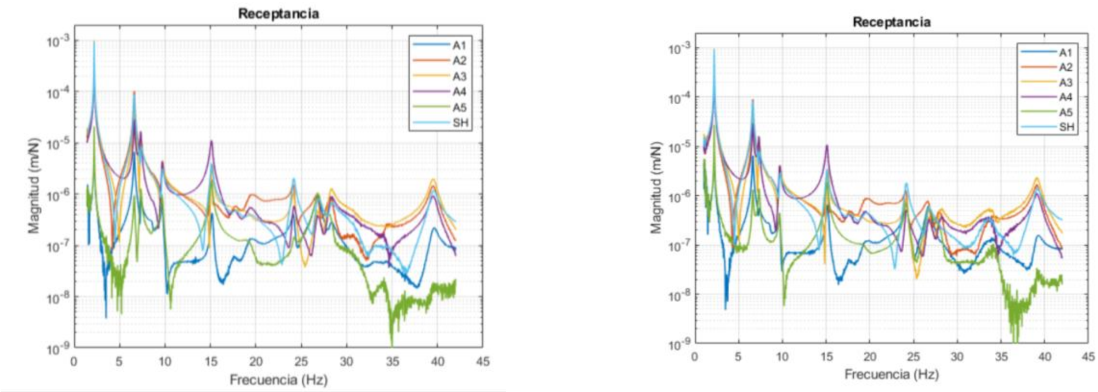
Structure was supported on free-free condition. Seven different timber support types were considered, with healthy and decay damages samples (Fig. 1), and different wood species (Table 1). The natural frequencies were experimentally estimated in two different ways: commercial one with SIRIUS/Dewsoft system and MATLAB software (Fig. 2a), and our own design platform with MyRIO/Amemome system and ModA analysis software (Fig. 2b). Modal shapes and natural frequencies did not show significant differences between timber supports tested; maintaining the main structure modal frequencies for all timber supports tested (Fig. 2). However, the values of damping ratio obtained were slightly differences for each sample. This date could be useful to detect any variation in the timber supports due to decay damage or any change in the support construction conditions.

(a) (b)

Figure 1. *Heathy (a) and decay damage (b) timber supports.*

Table 1. Characterization of timber supports tested.

#	Common name (*Scientific name*)	Type	Size (mm)	Density (kg/m^3)
1	Missandra (*Erythrophleum Afzel ex* G. Don Sp.)	healthy	60x100x160	920
2	European oak (*Quercus robur* L.)	healthy	60x100x160	710
3	Poplar (*Populus x euroamericana (Dade) Guinier)*	healthy	60x100x160	440
4	Foxglove tree (*Paulownia tomentosa* (Thunb.) Steud.)	healthy	60x100x160	270
5	Scots pine (*Pinus sylvestris* L.)	decay	200x200x150	520
6	Scots pine (*Pinus sylvestris* L.)	decay	200x200x150	520
7	Scots pine (Pinus sylvestris L.)	decay	200x200x150	520



(a) (b)

Figure 2. *Natural frecuencies of different samples tested. a) SIRIUS system. b) Amemome system.*

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GROUND REACTION FORCES GENERATION OF VIRTUAL HUMAN SUBJECTS APPLYING A FUZZY LOGIC- BASED ALGORITHM ON STATISTICAL INDICATORS EXTRACTED FROM EXPERIMENTAL DATA

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Keywords: Ground Reaction Forces, Human transit, Human-structure interaction, Fuzzy Logic

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ABSTRACT

Human activity upon the structures may be divided into passive (such as humans sitting or standing on the structure) and active (such as humans walking, jumping, bouncing or performing other rhythmic activities). While passive humans may influence the dynamic response of the structure by modifying its modal parameters (natural frequencies, modal shapes and modal damping factors) [1], active human activities can bring the structure into vibration [2]. Excessive vibration may occur if the motion frequency of human coincides with a resonant frequency of the structural system, and once the structure starts vibrating beyond certain limit, it results a serviceability problem.

Therefore, considering human-structure interaction is essential both in the design phases and when evaluating the serviceability of the structure. However, this effect is hard to quantify, since when walking on a vibrating surface, the pedestrian tends to modify his walking pattern to maximize his comfort. Apart from the already inconsistent and non-repetitive human walking characteristics. Different authors [3, 4] have analysed the forces generated by the interaction between the foot plant and the ground during the walking process, known as GRF (ground reaction forces), classifying the variables that influence their magnitude as follows:

- Intrinsic or associated with individuals [5], which can be further differentiated into "inter-subjects" (weight, height, age, sex and anatomical characteristics), and "intra-subject" (mobility, pathologies, mood, fatigue, alcohol or drug consumption).
- Extrinsic or associated with the environment [6], which can be classified as instrumental (measurement methods), kinematic (type and speed of walking), clothing (footwear, clothing, accessories), environment (wind, rain, snow) and terrain (hardness, slope, vibration).

Several models of human footfall forces have been developed, both based on statistical information of the walking force [7] and based on a mechanical model matching human characteristics and attempting to replicate the human-structure interaction effects [8].

The main objective of the presented paper is to generate vertical virtual forces equivalent to those produced by a specific person's gait pattern. In such a way that by entering the physical characteristics of a virtual subject as inputs, the developed system will provide the virtual GRFs and the associated gait parameters. The work is divided in two parts: a first one of experimental data acquisition, processing and statistical treatment, and a second part of generation of virtual forces and GRF, and development of the procedure to generate the statistically equivalent virtual gait.

Experimental GRF data were collected using LOADSOL sensorized insoles for 50 subjects of different physical characteristics (age, sex, height, weight) and walking at different frequencies on a rigid floor. Subsequently, these data were subjected to a statistical procedure in which, first, each of the steps taken in each transit were separated and normalized, then the outliers were removed and finally the mean values and the standard deviations in newtons of each foot were obtained.

These data were then separated into training and validation sets for a fuzzy logic-based algorithm, where, inputting the five studied variables (age, sex, height, weight and frequency), it shall provide the mean values and standard deviations of the normalized steps for each foot of the virtual subject and the gait parameters. The fuzzy logic controller parameters (membership functions and its associated function values) were selected applying optimization algorithms to minimize the error between the controller output and the validation data when inputting the same variables.

Afterwards, the inverse statistical procedure of generating the virtual gait during a defined period of time is performed according to the values provided by the algorithm. Thus, it will be possible to accurately predict the GRFs that a specific person will produce, enabling these GRFs to be reproduced by means of mechanical devices (electrodynamic shakers), therefore allowing the study of human-structure interaction phenomena without the need of involving transits with real subjects.

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INFLUENCE OF THE FRICTION EFFECTS ON THE EFFICIENCY OF A TUNED MASS DAMPER

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ABSTRACT

Lively structures are prone to vibrate when they are subjected to dynamic loading. To overcome this issue, passive mitigation devices (such as Tuned Mass Dampers, or TMDs) can be installed on them in order to reduce the contribution of a certain mode to the dynamic response [1,2]. Such a device can be assimilated to a single-degree-of-freedom (SDOF) system, like the one shown in Figure 1, with a certain amount of moving mass m_t and an elastic member with constant k_t which confer them a certain natural frequency ω_t. In an optimal scenario, the natural frequency of the TMD must be close to and under the natural frequency of the structural mode whose contribution is to be reduced [3]. Thanks to the mechanical coupling that occurs, a certain amount of the energy is transferred to the TMD, which must be mitigated. To do so, a damper must also be incorporated to the TMD in parallel to the elastic member, as shown in Figure 1. The most spread model for this damper is the ideal viscous one, characterized by a damping coefficient c_t which leads to a certain damping ratio ζ_t.

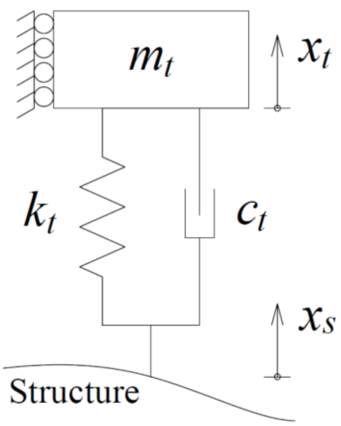

Figure 1. *Schema of an ideal TMD modelled as an SDOF system*

When a TMD is manufactured, however, ideal viscous dampers cannot be used. Real dampers can make use of different technology to mitigate energy as desired, and almost all of them contain elements that make arise friction effects. Depending on the technology of the damper, these effects, which are not linear, may be negligible and the ideal viscous model may be enough to accurately predict the final behaviour and efficiency of the TMD. However, sometimes the friction plays a relevant role in the damping capacity of the damper and the ideal viscous model do not provide meaningful predictions. As can be stated, although the overall damping capacity of the damper is preserved, depending on the amount of friction with respect to the amount of ideal viscous damping, the response of the ensemble structure + TMD may significantly change and, thus, the efficiency of the mitigation device may be compromised. This is investigated in this work by means of a series of simulations performed in Simscape/Simulink using the friction model included in the corresponding block of the software.

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EVALUATION OF VIBRATION TRANSMISSION OF L-SHAPED PLATES USING FINITE ELEMENT ANALYSIS

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Keywords: L-shaped plates, vibroacoustic, finite element analysis, vibration.

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ABSTRACT

The study of vibration transmission and energy flow between coupled plates improves the predictive models of structure-borne sound transmission. This is of interest in many fields of application, e.g. in automotive, aeronautic, marine and building industries [1].

In this paper we aim at analysing the vibroacoustic response obtained by FEM models in the case of L-linked plates, using the commercial FE package I-DEAS. The difference in velocity level between the excited element and the non-excited element, $D_{v,ij}$, will be used as an indicator of vibration transmission. This parameter is also used by other authors [1], [2] y [3]. The experimental model will be made using stone with concrete-like properties. The influence of the thickness of the connected plates, different characteristics of the material, meshes, types of excitation and the incorporation of two samples of elastic layers, similar to floating floors, will be studied. The results will be calibrated and validated using experimental measures and comparing different FEM calculation models (Fig. 1). Third-octave frequency bands within the frequency range 40-3150 Hz will be studied.

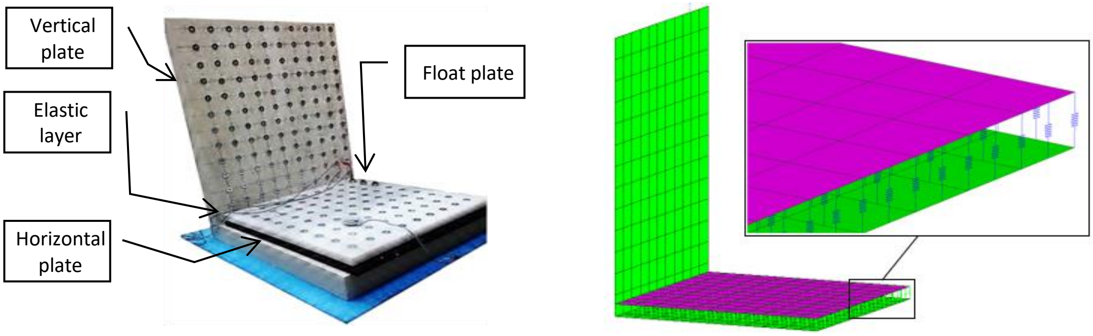

Figure 1. *Geometry of the joint connecting thick plates and floating plate and models with elastic layer (mesh for the plates and for the elastic layer).*

The models of plates without elastic layers, i.e. without a floating plate, were validated and calibrated first. To do this, the results of own frequencies, average quadratic velocity, speed level and speed level difference were used. Some of the material's properties were used to calibrate the results of FEM analyses. For this, modifications were studied in Young's modulus and in the material's density.

The velocity level difference between the source and receiving plate is used to study how vibration flows for third-octave frequency bands, within the frequency range 40-3150 Hz. The influence of different types of geometry, material properties, meshes and the incorporation of an elastic layer, simulating a floating floor were studied (Fig. 2).

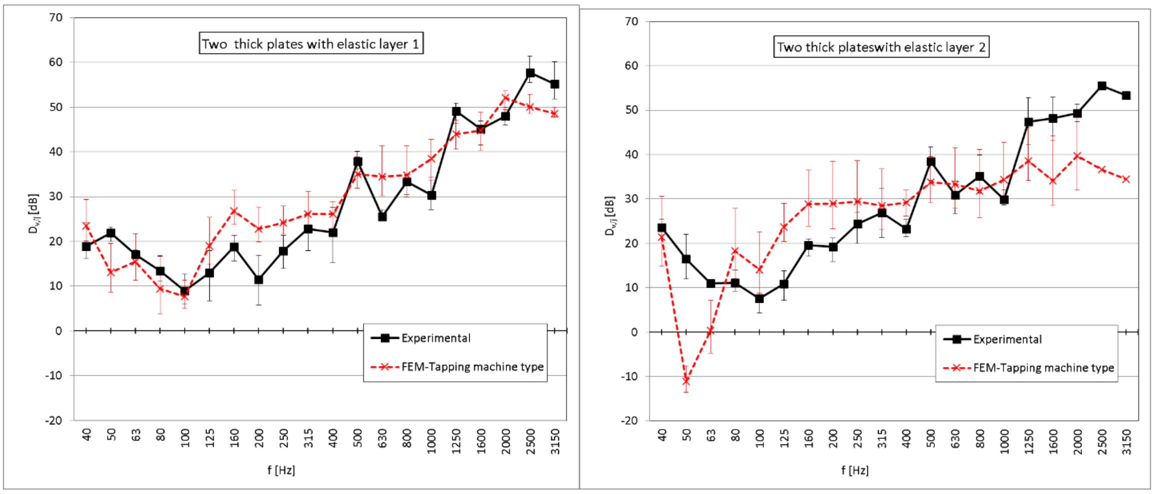

Figure 2. *Velocity level difference: two thick plates. Elastic layer 1 and 2. Average of three excitations and maximum and minimum values.*

The values of the weighted normalized impact sound pressure level, $L_{n,w}$, according to EN ISO 717-2:2013, for the different types of joints, are shown. The experimental mean values and the FEM mean values, for joints without an elastic layer, differ by less than 2 dB. For elastic-layer joints, the difference between the mean values is between 1 dB and 14.3 dB, though in three out of four cases it does not exceed 7 dB.

The use of finite elements models with 2D elements proved to be adequate and a good approximation was obtained from both experimental and finite element analysis results. This is a step forward in the use of virtual models in vibroacoustic study.

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DAMAGE DETECTION IN SLENDER STRUCTURES BASED ON A HYBRID SYSTEM OF SUPERVISED LEARNING ALGORITHMS AND MODEL UPDATING TO ANALYZE RAW DYNAMIC DATA

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Keywords: Structure health monitoring, Structural damage detection, Artificial Neural Network, Model Updating, Supervised learning algorithms

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ABSTRACT

Structural alteration can be caused by many factors, such as design and constructive problems, operational conditions, severe natural events, natural aging, etc. In most cases, modifications in structures may be associated with damage, and when damaged, the material and geometric characteristics of a structural component change, affecting the stiffness and stability of the structure.

Conventional damage assessment methods, which depend on periodic visual inspection of structures are not efficient especially for complex structures as they require highly-trained labor and easy access to the monitored structural members. Therefore, a significant amount of research has been conducted to develop automated local and global structural health monitoring techniques [1]. Structural Health Monitoring (SHM) allows detecting the presence of damage at an early stage, thus reducing maintenance costs and ensuring more comfort and safety to the users.

Vibration-based damage detection methods are used to assess the overall performance of the monitored structure by translating its vibration response measured by a network of accelerometers into meaningful indices reflecting the actual condition of the structure [2]. Within these vibration-based techniques, either a parametric (model-based) approach can be adopted, which consist in identifying the structure model at a certain status and comparing it with the model of the undamaged structure in order to identify and locate the modifications suffered, or a non-parametric (data-based) approach, which employs statistical means to identify the damage directly from the measured signals.

Computational learning methods are considered useful tools for solving structural damage assessment problems. These algorithms work as classifiers that try to identify damage levels using as input data characteristics extracted from dynamic responses. A popular computational intelligence technique used to address the issue of structural damage detection is the Artificial Neural Networks (ANN), as it can be seen in [3,4].

One of the problems of data-driven techniques lies in the need of available data from both the damaged and undamaged structure, which is not always feasible in real structures. To prevent this, the approach adopted in this paper has consisted in the implementation of a hybrid system for the

identification of damage in a structure, with the aim of locating this damage and identifying the type of damage suffered and its severity. In this way, the model of the structure is used to generate data from the undamaged and damaged cases and this data is fed to a machine learning algorithm capable of classifying the structure's status based on the temporary acceleration signals

Experimental validation of this system has been performed on a laboratory scale model of a 4-story shear building. The scheme of the implemented algorithm is shown in Figure 1, the structure model obtained from a modal identification is used to generate data of the undamaged structure and with different levels of damage. Two artificial neural networks are used, the first one to locate the presence of damage based on the temporal acceleration signals. And, once the floor or floors where the modification has occurred is defined, specific training data is generated to identify the type (change in stiffness, mass or both) and severity of the damage suffered.

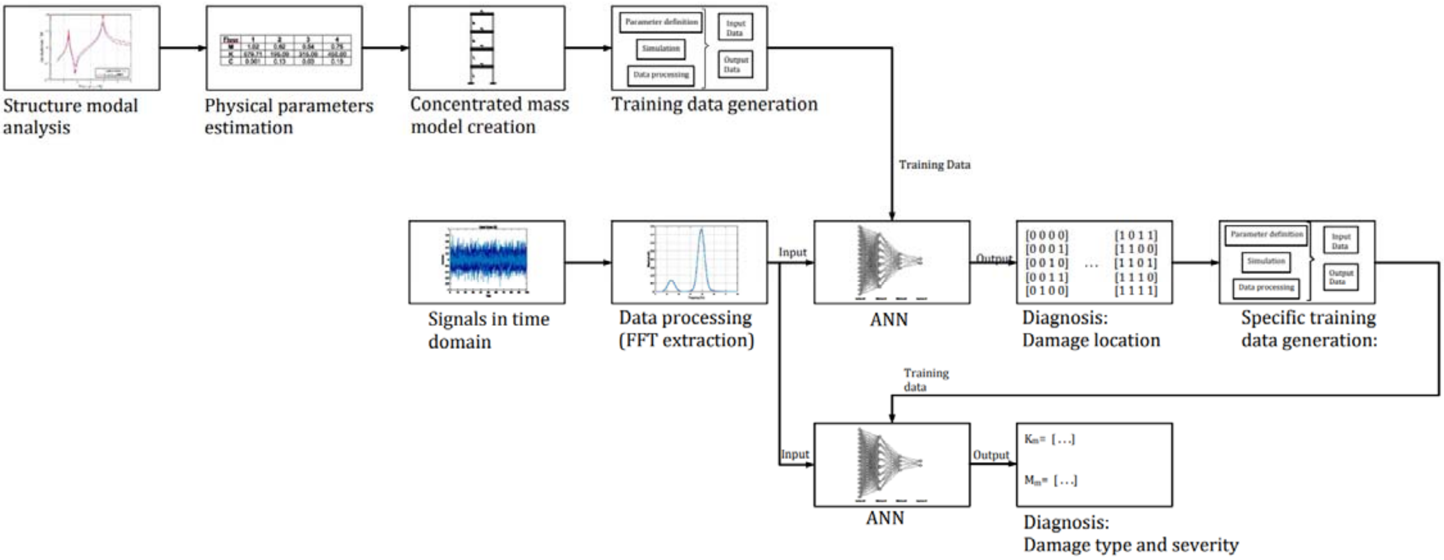

Figure 1: Scheme of the proposed methodology

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ESTIMATION OF SHORT-TERM DEFLECTION IN RC BEAMS USING EFFECTIVE MOMENTS OF INERTIA

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Keywords: Equivalent inertia; immediate deflection; tension stiffening.

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ABSTRACT

International practice codes for the design of RC structures use linear elastic formulation to calculate deflections by double integration of curvatures along the length of the element. If the member is cracked, different formulae of interpolation between uncracked and fully cracked states have been proposed in order to account for the concrete tension stiffening effect. A comparison of the short-term deflections obtained from two widely used procedures is carried out.

The deformation of the RC member is mainly due to the deformation of the B regions and the study of deflections is done by means of a differential equation that connects the curvature with the deflection of an elastic beam under flexure:

$$y''(x)=\frac{d^2y(x)}{dx^2}\approx\phi(x)=\frac{M(x)}{EI} \tag{1}$$

where x is the coordinate along an axis that coincides with the longitudinal axis of the member, $y(x)$ is the deformed shape of the element due to the bending moment distribution $M(x)$, $\phi(x)$ is the curvature of the section placed at x, E is the modulus of elasticity of the material and I is the moment of inertia of the section. In Eq. (1) it is assumed that deflections are small enough and that the beam theory is applicable.

When dealing with RC structures, it is common to assume properties of sections transformed to concrete and $E=E_c$. However, an important issue arises when employing Eq. (1) to compute deflections: what is the moment of inertia I to be used in calculations? If the bending moment along the member is lower than the cracking moment, $M(x)\leq M_{cr}$, the moment of inertia I to be used would be that which corresponds to the transformed uncracked section, I_{uncr}. Conversely, if along a portion of the RC member $M(x)>M_{cr}$ then some sections of the member within that length would be cracked and their moment of inertia would be I_{cr}. The mean contribution of concrete in tension in the cracked areas (where $M(x)>M_{cr}$) is known as the tension-stiffening effect, which indicates the capability of concrete between cracks to carry the tensile stress through the concrete-rebar interaction, contributing to the tensile stiffness of RC structures [1,2]. Therefore, an intermediate value of I between I_{cr} and I_{uncr} needs to be used to calculate short-term deflections.

The present work provides a study on the value of *I* to be introduced in Eq. (1) in order to get an accurate computation of the short-term deflection of an RC member. In order to do so, the method based on the effective moment of inertia proposed by Branson [3] is compared with the one proposed by EC2 [4]. The comparison is applied to two experimental campaigns available in literature (Al-Zaid et al. [5] and Washa and Fluck [6]).

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AVOIDING FAILURE PROPAGATION IN STEEL TRUSS BRIDGES: A CASE STUDY

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Keywords: Robustness, Steel Bridges, Finite Element Modelling, Structural Health Monitoring.

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ABSTRACT

The Hintze-Ribeiro Bridge (Portugal 2001), I-35W Bridge (Minneapolis 2007), I-5 Skagit River Bridge (Mount Vernon, Washington State 2013) and the Mexico City Overpass Bridge (Mexico 2021) are some of the most recent examples of catastrophic collapses of bridges around the world [1]. The common feature that linked these collapses was the disproportionate effect due to local failures the structures could not adequately absorb [1][2][3]. When it comes to riveted steel bridges, the problem of local damage triggering progressive failures is of paramount importance, especially considering that these structures were mostly constructed at the beginning of the 20th century and are now subjected to considerably heavier traffic than they were designed for, often receive poor maintenance, and suffer from environmental ageing.

-a -b

Figure 1. *Aerial view of the steel bridge (-a) and detail of the Finite Element model developed (-b).*

The present work discusses the results provided by an extensive numerical study involving linear static analysis (LSA) carried out on a riveted steel bridge in Valencia (Spain). This structure is a Pratt truss-like steel isostatic span dating back to 1913-1915 with riveted connections (**Figure 1-a**). The data obtained in the present case study are particularly valuable since they can easily be extended to draw conclusions and suggest recommendations for similar bridges, namely: geometry, construction technique and environmental exposure. A detailed 3D finite element model was proposed using solid brick finite elements and developed on Abaqus commercial software (**Figure 1-b**). The aim was to

obtain a detailed numerical model that accurately represented the structural behaviour of riveted steel bridges that could be used to analyse the robustness of this type of structure in different damage scenarios. The model was calibrated in the static and dynamic range based on several experimental results comprising: (i) the natural frequency from full-scale laboratory tests ([4][5]), and (ii) strain readings from the available experimental data. After validation, an extensive parametric study was carried out considering different groups of damage scenarios by deactivating single structural elements of the bridge prior to the passage of a train, involving: lateral primary elements (e.g. upper and lower chords, diagonals), secondary elements (e.g. top and bottom bracings) and primary beams (e.g. cross beams and stringers - **Figure 2**). The results of the train weight and bridge self-weight provided principal stress contour maps and Von Mises stress histories at key points along the structure and the overall deformed shapes of each damage scenario.

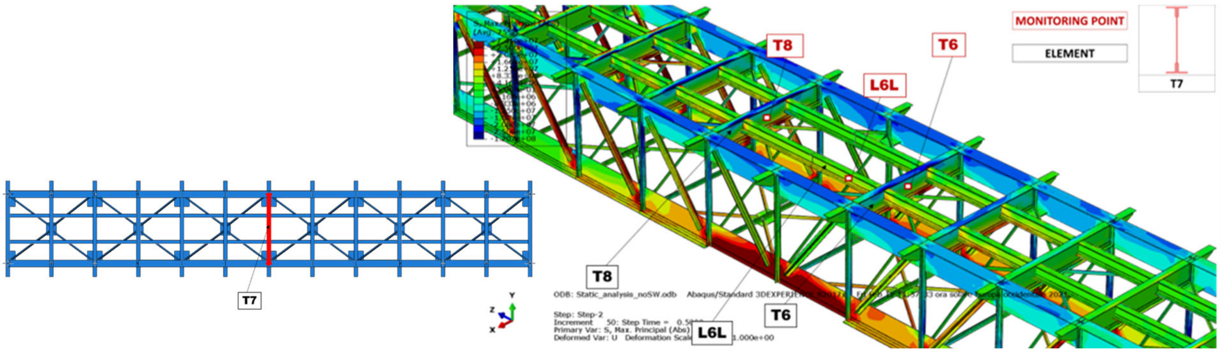

Figure 2. *Preliminary results obtained with the LSA analysis carried out on Abaqus.*

The model allowed: (i) the identification of the most vulnerable elements in the riveted steel bridge in both the undamaged and damaged scenarios, considering traffic loads and self-weight, (ii) the evaluation of the structural response in terms of stress increments produced by the loss of each element, the stress redistribution over intact components, and finally (iii) the robustness of truss-like steel bridges evaluated according to the different alternative load paths activated in the structure after losing different elements.

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THE OCTAHEDRON FAMILY AS A SOURCE OF TENSEGRITY STRUCTURES: STUDY OF THE EQUILIBRIUM CONFIGURATIONS CONSIDERING DIFFERENT FORCE:LENGTH RATIOS

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Keywords: Tensegrity; Octahedron family; Analytical form-finding; Force density method.

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ABSTRACT

Tensegrity structures are pre-stressed pin-jointed self-equilibrated structures composed by compression and tension members (called struts and cables respectively). They were first introduced by Fuller [1] and they have attracted the attention of researchers in the last years due to their lightweight, controllability, deployability and ingenious forms. Due to this, tensegrity structures has been applied in a wide diversity of fields as civil engineering [2], aerospace [3], biology [4] and robotic [5].

A tensegrity family is a group of tensegrity structures that share a common connectivity pattern [6]. It is considered that a tensegrity belongs to a family if it has as folded forms all the lower members of the family. The octahedron family is composed by three members: the octahedron, the expanded octahedron and the double-expanded octahedron [6]. The first member of the family is the octahedron (see Figure 1.a), which is composed by 15 members (12 cables and 3 struts) and 6 nodes. The expanded octahedron (see Figure 1.b) is the second member of the family, and it has 30 members (24 cables and 6 struts) and 12 nodes. Both tensegrities are well-known tensegrity forms present in numerous works in the literature. The expanded octahedron is the expansion of the octahedron (as it is indicated by its name), in such a way that each node, cable and strut of the octahedron is duplicated during the expansion process. Based on the expansion from the octahedron to the expanded octahedron, Fernández-Ruiz et al. [6] obtained the double-expanded octahedron, the third component of the octahedron family (see Figure 1.c). This new tensegrity form is composed by 60 members (48 cables and 12 struts) and 24 nodes. All the components of the octahedron family are formed by the combination of rhombic cells.

It is interesting to remark that in the case of the three members of the octahedron family represented in Figure 1 only two different force:length ratio (q) values were considered: q_c for cables and q_b for bars or struts (black and grey lines respectively in Figure 1).

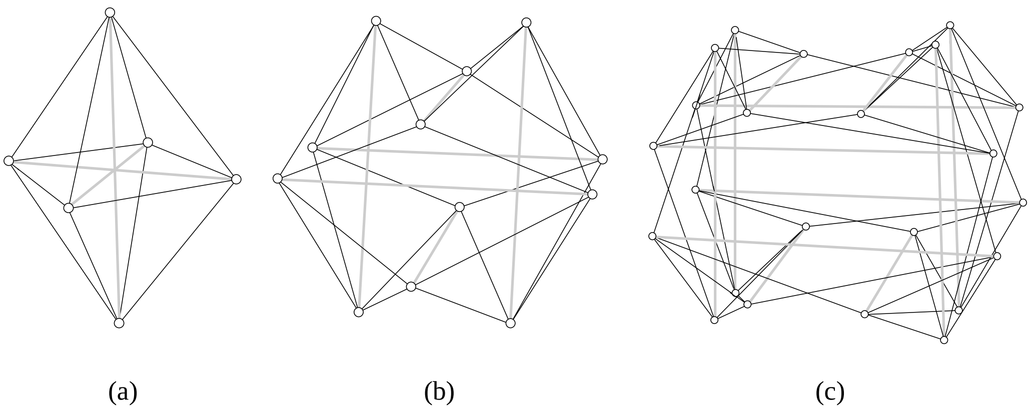

Figure 1. *Octahedron family: (a) octahedron, (b) expanded octahedron and (c) double-expanded octahedron. Black lines correspond to cables and grey lines to struts. Adapted from [7].*

In this work a higher number of possible force:length ratio values have been considered in order to find new members of the family. The values of the force:length ratios which satisfy the super-stability conditions have been computed analytically. New super-stable tensegrity forms of the octahedron family have been obtained. Results show that all of them are members of the octahedron family having as folded forms all the lower members of the family. Finally, based on topological rules, it has been proved that the double-expanded octahedron can be defined from a truncated cube.

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MECHANICAL BEHAVIOR OF DEMOUNTABLE AND REUSABLE JOINTS WITH WELDED STUDS

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Keywords: demountable joints; welded studs; joint characterization.

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ABSTRACT

The use of demountable structures has some advantages as the flexibility to change location, the reuse or positive environmental and economic effects [1]. However, the use of hollow structural sections in beam-to-column demountable joints is not widely extended due to difficulties executing and modelling the joint. The impossibility of access to the inner part of the tube leads to a difficulty of executing a bolted joint. Furthermore, Eurocode 3-1.8 focussed on design of joints does not include design equations to obtain the stiffness and resistance of beam-to-column joints formed by hollow columns and open-section beams. Therefore, the design of steel structures with this kind of connections requires carrying out numerical simulations or experimental test to obtain the mechanical properties of the joints. A simple joint, but hardly studied in some previous studies [2]–[4], is the demountable beam to column joint which consists of welding threaded studs to the tube wall, as it is showed in Figure 1.

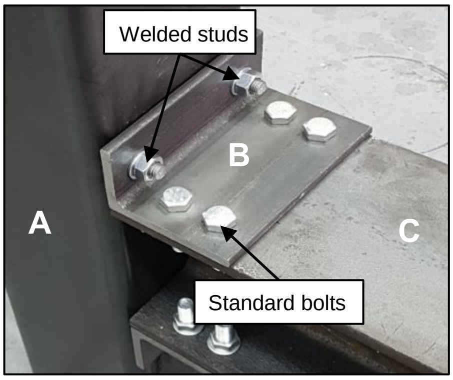

Figure 1. *Example of the beam-to column joint assembled with threaded welded studs. A: hollow-section column. B: angle cleat. C: open-section beam.*

In this paper, the stiffness and resistance of joints with threaded welded studs are studied. Initially, the mechanical properties of 4.8 grade studs and of 8MnSi7 studs (commercially designed as K800) welded to S355J2H tubular columns are assessed. The mechanical properties of the different regions of welded studs were estimated in two different ways: by using Small Punch Test (SPT) [5] and by using the relationships between hardness and strength proposed by some authors. The properties of the base material of the studs and columns were compared with those obtained in tensile tests. The Murphy and Arbtin´s approach is selected [6] when the ultimate strength of the studs is considered.

The K800 tested studs were used to assembly six different configurations of beam-to-column joints and they were tested until failure and classified by its rotational stiffness, following the Eurocode 3 [7] proposal for stiffness boundaries. According to the rotational stiffness obtained in the tests and showed in Table 1, the six joints can be classified as semi-rigid. A simplified component-based approach was also empirically calibrated with the experimental results. Finally, the material properties of the previously tested K800 studs were used to estimate their failure and the moment resistance of the joint, which is dominated by the failure of the studs. The observed failure mode was punching shear in the column when the tube had a thickness of 6 mm.

Table 1. Beam to column tested joints. Results of the experimental tests.

Joint	Column	Beam	$S_{j,ini,EXP}$ [kNm/rad]	$S_{j,ini}$ from empirical approach [kNm/rad]	Observed failure mode	$M_{Rj,EXP}$ [kNm]	M_{Rj} from the stud analytical failure [kNm]
SMS1	SHS200×6	HEB200	1973	1902	Punching shear	22,14	23,26
SMS2	SHS200×8	HEB200	2801	2903	Tension studs	34,71	31,34
SMS3	SHS200×10	HEB200	3671	3567	Tension studs	31,65	32,94
SMS4	SHS200×6	IPE300	2050	2106	Punching shear	30,37	32,55
SMS5	SHS200×8	IPE300	3795	3690	Tension studs	40,99	42,62
SMS6	SHS200×10	IPE300	4945	5049	Tension studs	41,34	42,57

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PROGRESSIVE COLLAPSE ASSESSMENT OF PRECAST REINFORCED CONCRETE STRUCTURES USING THE APPLIED ELEMENT METHOD

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Keywords: Robustness, Extreme events, Precast concrete, Column removal, Applied Element Method (AEM)

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ABSTRACT

The progressive collapse of structures has attracted considerable research interest in recent years [1]. Understood as the process by which initial local damage sets in motion a chain of failures that can lead to disproportionate or total collapse, it is a phenomenon that can often be triggered by abnormal loading caused by extreme events, which all types of buildings may be exposed to. There exist several known occurrences of progressive collapse which have led to grave negative consequences for society such as the Ronan Point collapse in London (1968), the collapse of the Twin Towers of the World Trade Center in New York (2001), and that of the Hard Rock Hotel in New Orleans (2019).

Precast concrete components are being increasingly used in construction due to significant advantages in terms of cost-effectiveness, quality assurance and durability. However, the specific features of this structural typology make them particularly vulnerable to extreme events since they consist of distinct elements connected together and therefore exhibit clear lines of weakness at the joints [2]. Despite this apparent vulnerability, there have been very few studies on the progressive collapse of precast concrete structures when compared to research on cast-in-place and steel-composite structures.

Numerical models calibrated based on experimental results are one of the most promising tools for better understanding the response of precast concrete structures to accidental actions since they allow them to be studied under a wide variety of loading scenarios. However, the obtention of accurate results with respect to the response of critical parts (joints) using conventional models based on the Finite Element Method (FEM) presents several important challenges. Primordially, it requires very detailed and tedious modelling of the joints which may in turn require the definition of parameters that cannot be easily determined experimentally.

A novel numerical modelling technique that emerged in the late 1990s and known as the Applied Element Method (AEM)[3] presents several advantages for studying the progressive collapse behaviour of precast concrete structures. By combining traits of both the FEM and the Discrete Element Method (DEM), it has been demonstrated that AEM is able to accurately model structural collapse behaviour through all stages of loading including elastic response, crack initiation and propagation in brittle materials, reinforcement yielding, element separation, and even collision. This is achieved through an efficient formulation which employs small elements connected by normal and shear springs distributed on their faces.

This paper presents the preliminary results of simulations performed using the AEM of a real-scale two-storey precast concrete test structure that will be specifically built and tested in order to better understand the progressive collapse resistance of this structural typology. The experimental program of

the real-scale structure involves three individual tests, each intended to simulate the removal of a specific column as shown in Figure 1.

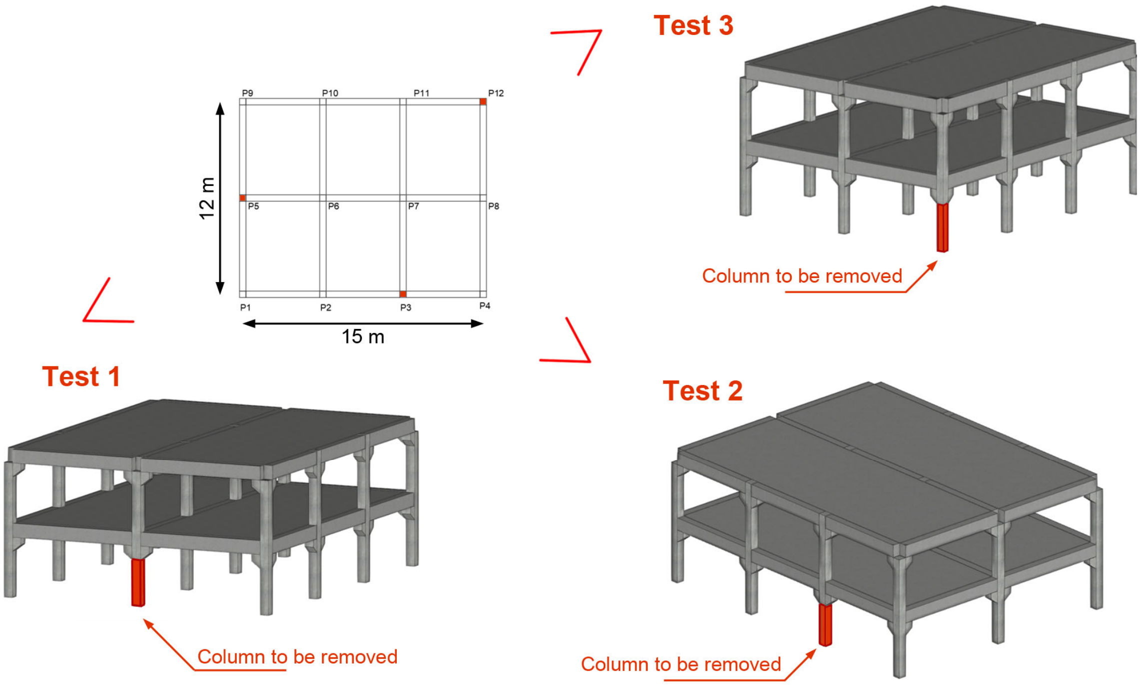

Figure 1. *Column removal scenarios to be investigated during real-scale experimental program.*

These models were created with the aim of creating a detailed numerical representation of the planned experimental tests in order to identify the most important parameters that need to be monitored during each test. The results of the different simulations are presented and the corresponding monitoring strategies are discussed.

After the completion of the experimental campaign, the model will be calibrated and used to perform parametric studies to better understand the response of precast concrete structures under different accidental loading scenarios.

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ANALYSIS OF SPHERICAL SHELL STRUCTURES USING THREE-DIMENSIONAL FINITE ELEMENTS FORMULATED IN GENERAL CURVILINEAR COORDINATES

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Keywords: Shell structures, finite elements, general curvilinear coordinates.

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ABSTRACT

Shell structures are structures of great beauty that have been present for many centuries in our architecture and civil works. The calculation of this type of structures is complex and we only have analytical solutions to the problem for certain types of loading, boundary conditions and specific geometries. In addition, in general, to obtain solutions of this type we assume that they work in a membrane state, a true hypothesis for well-designed shells, but a little refined one to study certain areas of the shell structure, such as the changes in cross-sections, proximity to the supports or to the concentrated (punctual) loads etc. where the appearance of the flexure phenomena becomes unavoidable.

In this work, we propose the study of spherical shells by means of the three-dimensional finite element of 20 nodes but formulated in spherical coordinates, Fig. (1). The author's experience with this type of elements is very positive both in terms of computational cost and the non-appearance of shear or membrane locking for thin thicknesses, with an adequate treatment of this element.

One of the novelties in the formulation of this finite element is the expression of the deformation-displacements relations in a general curvilinear reference system, [1],

$$
\begin{aligned}
\varepsilon_{\alpha_i} &= \frac{\partial}{\partial \alpha_i}\left(\frac{v_i}{\sqrt{h_{ii}}}\right) + \frac{v_n}{\sqrt{h_{nn}h_{ii}}}\frac{\partial\sqrt{h_{ii}}}{\partial \alpha_n} \\
\gamma_{ij} &= \sqrt{\frac{h_{ii}}{h_{jj}}}\frac{\partial}{\partial \alpha_j}\left(\frac{v_i}{\sqrt{h_{ii}}}\right) + \sqrt{\frac{h_{jj}}{h_{ii}}}\frac{\partial}{\partial \alpha_i}\left(\frac{v_j}{\sqrt{h_{jj}}}\right)
\end{aligned} \tag{1}
$$

where ε_{α_i} are the normal strains, γ_{ij} are the shear strains , h_{ij} are the components of the metric tensor in the shell space , α_i are the general curvilinear coordinates of the reference shell surface and v_i are the displacements. These expressions are written in terms of the physical components of the displacements so they can be directly interpolated by the shape functions.

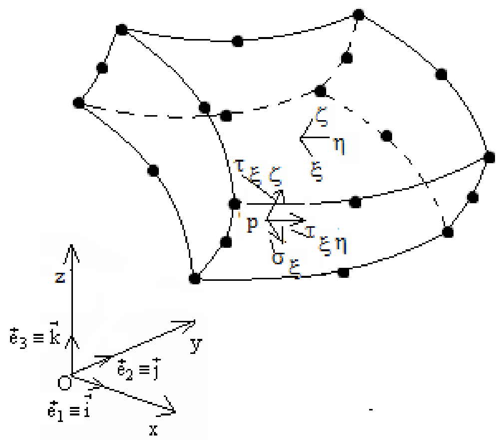

Figure 1. *Finite Element of 20 nodes. The Cartesian coordinates system and the representation of the isoparametric system* $\{\zeta \quad \eta \quad \xi\}$.

The formulation of the stiffness matrix of the element is achieved in a similar way to the classical formulation, but taking into account the three existing reference systems: the Cartesian system, the general curvilinear one referred to the medium surface, and the isoparametric one. For spherical shells, the relation between the unit vectors of the Cartesian system and those tangents to the reference surface is, [2],

$$\begin{bmatrix} \vec{t}_r = \dfrac{\vec{h}_r}{|\vec{h}_r|} \\ \vec{t}_\vartheta = \dfrac{\vec{h}_\vartheta}{|\vec{h}_\vartheta|} \\ \vec{t}_\varphi = \dfrac{\vec{h}_\varphi}{|\vec{h}_\varphi|} \end{bmatrix} = \begin{bmatrix} \cos\varphi\cos\vartheta & \cos\varphi\sin\vartheta & \sin\varphi \\ -\sin\vartheta & \cos\vartheta & 0 \\ -\sin\varphi\cos\vartheta & -\sin\varphi\sin\vartheta & \cos\varphi \end{bmatrix} \begin{bmatrix} \vec{\imath} \\ \vec{\jmath} \\ \vec{k} \end{bmatrix} = C \begin{bmatrix} \vec{\imath} \\ \vec{\jmath} \\ \vec{k} \end{bmatrix} \qquad (2)$$

where $\{\vec{t}_r \quad \vec{t}_\vartheta \quad \vec{t}_\varphi\}$ are the tangent vectors to the spherical shell. This change-of-basis matrix intervenes in the formulation of the stiffness matrix of the finite element, $[\boldsymbol{k_e}]$, through the jacobian matrix, $[\boldsymbol{J}]$,

$$[\boldsymbol{k_e}] = \int_{-1}^{+1}\int_{-1}^{+1}\int_{-1}^{+1} [\boldsymbol{B}]^T[\boldsymbol{D}][\boldsymbol{B}]det[\boldsymbol{J}]d\xi d\eta d\,\zeta \qquad (3)$$

Where $[\boldsymbol{B}]$ is the strain- displacement matrix, and $[\boldsymbol{D}]$ is the elastic constitutive matrix. In case of wanting to perform modal analysis, we follow similar rules for the formulation of the mass matrix of the element.

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MODELLING VARIABLE PEDESTRIAN DYNAMIC LOADING FACTORS INDUCED ON RIGID SURFACES

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Keywords: pedestrian load, dynamic load factors, vibration serviceability, rigid surfaces, load modelling.

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ABSTRACT

Starting from the previously developed models of variable walking speed [1] and spatiotemporal parameters in a walking trial [2], this study derived a complementary model of variable dynamic loading factors (DLFs) corresponding to the first five dominant harmonics and subharmonics of the walking force. The force model is based on the force signals from fifty test subjects walking on an instrumented treadmill. Each signal was normalised to body weight and cut into segments corresponding to both step and stride intervals. Each segment corresponding to a step interval was run through the fast Fourier transform (FFT) algorithm to extract the amplitudes (DLFs) of the first five dominant harmonics and subharmonics. Both the mean and coefficient of variation of DLFs are described as the product of two factors. The first represents the deterministic dependence on the step speed and is modelled as a second-order polynomial. The second factor reproduces the random inter-pedestrian variability of the DLFs, which is defined by a Beta distribution.

Comparison with other experimental studies reveals a good agreement of results. Fig. 1 shows widely popular deterministic DLF models of the first four walking harmonics derived by Kerr using single footfall GRFs recorded by a force plate [3]. Kerr fitted a third order polynomial curve to DLFs of the first harmonic as a function of walking frequency. DLF values of the other three higher order harmonics were found independent from the walking frequency, thus modelled as constants. Fig. 1 also shows synthetic DLF data from this study corresponding to the Kerr's model. They include only deterministic components of DLFs.

The plots relevant to the first harmonic show the same growing trend of DLFs as walking frequencies increase up to 2.3 Hz. The two curves run in parallel with a small offset of approximately 0.05. However, the present model is still within the 95% confidence bounds. Above 2.3 Hz, the DLF follow two opposite trends. Kerr's model suggests decreasing while the present study shows increasing DLF amplitudes with further increments of walking frequency. Nevertheless, Kerr himself noted that his results above 2.2 Hz are likely to be untrue due to a great level of data scarcity. Considering different experimental setups and the large scatter in the data points in both studies, the models generate fairly close results. The present study derived the DLFs from continuously measured treadmill walking including many successive footfalls rather than just a single footfall as collected by Kerr.

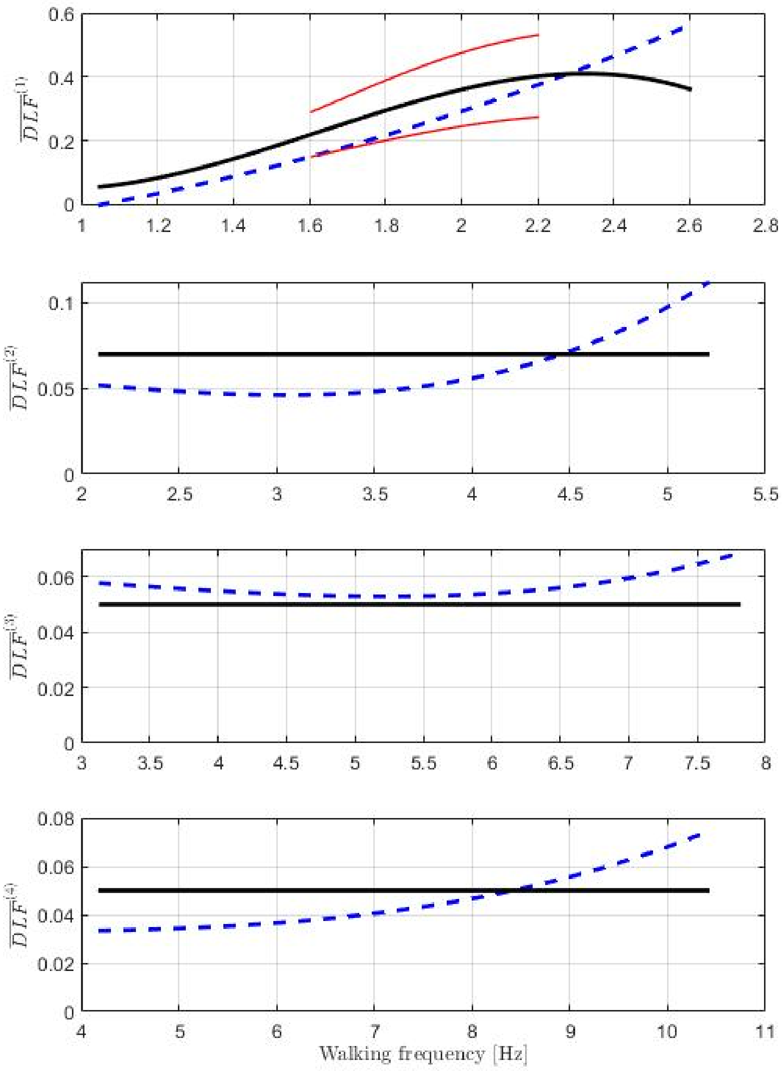

Figure 1. *Determinist component of DLF vs walking frequency. Solid lines: Kerr's study. Bold line: averages, Fine line: 95% confidence bounds. Dashed lines: present study..*

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HORMIGÓN DE MUY ALTA RESISTENCIA (HMAR) CON SUSTITUCIÓN DE RESIDUOS EN MATRICES CEMENTOSAS

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Palabras clave: *Hormigón de muy alta resistencia, residuos, resistencia a tracción y compresión, FCC, GGBFS*
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RESUMEN

The Campo of Gibraltar has one of the most significant industrial points in Andalusia, generating a significant amount of solid waste that is later taken to landfills. By incorporating them into civil engineering in cementitious matrices, said residues are valued giving them a new possibility of handling in very high resistance concrete (HMAR), being used in turn for the execution of new uses such as the rehabilitation of the system maritime by improving and strengthening the port work, as well as the consolidation of the industrial infrastructure of the area or on the maritime land coastline. The efficiency of concrete structures necessarily leads to an improvement in their overall performance not only from a structural point of view but also from a sustainability point of view. [1–3]

The proposed concrete model has the quality of being supported by simple and well-known laws for each of its components. Three different dosages were carried out, an initial standard, the replacement of 5% of petroleum cracking catalysts (FCC) and a third where 5% of FCC and blast furnace slag (GGBFS) were replaced by cement.

Once the study of the tests had been carried out, the results of the hardening curve obtained were the following:

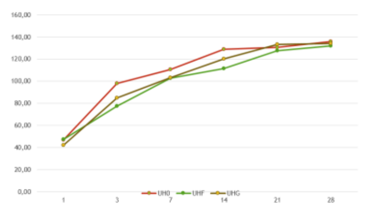

Figure 1. *28 day compression strength*

It is observed that at early ages the resistant capacity is very high, it is observed that with the replacement of these residues at 28 days it reaches the same resistant capacity as without substitution.

Regarding the flexural-tensile strength at 28 days, the result is the one shown in the graphs:

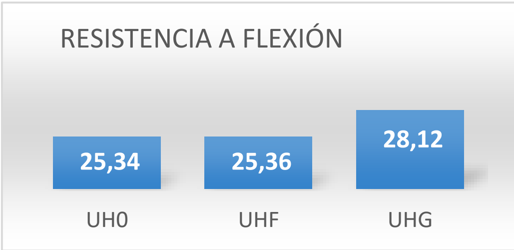

Figure 2. *Tensile strength at 28 days*

It is observed that the addition of 5% FCC and 5% addition of GGBFS considerably increases the flexural strength with respect to the reference concrete.

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COST-EFFICIENT SURROGATE MODELING OF THE ELASTIC PROPERTIES OF FIBER-REINFORCED COMPOSITES

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Keywords: Surrogate modelling, Composites, Homogenization, RVE, Numerical homogenization.

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ABSTRACT

Owing to the enormous potential of polymer nano/micro-composites for the design of high performance and multifunctional structures, their implementation in aircraft, aerospace, automotive and construction industries has undergone a sustainable growth in recent years [1]. Prominent examples of this trend are the Boeing 787 and Airbus 350 transport aircrafts, in which composites contribute over 50% of the total structural mass. Fueled by the progressive cheapening of their production along with recent advances in the development of carbon-based nano-modified composites and additive manufacturing, the global composite market is projected to reach USD 160.54 billion by 2027 at a compound annual growth rate (CAGR) of 7.6% between the period 2020-2027 [2].

The implementation of such composites into engineering systems implies a higher level of complexity in the design, requiring a further analysis of the constituent materials and their interaction. The material properties of these composites depend upon many factors such as the volume fraction, filler orientation, distribution, and geometry of the fillers, as well as their interaction with the host matrix material. A wide variety of homogenization techniques has been proposed in the literature, ranging from analytical mean-field homogenization approaches to numerical techniques, using finite element and boundary element methods, atomistic-based continuum mechanics, molecular dynamics simulations, Fast Fourier Transform techniques, just to mention a few [3,4]. Approaches using the finite element method for the virtual testing of representative volume elements (RVEs) under periodic boundary conditions have become particularly popular due to their flexibility to model a large variety of microstructures. Such approaches allow to accurately represent the actual geometry of the inclusions, and the number of assumptions and simplifications of the underlying microstructure is kept minimal. Nevertheless, the mesh densities required to accurately represent the microstructure usually imply considerable computational burdens, limiting their applicability when modelling the response of full-scale macro-structural systems.

In order to tackle these limitations, this work proposes the use of adaptive sparse Polynomial Chaos Expansion (PCE) as a computationally efficient surrogate model to bypass the estimates from the numerical homogenization of a RVE of short fiber-reinforced polymer composites to be used in full scale macro structural systems. Assuming the microstructural properties of interest (e.g. filler geometry, volume fraction, orientation) as independent random variables arranged in a vector $\boldsymbol{x}$, the PCE representation of the effective properties y obtained from the numerical homogenization of a RVE (Fig. 1) is defined as an expansion of y onto an orthogonal multivariable polynomial basis as [5]:

$$y = M(\boldsymbol{x}) = \sum_{\boldsymbol{\alpha}\in\mathbb{N}^M} a_{\boldsymbol{\alpha}}\Psi_{\boldsymbol{\alpha}}(\boldsymbol{x}), \tag{1}$$

with $a_{\boldsymbol{\alpha}}$ being unknown deterministic coefficients, and $\Psi_{\boldsymbol{\alpha}}$ are multivariate polynomials built up by a family of orthogonal polynomials as:

$$\Psi_{\boldsymbol{\alpha}}(\boldsymbol{x}) = \prod_{i=1}^{M} \Psi_{\alpha i}^{(i)}(x_i)\,, \tag{2}$$

where the multidimensional index notation $\boldsymbol{\alpha} = [\alpha_1, \dots, \alpha_M]$ is adopted. The PCE coefficients can be estimated by least squares regression on a set of N realizations of the input variables, also referred to as the experimental design (ED). In this work, numerical results and discussion are presented to demonstrate the ability of the proposed methodology to train accurate surrogate models using experimental designs limited in number and, consequently, with affordable computational efforts. Finally, a surrogate model-assisted 3D FEM of a full-scale structural system incorporating composites with heterogeneous microstructures is presented to demonstrate the usefulness of the proposed approach for the simulation of macro-composite structures and material optimization.

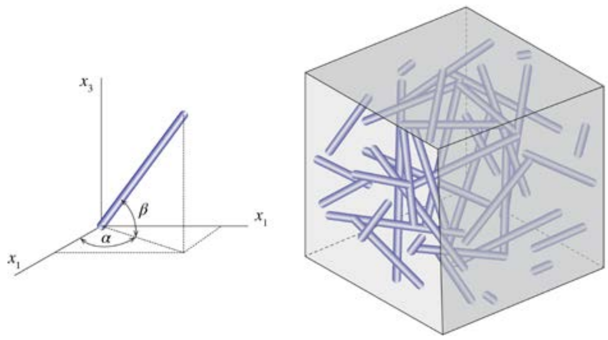

Figure 1. RVE of a short fiber-reinforced composite material, with α and β being the Euler angles used to represent the relative orientation of the fillers.

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ANALYSING THE PERFORMANCE OF DIFFERENT ALGORITHMS FOR THE BAYESIAN FINITE ELEMENT MODEL UPDATING OF CIVIL ENGINEERING STRUCTURES

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Keywords: Finite Element Model Updating, Modal Domain, Bayesian Inference, Parallel Computing, Civil Engineering Structures

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ABSTRACT

Finite element (FE) models are widely used to determine numerically the modal properties of civil engineering structures. However, these numerical models often give results that differ from the modal properties obtained experimentally, and therefore they need to be updated to better reflect the actual behaviour of these structures. Among the different possible domains, FE model updating of civil engineering structures is usually performed under modal domain.

To date, FE model updating of civil engineering structures have been mainly performed via the Maximum Likelihood approach. Although this approach has been applied successfully for this purpose, it presents the following shortcomings: (i) it does not allow charactering probabilistically the physical parameters of the FE model, (ii) the regularization terms considered to control the complexity of the updated model are not always adequately defined, and (iii) the solution of the FE model updating problem may not be unique under this approach (especially for complex models).

In order to overcome these limitations, the Bayesian approach has been proposed. This approach is especially designed to deal with the uncertainties associated with the estimation of the main physical parameters of the FE models. The Bayesian approach is usually implemented via numerical methods, denominated sampling methods. According to this, the FE model updating procedure consists of determining an efficient sampling of each considered physical parameter of the model.

In this manuscript, three sampling techniques, the Metropolis-Hastings (MH) algorithm, the Slice Sampling (SS) and the Hybrid Monte Carlo (HMC) technique, are compared when they are implemented for the FE model updating of a real civil engineering structure, concretely a slender steel footbridge. In order to reduce the simulation time required to solve each updating problem, the different techniques have been implemented under a parallel computing approach. The modal properties of this footbridge

have been determined experimentally via operational modal analysis. The advantages and disadvantages of each technique are determined according to the results of this case-study.

DYNAMIC RESPONSE OF A FOOTBRIDGE WHEN USED FOR A GROUP OF SINCHRONIZED WALKERS

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Keywords: dynamic loading models, serviceability, dynamic simulations, vibrations, modal parameters

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ABSTRACT

For experimental acceleration recordings on a pedestrian footbridge (figure 1) excited by a shaker and also due to the transit of a group of six pedestrians, a synchronized simulated gait at $f_s = 2\,Hz$ is proposed. Using the shaker induced response, an EMA (Experimental Modal Analysis) is carried our to obtain the first eigenfrequencies and modal damping factors. With the second records, a experimental reference is obtained to check the correspondence with the numerical simulation results [1].

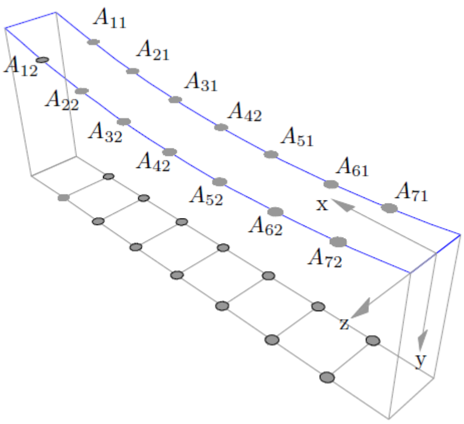

Figure 1. *Footbridge model. Location of the accelerometers.*

For the comparison, the numerical simulations use a simple mechanical model that can reproduce the gait of a group of synchronized pedestrians [2]. The dynamic analysis of the footbridge under a group of six synchronized pedestrians [3, 4] shows acceleration levels that match quite well with those recorded. For the comparison, maximum and minimum values and also RMS values are considered.

Simulations of the dynamic load model DLM2 established by the Eurocode [5] are also carried out, for which several dynamic analyses are performed where the load application section is modified and accelerations are measured at all nodes of the spatial discretization of the footbridge (Figure 2). The acceleration limits set by this standard for the comfort criterion are very demanding, so it is relatively easy to exceed these acceleration levels in several scenarios.

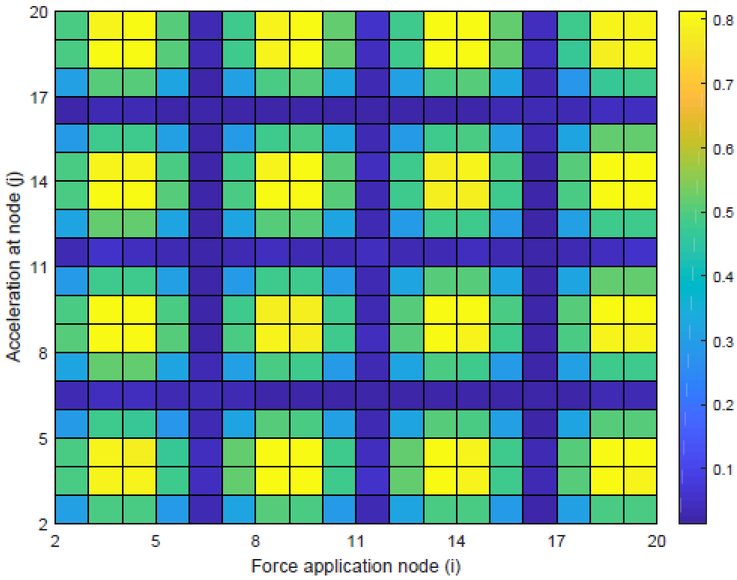

Figure 2. *DLM2 loading model.*

Finally, the pedestrian mechanical model [4] is applied for the dynamic analysis of the footbridge. Again, it is found that it fits the experimental results quite well. Therefore, it is concluded that it is possible to use the excitation generated by the virtual pedestrian mechanical model for the dynamic analysis and estimations in this type of structures.

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COMPOSITE BRIDGE DECK OPTIMIZATION WITH TRAJECTORY BASED ALGORITHMS

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Keywords: Optimization, Structures, Composite bridges, Metaheuristics, Trajectory-based algorithms

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ABSTRACT

Structure's construction is in constant evolution, and process optimization is becoming more and more important for the industry. This optimization translates into the search for a reduction in costs, time and emissions, becoming these criteria minimization objectives in projects in the field of civil engineering in general and especially in those problems related to structural design.

Indirectly to the search for a reduction in emissions or costs, these optimization processes seek the maximum harnessing of the of the structural elements materials. As a consequence of this, new geometries are proposed in bridge sections that allow better performance from the structural point of view. This is common in structural elements such as composite bridges in which the deck materializes by means of steel plates welded together to form the final resistant section. In addition, this type of deck, since its cross-section is mainly composed of steel, stands out for the great recycling capacity of its components [1].

This type of deck has already been the subject of optimization in simpler works in which a simply supported beam structural system was proposed and whose loads corresponded to those of a footbridge, that is to say, whose destination was the passage of people [2]. In addition, other studies have carried out the optimization of some types of composite deck geometries, having carried out the optimization through the use of swarm algorithms [3].

Currently, the field of study of structural optimization is booming since, with the growth of computational capacity, it is possible to implement more complex heuristic and metaheuristic algorithms that allow finding optimal solutions in a reasonable analysis time. These heuristic methods, although they do not guarantee the best solution, do reach values very close to it. The success of these algorithms is greater the closer the solution is to the global optimum, which is why the algorithms sometimes accept worse solutions in order to avoid local optima [4], [5].

The present work consists of the approach and development of an optimization problem for a composite bridge deck. For this purpose, the modeling of this element has been carried out considering a continuous beam structural system with inner cells in the cross section. The load distribution is the

one defined by IAP-11, corresponding to the loads due to the traffic of a road bridge. To carry out the optimization, metaheuristic algorithms based on trajectories have been used, searching for the optimal value considering the cost of the element as the objective function. The problem considers both geometric variables and the characteristics of the materials that compose it.

This work seeks to verify that the addition of cells in the cross section is structurally safe and economically feasible. For this purpose, a method previously used in the field of optimization of structural elements that has shown a high efficiency in achieving results with respect to the search for optimal solutions is carried out. This work will open the door to the approach of more complex problems of optimization of composite bridges and the obtaining of conclusions with respect to the most determinant design factors of these elements.

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NEUTROSOPHIC LOGIC APPLIED TO THE MULTI-CRITERIA EVALUATION OF SUSTAINABLE ALTERNATIVES FOR EARTH-RETAINING WALLS.

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Keywords: Sustainability, Retaining walls, Neutrosophic logic, AHP, Multi-Criteria Decision Making

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ABSTRACT

The serious threats to the planet are forcing us to make important decisions for the future. The global climate emergency is a reality and from the construction sector we must be able to conceive buildings from a responsible perspective with society and the environment. The Sustainable Development Goals (SDG) adopted in 2015 by the United Nations set specific targets to be achieved in the next 15 years. Specifically, SDG-9 calls for *"building resilient infrastructure, promoting sustainable industrialization and fostering innovation"* which requires a shift in conventional design practices. Construction is globally among the main environmental and economic stress activities that compromise our society, being the cement industry the one that generates one of the greatest impacts [1]. Concepts such as sustainability or circular economy have to be implemented as soon as possible in the construction sector, in general, and in structures, in particular.

With the need to adopt a holistic approach to sustainable design problems, multi-criteria decision making techniques are used, which provide a rational procedure for decisions based on certain information, experience and judgment. However, in real life problems it is difficult to apply, as there is always uncertainty in the assessments or in the comparisons between criteria that are often contradictory. This becomes much more complicated when the decision-maker is not an individual but a group whose members manifest different interests. Zadeh [2] has already pointed out that the ability of an individual to make rigorous and accurate judgments decreases as the complexity of the problem to be addressed increases. This is why many of these methods combine tools such as fuzzy theory, the Monte Carlo method, Grey numbers and, more recently, neutrosophic set (NS) theory. Introduced by Smarandache [3] it constitutes the most advanced generalization of fuzzy logic and intuitionistic logic, being rather difficult to apply in the real engineering domain, since neutrosophic sets are defined on standard and non-standard real subsets. Only in recent years, the theory of neutrosophic sets has reached a sufficient level of development to be used in a practical way in civil engineering problems, being successfully applied in the sustainable design of bridges [4] and in building structures [5].

This paper proposes a different approach with which to evaluate sustainability among different design alternatives for retaining walls, to which an environmental life cycle analysis (E-LCA) was applied in

previous studies [6]. For this purpose, neutrosophic sets (NS) integrated in a group analytic hierarchy process (NAHP-G) are used, which allows capturing the vagueness and uncertainty contained in the judgments issued by the decision makers. The characterization of opinions by means of triangular neutrosophic numbers (T, F, I) is particularly important when a significant number of criteria are involved, since the greater the number of comparisons, the greater the dilution of the decision-maker's attention, leading to judgments that, at the expense of credibility, are less rigorous. The response associated with each alternative is obtained according to the ReCiPe methodology, which calculates the impact score based on three environmental endpoint indicators, namely, damage to ecosystems, depletion of natural resources and damage to human health. The process concludes by transforming the neutrosophic weights to diffuse, and these to scalar weights, thus obtaining the weights with the importance of each criterion. Finally, an MCDM technique is applied to aggregate the different criteria to evaluate the sustainability of the different alternatives.

The aim of this work is to increase knowledge in sustainable design applied to retaining structures, proposing tools to support weighting techniques for multi-criteria decision making. From the methodology it is derived that working in a neutrosophic environment allows to deepen in the field of subjectivity considering the non-probabilistic uncertainties inherent to the vagueness of human thought. From the results, it is obtained the capture of more implicit information in the judgments, which endows the decision making with robustness, rigor and more reliability in comparison, for example, with the conventional AHP.

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NUMERICAL SIMULATION OF HIGH-EFFICIENCY ONE PASS WELDING PROCESS OF THICK PLATES

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Keywords: structural steel, strain hardening, plasticity models, D-Arc welding, thick plates

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ABSTRACT

Fusion welding is one of the cheapest, fastest and most common joining techniques in production. In recent times, there is an increased interest in finding more efficient welding processes of joining thick plates, which is a rather interesting topic in large industries like ship building, heavy-duty machinery building, civil engineering, manufacturing of pipelines, etc. The welding of thicker base materials is usually done in multiple passes, which is time-consuming and requires more production preparation procedures. In addition, multi-pass welding induces more heat in welded joints which increases the angular distortion

In this contribution, D-arc [1] methodology is considered for joining of thick plates. It is a relatively new high current welding process that implements the buried-arc-transfer technology, which enables joining metal plates in one pass. The electric arc is established below the surface of molten metal and currents higher than 500 A are applied, which allows for better penetration and higher weld deposits. The former enables welding grooves with smaller opening angles and welding in smaller number of passes, which in return leads to smaller deformations. It is notable to mention that the consumption of CO_2 shielding gas is smaller than in conventional MAG welding, which makes this technology more environmentally friendly. The downside of this technology comes from its advantages, mainly deep penetration and high weld deposit, because it can only be done by means of robots and automation, for which it requires water-cooled torch and durable wire-feeding system.

Experimental investigations presented in the paper are used for validation of the numerical models. They were done by the single-pass butt welding of two plates, using the 7-axis robot from OTC Daihen Corporation, made of S355 J2 + N with dimensions 300 mm X 300 mm X 20 mm [2]. Joint preparation consisted of placing a 3 mm gap between two plates positioned in the same plane in a way that eliminates any possible misalignment. Ceramic backing plate was used in order to achieve better penetration, as well as weld-in and weld-out plates. Full penetration was achieved in a single pass with wire feed speed 12.3 m/min, welding current I = 450 A, arc voltage U = 41 V and welding speed v = 300 mm/min with 100% CO_2 gas with gas flow 25 L/min.

With all its economical and weight-reducing qualities, the fusion welding is a production process which has its own negative side-effects, mainly residual stresses and deformations. The first can be as high as the yielding stress of a material, and the latter are more pronounced in the welding of thin metal sheets. The goal is to predict these consequences using numerical analysis in order to replace expensive and

time-consuming experimental methods of measuring residual stress distributions, which could yield lower research & development costs and more affordable product with same or better quality.

Numerical prediction of residual stresses and deformations will be done in Abaqus and/or Sysweld using sequentially coupled thermo-mechanical computation approach. In order to investigate the influence of strain hardening on the accuracy of estimating residual stresses in structural steel S355, three plasticity models will be used in numerical analysis the isotropic, kinematic and Lemaitre-Chaboche hardening model. In most of the available literature isotropic hardening models without [3] and with phase transformations [4] have been used for the numerical prediction of residual stresses in metal active gas welding of steel plates made of S355.

The material model will be based on experimental data from literature [5] and the validation of numerical model will be done in two steps. The first step will be comparing results to the ones in literature [2], in which a sequentially coupled thermo-mechanical computation approach has been used while utilizing elastic perfectly plastic material model. The second step will be comparing numerical results to data which will be obtained by experimental testing. Measuring the residual stress distribution will be done by using the hole-drilling strain gauge method and/or X-ray diffraction.

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THE APPLICATION OF ARTIFICIAL NEURAL NETWORKS AND REGRESSORS IN OPTIMAL VIBRATION CONTROL DESIGN

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Keywords: regression models, neural networks, CRO-SL, vibration control, vibration isolation, actuator-structure interaction

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ABSTRACT

This paper deals with the application of regression models for the learning of the optimal parameter configuration in an active vibration isolation (VI) system, when the interaction between the isolator system and the base structure is considered. The problem consists of an active VI system, composed by three isolators, situated on the non-rigid supporting structure (Figure 1).

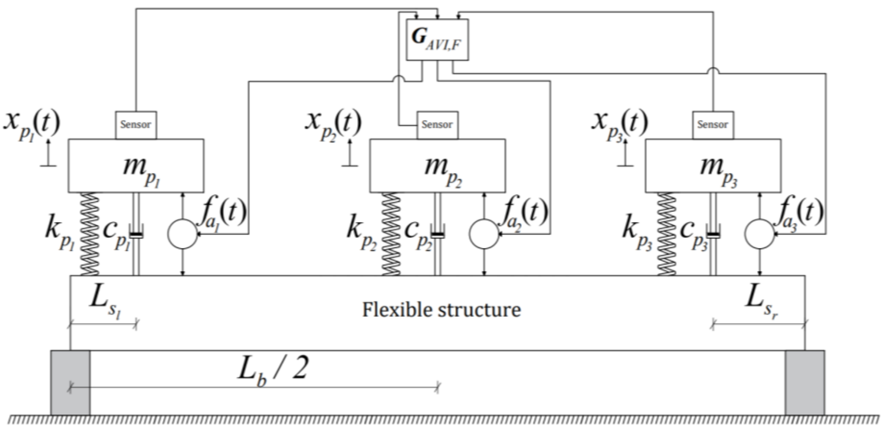

Figure 1: Active VI problem studied in this work.

A dual control objective, which is based on: 1) reducing the vibration level of every platform, 2) maintaining relative position between platforms, is used to optimally design the control law ($\mathbf{G}_{AVI,F}$). In this work, Multiple-Input-Multiple-Output control strategy is adopted, where each active force ($f_{a1}(t)$, $f_{a2}(t)$ and $f_{a3}(t)$) depends on the accelerations measured at all isolator masses (m_{p1}, m_{p2} and m_{p3}). Thus, a total of nine control gains of the 3 by 3 matrix of $\mathbf{G}_{AVI,F}$ can be tuned to achieve the optimal control performance (i.e., the dual control objective is minimized), which can be tuned either by classical [1,2,3] or metaheuristic [4,5] methods.

This work proposes a novel solution to the practical problem of changes in the system parameters, which can be, for example, due to changes in isolator configurations, such as the values of the masses of the devices isolated (m_{p1}, m_{p2} and m_{p3}), or in the isolation locations (L_{sl} and L_{sr}). These system parameter modifications may affect to the controller performance, being necessary the recalculation of the optimal control gains, which also involves a new system identification. Therefore, it would be very useful if the control $\mathbf{G}_{AVI,F}$ are tuned automatically, reducing the costs derived of a new optimum control design.

The aim of this work is to introduce a framework where many scenarios with different mass and frequency ratios between VI and supporting structure are designed. The optimal control gains for these cases are obtained by means of Coral Reefs Optimization algorithm with Substrate Layers (CRO-SL) [6]. The use of these data are used to train ant test different regression models and artificial neural networks [7,8], for which the prediction variables will be mass and frequency rations, and the targets will be the control gains. Therefore, the aim of this work is to explore the possibility of generalizing the optimization of control gain parameters in a MIMO VI system using regression techniques in order to reduce the costs derived of a new the optimum control design of this active VI.

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APPLICATION OF NSGA-II TO DESIGN MULTIPLE MITIGATION DEVICES IN SLENDER STRUCTURES.

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ABSTRACT

In this paper, evolutionary multi-objective optimization methods are applied to assist in the design of passive mitigation devices, commonly referred to as Tuned Mass Dampers (TMD). Metaheuristic algorithms, and more specifically the multi-objective evolutionary algorithms, can be applied to solve problems that contain complex restrictions. A common challenge is obtaining a set of optimal Pareto Points, evenly distributed along the Pareto Front. In this work, Non Dominated Sorting Genetic Algorithm (NSGA) are proposed for that purpose.

For a better comprehension, the problem under study is applied to a 2-storey building. Any building structure must be comfortable, functional and safe at the same time, regardless the loading conditions. To meet this, some standards provide guidelines in terms of limit values for some physical magnitudes such as stresses (safety) or accelerations (comfort). In this sense, the standards make the difference between Serviceability Limit States (SLS) and Ultimate Limit States (ULS). The SLS usually defines threshold values for the acceleration response taking into consideration the perception of the occupants of the structure. The ULS focuses on the highest stresses the material can eventually develop when the structure is subjected to the worst loading scenario. These two states are used as objective functions to articulate the multi-objective optimization procedure. Note that both the effectiveness of the device and its cost highly depend on the value of its moving mass, being desirable to achieve the required protection by using the minimum amount.

The SLS (objective number 1) can be evaluated through the accelerance frequency response functions (figure 1). For the original building (dotted lines) the peak of mode 1 (at floor 2) is higher than the rest, so it is well known that in case of installing a single TMD, it will affect to mode 1 and will be located on the second floor (with higher modal amplitude). Figure 1 shows (in solid line) the corresponding FRF. Note that the TMD manages to decrease the peaks around the frequency of mode 1 below peaks of mode 2. Thus, it can be assumed that a second TMD could further decrease the peaks of mode 2, as they are now higher than the peaks around mode 1.

The ULS (objective number 2) is considered by evaluating the drift between storeys when undergoing, for example, a particular earthquake. Note that the drift is proportional to the stresses in the columns,

which must be under their carrying capacity. Figure 2 shows that the maximum drifts can decrease when TMDs are installed.

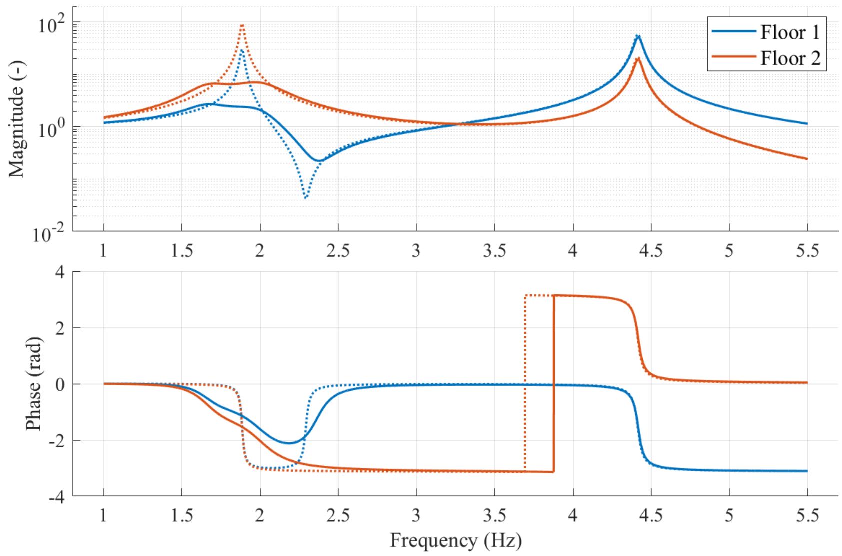

Figure 1. *FRF in terms of accelerance for the original building (dotted) and for the building with a TMD (solid).*

The objective of the work is then to determine the Pareto Front, indicating the TMD or TMDs to install, considering those two objective functions, so that the mass of the TMDs to be put (1 or 2) is bounded. Depending on the frequency content of the time excitation (earthquake) and on the comfort required, it will be concluded that there will be solutions with a single TMD (including all the mass) affecting to mode 1 or mode 2 (located on the first or the second floor) or with two TMDs (with the same total mass).

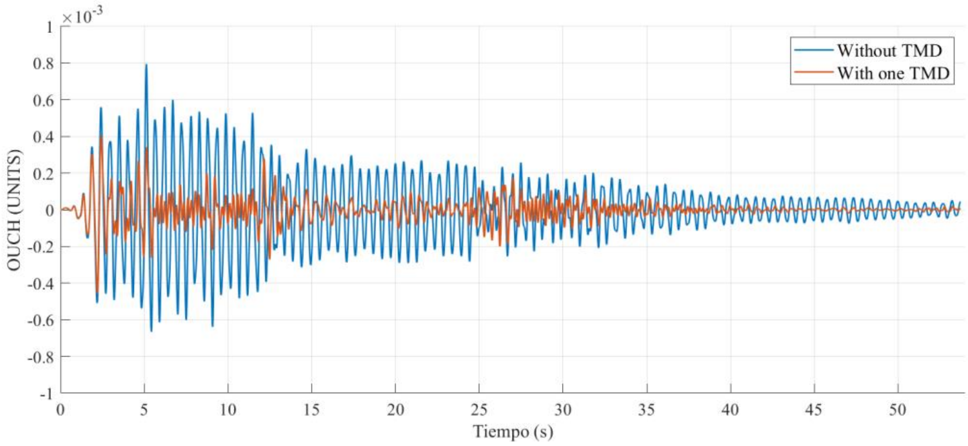

Figure 2. *Time response* with a particular earthquake.

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METAMODELING OF THE ADDITIONAL PLATE IN BENDING IN BEAM-TO-BEAM STEEL CONNECTIONS.

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Keywords: *kriging, metamodeling, beam-to-beam, steel joints.*

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ABSTRACT

Over the last years wide experimental, numerical and analytical researches have been carried out in beam-to-column steel joints. However, the beam-to-beam connections [1-2] have been less studied, although they are as important as beam-to-column.

In orthogonal beam-to-beam connections there are many ways to solve the connection. Traditionally, in welded connections the secondary is welded directly to the main beam. If the solution is bolted the secondary beam has an end plate that is bolted to a T shape stub welded to the flanges and the web of the primary beam. In both exposed cases, the flanges of the beam or the T shape stub must be cut with the cost increment that it entails. An alternative for the exposed solutions could be to bolt the end plate of the secondary beam to a simple additional plate welded between the flanges of the primary one. Figure 1 shows this configuration.

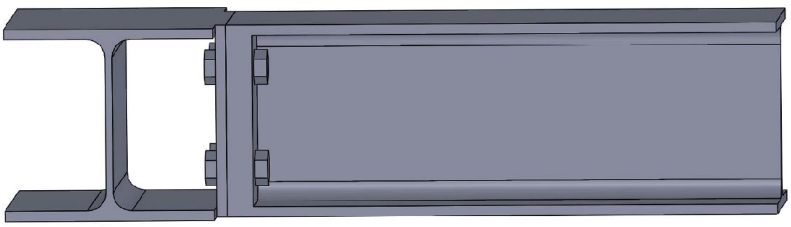

Figure 1. *Beam-to-beam connection with additional plate.*

Lopez et al. [2] have studied this solution, where it was figured out that the additional plate in bending was the most relevant component in behaviour of the joint. This conclusion was reached after performing experimental test and an extensive parametric study with calibrated finite element models. Finally, they proposed an analytical formulation for the stiffness and resistance of the additional plate in bending.

In this article a metamodel of the component additional plate in bending is presented and developed using Kriging's method to obtain its stiffness. The data of the parametric study with finite elements models performed by Lopez et al. [2] was used to develop the metamodel, showing very good accuracy in the stiffness prediction. The parametric study was published by Lopez et al. [2] and consisted in a

configuration of one primary beam with the additional plates attached by eight bolts to two secondary beams with flush end plates, with a total of 288 different geometries. The finite element models were performed using Abaqus package using solid elements.

The Kriging's method predicts the response based in regression model and a radial model. The Matlab application, DACE [3], has been used to implement the method. The parameters were determined minimizing the error. The geometrical parameters that have been used as input of the model were: beam height, beam width, thickness of flange, vertical distance between bolts, horizontal distance between bolts, thickness of the additional plate and bolt diameter. A linear regression model and a Gaussian correlation model have been used in the model. From the 288 cases, 66% have been used to train the model and the 33% to validate the model.

Analysing these results, the average of the error was 0.43% and its standard deviation was 0.019. The maximum error was 12%. Therefore, the Kriging's model shows good accuracy predicting the stiffness of the additional plate (see Figure 2).

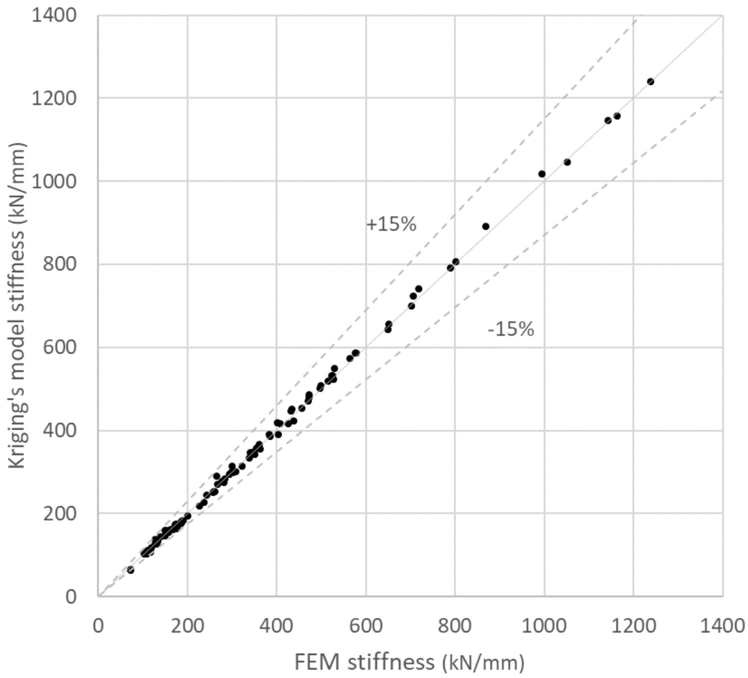

Figure 2. *Stiffness comparison between FEM and Kriging's model.*

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NON-LINEAR VISCOELASTIC BEHAVIOR EXPERIMENTAL CALIBRATION OF A RECYCLED RUBBER FROM ELTs

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Keywords: End of life tires, semi vulcanization, non-linear viscoelasticity, compression impact test, Bergström-Boyce behavior model

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ABSTRACT

An experimental setup is presented for non-linear viscoelastic properties evaluation via impact compression tests.

The material under evaluation (Fig. 1, left) is a commercial recycled rubber obtained from end-of-life tires (ELTs) by the Danish company Genan®.

Due to the fabrication technique, the material suffers a spontaneous semi-vulcanization process, because of temperature and pressure conditions, which gives to the material similar properties to a new rubber.

Other consequences of the fabrication procedure are (i) the shape of the material as small cylinders -called pellets henceforward-, and (ii) the high number of defects of those pellets. Both aspects cause that only compression tests can be done.

The aim of our work is to evaluate this material, as energy sink, inside a mechanical system. For this purpose, it is essential to know its viscoelastic properties under high strain rate consideration. This way, the energy dissipation capability of this material can be measured.

The product commercialized by Genan® is an agglomerated of those cylinders using a polyurethane resin as binder. For this reason, rubber only -uncoated- and rubber-polyurethane -coated- pellets were tested.

Among the few models that can be found in the literature for those kind of materials, Bergström-Boyce model [1],[2] is the best option to capture the hyperelastic and non-linear viscoelastic properties expected for this material.

The straighter specimens have been selected to develop the impact compression test and the basal surfaces have been polished to guarantee the perpendicularity of the load. The test has been made in a drop test whose load cell was too big to register the load for such specimens. To overcome this problem, a smaller load cell was used as support of the specimen during the test (Fig. 1, left).

Digital image correlations -DIC- techniques have been used to compare with the drop test's software computations. Fig. 1, right, shows a sequence of one test. The speckled hammer, allowing DIC technique, and the reduction of the pellet's length can be observed.

Bergström-Boyce model is defined by nine parameters characterizing the main aspects of the polymer's behavior: hyperelasticiy, viscoelastic flow, different stress-strain relationship for rising and diminishing loads, etc.

Those parameters are obtained from engineering stress vs. engineering strain curves obtained from test under strain rates varying from 133.3 1/s to 400 1/s (impact velocities of 2, 3, 4, 5 & 6 m/s). Fig. 1 center, shows results for the biggest used strain rate, where the stiffener effect of the resin is evident. This effect has been observed for all the tests.

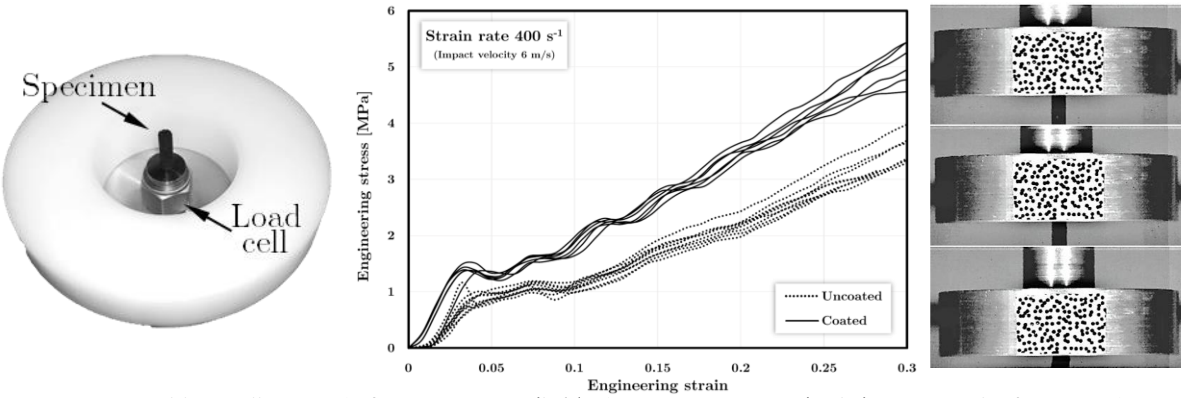

Figure 1. *Rubber pellets ready for impact test (left); during impact test (right). Test results for coated and uncoated pellets (center)*

The parameters of the model were obtained, via optimization procedures with different objective functions and optimization algorithms using the software MCalibration® by PolymerFEM®. The results show an important dispersion depending on the optimization process, see Table 1, where results are showed for different optimization procedures

Table 1. *Bergtröm-Boyce parameter sets for uncoated (lef) and coated (right) pellets.*

Objective function: R^2				
Mat. param.	GSM	EAM1	EAM2	QAM
$\mu[MPa]$	1.28076	1.2635	1.33607	9.63448E-1
$\lambda_L[-]^*$	7.67626	9.93675	8.01801	3.93525
$\kappa[MPa]$	90.76	58.4413	884.384	51.2614
$s[-]$	5.251	4.41498	4.50317	4.95057
$\xi[-]$	3.19576E-3	7.39389E-2	9.22629E-2	2.77466E-2
$C[-]$	-0.220491	-1.41998	-1.43726	-1.26653
$\tau_{base}[MPa]$	5.18063E-3	5.58587E-2	3.92156E-2	1.76038E-1
$m[-]$	1.10001	1.11533	1.10001	1.31022
$\hat{\tau}_{cut}[-]$	0.21287	6.7883e-06	6.22886E-4	3.89562E-4

Objective function: R^2				
Mat. param.	GSM	EAM1	EAM2	QAM
$\mu[MPa]$	2.42554	2.39849	2.47413	1.65875
$\lambda_L[-]^*$	2.57821	6.03887	9.58263	4.1123
$\kappa[MPa]$	109.814	9.405	4.07078	156.4
$s[-]$	3.94092	4.94298	7.17237	3.84955
$\xi[-]$	2.84044E-1	1.1547E-1	6.59718E-2	3.68347E-2
$C[-]$	-1.44603	-1.22158	-1.30899	-1.24697
$\tau_{base}[MPa]$	1.75539E-2	4.36568E-2	1.05716E-1	2.63624E-1
$m[-]$	1.13918	1.1615	1.1001	1.40383
$\hat{\tau}_{cut}[-]$	1.82253E-2	7.92286E-2	6.97594e-05	9.81355e-05

Consequently, a subsequent numerical step will be necessary to evaluate which parameter set is more accurate, i.e., which optimization procedure is better to calibrate the material from this unique test.

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NUMERICAL MODEL FOR THE PARAMETRIC ANALYSIS OF THE IMPACT BALL-PADDLE RACQUET

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Keywords: Ball & racquet numerical model, ball-racquet impact, parametric analysis, racquet comparison.

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ABSTRACT

Paddle racquets are structures subjected to impacts that must combine characteristics such as lightness, rigidity and durability. The answer to these requirements is a multi-material structure composed of glass and carbon fiber textile composites and high-tech foams.

The objective of this work is to develop a finite element model of the paddle racquet that allows the designer to have objective criteria of a new racquet's behavior before manufacturing it. This work has been developed on the MARVEL model of the SHARK PADEL S.L. company.

In a previous work [1], a finite element model was developed allowing to analyze the behavior of the raw paddle racquet, as a function of the used structural materials. This model was validated both statically and under impact loads. However, in the aforementioned work was not analyzed the influence of the distribution of holes that, following the current regulations, it is mandatory that the paddle racquets have. The distribution and size of the holes will have a notable influence both on the life and on the response of the paddle racquet depending on the point of incidence of the ball.

To carry out this study, it is essential to model the ball-paddle racquet contact. An explicit finite element model using MSC Nastran SOL700 solver has been developed. In the present work has been modeled the rubber ball using the hyperelastic Ogden model. The numerical model of the ball is based on modeling a hollow sphere of hyperelastic material, where air is confined at a relative pressure of $0.82\ bar$ [2]. To do this, the AIRBAG card is used. To validate the model, it has been simulated the test that must pass the paddle balls according to the regulations of the International Paddle Federation. To do this, the standard ball is dropped freely from $2.56\ m$ high on a concrete floor, having to bounce between $1.35 - 1.45\ m$. Fig. 1 (left) shows the results obtained, thus validating the model of the ball.

The regulations require that the hitting area be perforated, fixing the maximum and minimum diameter of holes. The objective of these is fundamentally aerodynamic, although they have a crucial importance both in the life and in the response of the racquet depending on the position of hitting. In this work we have analyzed the MARVEL model without holes (M1) of the SHARK PADEL S.L. company and three different distributions of holes: Marvel (M2), Varlion (M3) and R4 (M4) (Fig. 1, right). The latter is the one proposed from an aerodynamic point of view in [3].

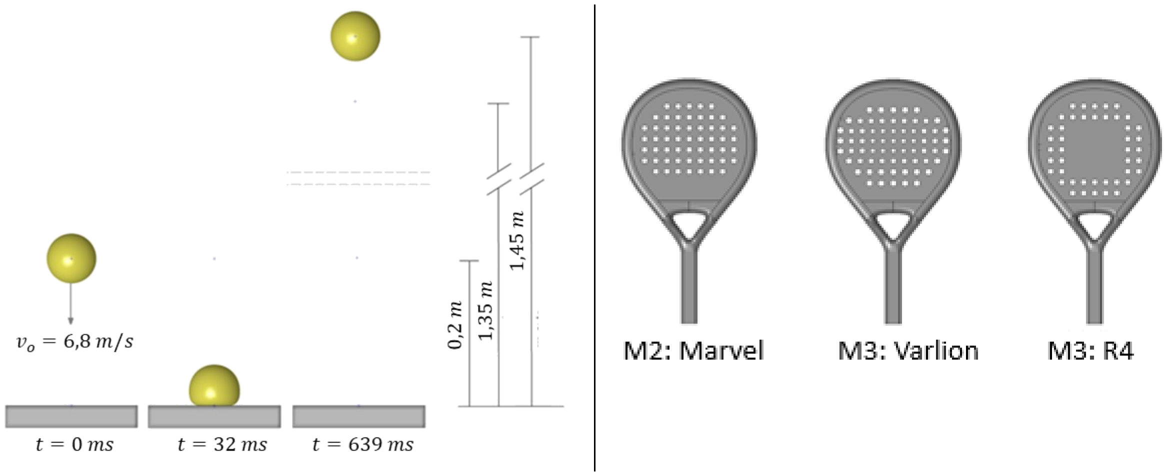

Figure 1. *Ball model validation (left). Studied racquet models (right)*

Four hit points have been analyzed (Fig. 2, left). An incidence ball speed of 30 m/s (108 km/h) has been considered. To compare the behavior of the analyzed racquets different aspects have been taken into account:

- Ball speed after impact. This value gives an idea of the response capability of the racquet.
- Ball angle exit respecting incidence direction giving an idea of the ball control.
- Safety factor using Tsai-Wu criteria, that gives an idea of the durability of the racquet.
- Reactions in the grip.

Fig. 2, right, shows the sequence of the ball-racquet impact simulation for the Marvel racquet.

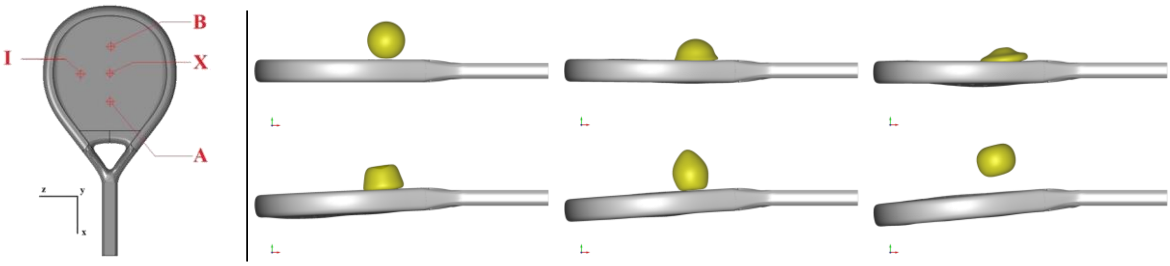

Figure 2. *Analyzed incident points (left). Sequence of ball-racquet impact (right).*

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ON THE EVALUATION, AS A SENSOR IN STRUCTURAL ANALYSIS, OF AN EPOXY-VINYL-ESTER RESIN DOPED WITH CNFs & CNTs

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Key words: carbon nanotube, carbon nanofiber, piezoresistive behavior, humidity influence, UVA-radiation influence.

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ABSTRACT

In the last two decades, with the improvement of techniques of nanomaterials' manufacturing, the use of multifunctional material as sensors in many fields has focused the attention of researchers, see [1] for instance.

Civil engineering applications, specifically structural health monitoring, is one of the fields were many research are centering their efforts, see [2,3] among many others.

With the target of use composite patches as sensitive reinforcement of structures, the piezorresistive behavior of a commercial epoxy vinyl ester resin (DERAKANE® 8084) dopped with carbon nanofibers -CNFs- and carbon nanotubes -CNTs- has been analyzed in this research.

This resin has been selected because its good behavior in outdoors uses. As CNFs, it has been used GANF: a commercial helical-ribbon stacked-cup-like CNFs, produced by Grupo Antolín Ingeniería [4]. As CTNs, a commercial presentation of MWCNTs by NANOCYL® (NC7000™) has been used.

Fig. 1 shows specimens for volumetric and superficial resistance measurements during tensile test.

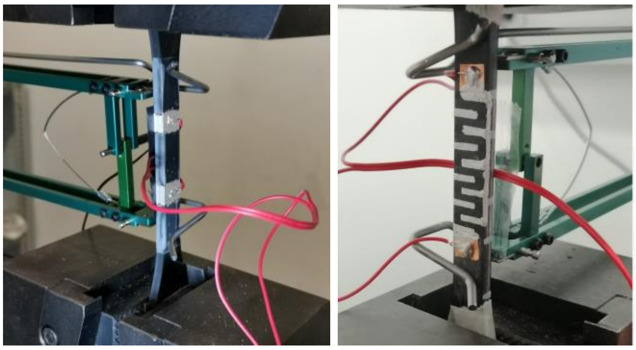

Figure 1. *Specimens of enriched resin under tensile test.*
Left: volumetric measurement. Right: Superficial measurement.

The results show that, even although each specimen can behave in a different manner (i) its resistance is rather stable since the beginning, showing a negligible polarization effect (ii) the percolation limit is between 1 wt% and 2 wt% of GANF.

Preliminary results for the DERAKANE® 8084-GANF system is shown in Fig. 2.

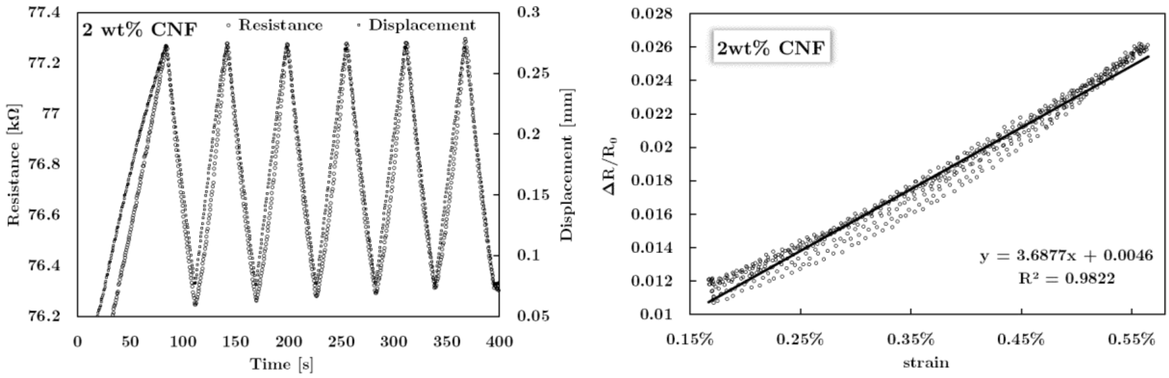

Figure 2. *Resistance variation during static cycling tensile load (left). Unit resistance variation vs. strain (right).*

During static tensile cycling tests, the variation of resistance successfully fits the load history, as it can be seen at Fig. 2, left.

Fig. 2, right, shows the quasi-linear relationship between the strain and the change of resistance in the specimen. This result will allow to define an adequate gauge factor to obtain mechanical information of the future patches from their electrical response.

The dispersion of CTNs in this resin has been much more complicated. The only formulation obtained by now has not given results so promising as the ones shown for GANF.

Considering that these patches would be under environmental conditions the aging of this material is a factor under investigation in this work.

Acknowledgements

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ESTIMATION AND VALIDATION OF MODAL MASSES IN CONSTANT MASS-DENSITY SYSTEMS

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Keywords: modal mass, OMA, EMA, mode shape normalization.

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ABSTRACT

A modal model describes the structural dynamic behaviour in terms of modal parameters: natural frequencies, damping ratios, mode shapes and modal masses. Mode shapes can be normalized in many different ways, being mass normalization and normalization to the largest component equal to unity, the techniques used in FEM software [1-3]. Mass normalized mode shapes contain information of both the modal mass (magnitude of the vector) and the shape of the mode (deflection shape). The modal mass in constant mass-density systems is equal to the product between the total mass of the structure, and the length of the mode shapes squared [4]. This means that a relationship between the modal masses of the different modes exists.

In this paper, the modal masses of a steel structure (see Figure 1) are estimated using different techniques.

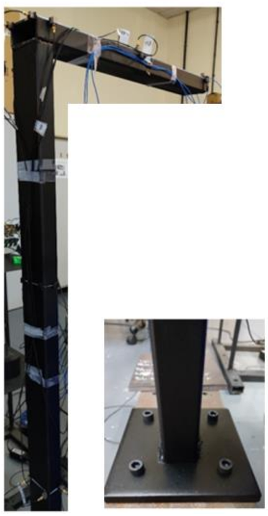

Figure 1. *The steel structure used in the experiments*

Firstly, a finite element model was assembled in ABAQUS, from which the natural frequencies, mode shapes and modal masses were extracted with a frequency analysis (see Figure 2).

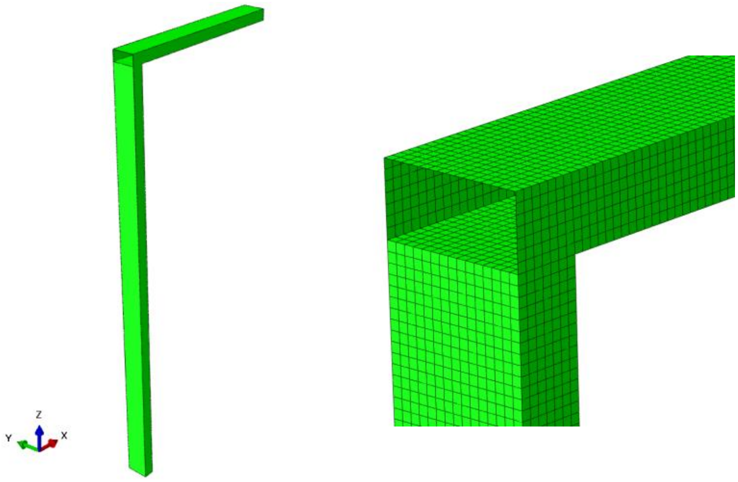

Figure 2. *Numerical shell model (ABAQUS)*

Then, the experimental modal parameters were estimated with operational modal analysis (OMA). In OMA, the forces are unknown, and the modal masses cannot be estimated. If the modal masses are needed, additional procedures to estimate the modal masses have to be used. In this paper the modal masses were estimated with the following equation:

$$m_x = \boldsymbol{T}^T \boldsymbol{T} \tag{2}$$

where $\boldsymbol{T}$ is a transformation matrix estimated combining experimental and numerical mode shapes [5].

The modal masses were also estimated with experimental modal analysis where the modal masses are obtained from the experimental FRF's using some of the several identification techniques proposed in the literature [1-3].

Finally, the modal masses extracted from the numerical model, and those estimated from the experimental results are compared and validated.

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STUDY OF THE REINFORCEMENT IN A FOOTBRIDGE WITH VIBRATION PROBLEMS

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ABSTRACT

The vibration serviceability assessment is one of the criteria that must be taken into account in the design of footbridges which are often susceptible to human induced vibrations due to their low mass and low damping. In this work, the dynamic behavior of the "Pumarin-Moreda" pedestrian footbridge (see Figure 1), located in the city of Gijón (Spain), is studied. The bridge entered into service in 1995 and since then, the users reported some discomfort during the use of the structure due to excessive vibration levels in both vertical and transversal directions.

Figure 1. *Pumarin-Moreda footbridge*

A study of the dynamic behavior of this structure was carried by numerical and experimental techniques. A finite element model was assembled in ABAQUS (see Figure 2) and the natural frequencies and the mode shapes were extracted by a frequency analysis. The numerical results were compared with those obtained by operational modal analysis.

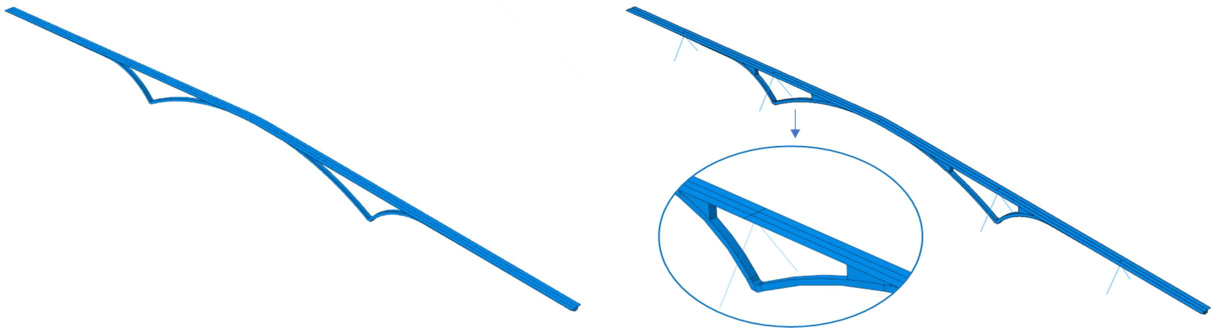

Figure 2. *FE ABAQUS model before (left) and after reinforcement (right)*

The footbridge was reinforced in 2014 to improve its dynamic behavior. In this paper, the initial numerical model was modified considering the new structural elements (see Figure 2) and a new set of natural frequencies and mode shapes were extracted (Table 1). In this paper, the dynamic behavior of the reinforced pedestrian footbridge is studied comparing the modal parameters of both (before and after the reinforcement) numerical models.

Table 1. Numerical natural frequencies (left: before reinforcement, right: after reinforcement)

Mode	Direction	$f_{num0}[Hz]$	Mode	Direction	$f_{num1}[Hz]$
1	L	0.82	1	L	1.59
2	L	1.37	2	L	4.30
3	L	1.68	3	V	4.90
4	V	2.12	4	V	5.24
5	V	2.13	5	L	5.35
6	L	2.68	6	L	5.67
7	V	3.25	7	V	6.55
8	V	3.28	8	V	7.09
9	L	4.04	9	L	7.91
10	V	4.75	10	V	8.08

According to the structural design codes [1-5], this footbridge presented natural frequencies within the critical range to be avoid, and the maximum accelerations exceeding the comfort limits. After reinforcement most of the problems disappeared, confirming the improvement of the dynamic behaviour of the structure.

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DETECTION OF STRUCTURAL DAMAGE IN LAMINTED WOOD STRUCTURES THROUGH FINITE ELEMENT METHOD AND MODAL UPDATING

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Keywords: Laminated wood, Structural damage, Evolutionary optimization, Modal analysis.

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ABSTRACT

During the last years, the use of laminated wood, also known as Glulam, has been growing in interest for several reasons. In fact, it is a product that has been used in the construction of very different types of structures (e.g. sports facilities, airports, pedestrian bridges, etc.). Different motivations justify the increasing importance, but we can select two features that stand out as the main ones. First, it is an ecological and sustainable material. The use of this material in construction is one of the best ways to increase our respect for the environment. Secondly, is the aesthetic side of the material, since these structures generate comfortable environments achieving better adaptations to natural spaces (see Fig. 1).

However, one of the main drawbacks of this material is the lack of knowledge about its structural behaviour and the degradation that Glulam can experience over time. Wood is a living material, markedly anisotropic and hygroscopic, and for this reason, it does not have as well defined mechanical properties as occurs in other materials used in construction. Furthermore, laminated wood is combined with adhesive, making it a composite material. The result is that it is more difficult to model than other typical materials used in construction. The deterioration processes (biotic and abiotic) are also very diverse [1] and therefore increase the difficulty of the study of this material.

Figure 1. *Pedestrian walkway built using laminated wood in the town of Cieza (Cantabria).*

The aforementioned reasons makes necessary the development of non-destructive methodologies that can be applied in-situ for the detection of structural damage in this type of material [2]. In this work, a methodology based on finite element updating [3] for the detection of damage based on the dynamic behavior of structural elements is presented. To this aim, the experimental results are compared with the theoretical results and the mechanical parameters are adjusted by means of particle swarm optimization, a procedure that has been shown to have good precision in other fields [4]. The procedure used is based on the formulation of an objective function that compares the natural modes and frequencies. Thus, numerous experimental tests have been carried out on wooden elements by means of experimental modal analysis on simple boards and laminated wooden elements (Fig. 2). These results show the strong influence of the variability of the material properties and the influence of the defects in the modal parameters. It is concluded that it is necessary to introduce an uncertainty model that takes into account the statistical dispersion of the mechanical parameters.

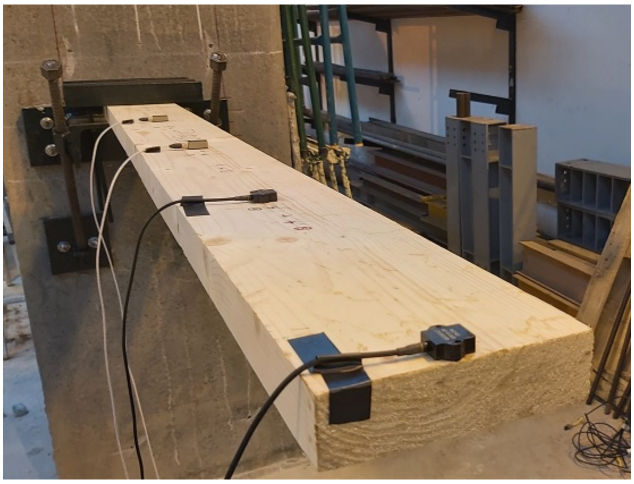

Figure 2. *Dynamic analysis of a structural element of wood.*

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PHYSICALLY BASED MODEL TO SIMULATE THE DIRECT CONNECTION BETWEEN MICROPILES AND EXISTING FOUNDATIONS

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Keywords: stress, strain, structure simulation, bonded materials, Airy stress function.

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RESUMEN

Micropiles are cylindrical structural members of small diameter, less than 300 mm, made in situ by rotary drilling. They are basically compound of cement slurry and a tubular steel reinforcement to which corrugated bars are welded [1]. This type of foundation makes it possible to transmit loads to more resistant soil layers located at greater depths; consequently, in addition to increase the loads on the structure with negligible settlements, they allow reinforcing the existing foundation when the soil has lost its bearing capacity. Due to these reasons, besides the simplicity of their execution, the use of micropiles in the underpinning of foundations is currently the most common solution.

In the context of underpinning, the connection between the micropiles and the existing foundation is performed in a direct way, by drilling the second one and joining the micropile through a cylindrical contact surface. Calculating the strength of this connection is straightforward by multiplying the cylindrical contact surface by an average value of slurry-concrete bond stress. It is a simple method to execute, but the number of micropiles is limited to the geometrical dimensions of the foundation. Therefore, the strength of this connection is usually the one that limits the amount of load transmitted by each micropile [1], thus conditioning the final solution to be adopted.

Technical literature about bond stresses is sparse [1, 2]. For this reason, in this case the bond stress is usually assimilated to a type of strength: originally, to the shear strength of concrete [3] and, currently, to the transverse shear strength in concrete joints [4-6]. At both Eurocode 2 [4] and the Spanish regulations EHE-08 [5] the transverse shear stress formulations depend on a roughness parameter in the contact surface whose predicted value presents some uncertainty [4-5]. In contrast, ACI-318 [6] prescribes a fixed value, which is non-dependent neither such roughness coefficient nor the constitutive model of the involved materials. The absence of a specific mechanical model for this type of connection is the origin of this research.

The objective of this work is to develop a mechanical model for predicting the structural response of the direct connection between micropiles and the existing foundation. Analytical developments are feasible in the context of simple cases, whereas a numerical implementation is required in the case of

more complex systems. The three-dimensional elastic problem is simplified by taking advantage of the symmetry of the micropiles. In the analytical developments, classical solutions are considered, such as Love's deformation function for axial symmetry, or Airy's stress function for plane elasticity. Likewise, different stress distribution profiles are proposed for the contact zone (both for tangential and compressive normal stresses), and a numerical contact model between the involved materials is implemented.

Both analytical and numerical results provide insights for predicting the connection strength in a more accurate way, as well as several strategies for its calibration. In addition, such results will allow adapting the values of the roughness coefficient in concrete joints to the specific problem of the direct connection between the existing foundation and the micropiles, improving thus the design of the underpinning.

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ECONOMIC REPERCUSSION THAT THE DIRECT CONNECTION MICROPILE-FOUNDATION HAS ON THE UNDERPINNING PROJECTS COST

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keywords: bond stress, grout, shear, horizontal shear, Monte Carlo.

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RESUMEN

The building underpinning by micropiles directly connected to the footings of shallow foundations is the most common solution. In this kind of rehabilitation projects some structural verifications are necessary, and those addressed to ensure the loads transmission are critical [1]. Among them, the strength of the micropile-foundation connection is the most relevant, since it usually decides the final design. Such strength is prescribed by the reinforcement concrete (RC) codes, and it is calculated by multiplying the lateral area of the foundation drilling and the shear strength acting between the cement grout (micropile) and the concrete (foundation). This shear strength is usually referred as bond stress.

In absence of a specific resistance model for the bond stress, at the beginning this was equated to the shear strength of concrete [2]. Later, in Spain, the formulation proposed by the “Guide for the design and execution of micropiles in road works” [3] was the horizontal shear in the joints corresponding to different times in the concrete cast process [4]. Recently, a new Structural Code has been authorized in Spain [5], and it incorporates the horizontal shear formulation of Eurocode 2 [6], which is similar to the one contained in the previous Spanish RC code [4]. The changes so introduced imply a reduction by around 50% in the connection strength value, converting this last parameter to a critical issue within the design process of underpinnings. Therefore, despite complying with the rest of the structural verifications, frequently it is necessary to add more micropiles in order to reduce the load transmitted to each micropile connection, increasing the building underpinning cost.

These aforementioned changes in the resistant model produce uncertainty. Moreover, the parameters involved in these formulations introduce also some uncertainty. Thus, such parameters depend on the drilling roughness, which usually is performed by wet rotation in order to not introducing vibrations under foundation. The interface so obtained is smooth, and consequently, relative low roughness parameters are considered, which derives in low bond stress values.

Due to these reasons, the main objective of this work is to analyze the economic impact that the use of a certain bond stress value presents on the cost of underpinning projects. To this aim, and after an exhaustive bibliographic review, 7 bond stress values based on shear and horizontal shear formulations will be applied, comparing thus the cost of the resulting underpinning designs. Among them, those corresponding to the structural concrete regulations of Spain [4], Europe [5] and the United States [6] stand out. Likewise, bond stress values obtained through experimentation will also be applied. For this last purpose, the bond stress distribution obtained by Pachla [7] is adopted and a

Monte Carlo simulation has been performed. Thus, this simulation, besides to contrast the goodness between the formulations and the experimental data, will serve as a sensitivity analysis of the bond stress parameter in the cost of the underpinning projects.

Results so obtained conclude that the consideration of the American ACI-318-19 standards [6] instead of the European [4] or Spanish [5] ones implies an economic saving of 22%. Moreover, savings can reach values around 40% for buildings with small thickness footings supported on high strength soils and subjected to high loads. Therefore, a specific research about the resistant model for this type of connection would be justified.

By using a probability distribution of experimental bond stresses, it has been found that the design strength value of the ACI-318-19 (0.552 MPa) is adjusted to the 95% percentile of this distribution (0.585 MPa), while European (0.309 MPa) and Spanish (0.328 MPa) codes are more restrictive as they are in the 100% percentile (without considering load partial factors). Likewise, the Monte Carlo results indicate that, for common underpinnings, bond stress values exceeding of 0.60 MPa are not economically justified. In fact, reaching a higher bond stress value (close to 1.00 MPa) would imply reinforcing the micropiles themselves, compensating for the savings of executing fewer micropiles.

Finally, it should be noted that the bond stress of the ACI-318-19 is a constant value (0.552 MPa), while in the European and Spanish RC codes it depends on the aforementioned roughness parameter, whose value is usually set at 0.3. Therefore, in order to equate the resistance of the European and Spanish regulations to the American one, and within the 95% percentile, it would be advisable to increase the value of this roughness coefficient to 0.5. Thus, bond stress values of 0.547 and 0.516 MPa, respectively, would be obtained, which, statistically, would present the usual guarantees for this type of structural calculations.

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PIEZOELECTRIC 1D FINITE ELEMENT FOR DESCRIBING FRACTURE IN LATTICE MODELS

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Keywords: piezoelectric materials, lattice models, truss and beam elements with embedded discontinuity

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ABSTRACT

Due to the technological advance, in modern times many devices and structures carry the attribute “smart”. Such systems must be able to sense a certain external stimulus and to respond to it in a predetermined manner. Two types of elements are used to build “smart” systems, load-bearing and active elements. Load-bearing elements are made of passive materials (steel, composites, etc.) and active elements are sensors and actuators that are built of smart materials. These active elements should have the ability to detect the real-time behaviour of the structure (sensors) and adapt this behaviour according to the predefined response (actuators). Because of their ability to transform mechanical energy into electrical and vice versa, piezoelectric materials are mostly used as parts of these sensors and actuators [1].

Piezoelectric materials in smart structures are often subjected to mechanical loadings and since majority of piezoelectric materials of practical importance are brittle or quasi-brittle, it is important to properly describe their behaviour during damage and fracture in order to estimate their reliability. Many numerical models for failure in piezoelectric materials incorporating continuum theories are developed [2]. In such models, many complex numerical procedures to avoid difficulties in describing phenomena depending on lower material length scales (modelling multiple cracks, fragmenting, etc.) are needed. The lattice models are an alternative to continuum models for modelling fracture phenomena in brittle materials because they are inherently able to model size-effect [3]. In the lattice models, continuum is represented by a number of rigid particles which interact through one-dimensional elements that represent cohesive forces between the particles. Depending on the topology, lattices can be regular or irregular. In the regular lattices, all of the elements have the same geometric properties and it is easy to determine their material properties depending on the material properties of the real material and to describe uniform straining. Although describing uniform straining with irregular lattices is not a trivial task, they are used more often in fracture mechanics, because they are better suited for capturing the direction of crack propagation correctly. In these lattices, discretization of the domain is usually based on the Voronoi tessellation, with the edges of Delaunay triangles as the lattice elements. In such cases, the cross section area of the elements can be defined as the length of side of the Voronoi cell that element intersects [3]. Material parameters of the lattice elements follow from the equivalence of the continuum and the lattice unit cell enthalpy [4].

The simplest lattice element is piezoelectric truss element with two nodes and three degrees of freedom in each node, which are two displacements and electric potential. Polarization of the element is in the direction of the axial axis of the element. These elements can carry mechanical loading and electric field only in the axial direction. Material parameters needed for the piezoelectric truss elements are the Young’s modulus, the coupling parameter which connects axial stress in the element with the electric field in the axial direction and

permittivity. These elements can get accurate results only for the materials in which some constrains regarding the values of the material properties are met [4]. Damage in the element is achieved by activating the discontinuity in the displacement and strain fields when the stress reaches a limit value [3]. The main difficulty in the simple truss elements is that they can only break in Mode I and that is why they cannot properly describe damage in real material. To get a global softening in the stress-strain curve, it is necessary to weaken the zone in the material. However, in such model, in the elements that are approximately perpendicular to the loading direction, discontinuity is practically never activated. When crack appears in the model, it should also affect electric part of the element. The simplest manner to achieve this is through permittivity drop. When mechanical discontinuity is activated, its permittivity also drops momentarily from material parameter for undamaged material to the vacuum permittivity, characteristical for the totally damaged material.

To get a more faithful representation of the real piezoelectric material, piezoelectric beam element should be developed. The appropriate beam element could be the one based on Timoshenko beam theory [5, 6] and with that element, mechanical restrictions of the real material are alleviated. Beam element can break in Mode I and Mode II and that allows the model to break in an more realistic manner. To further enable the more realistic material modelling, the polarization of the element should be in arbitrary direction [7]. In that case, a proper transformation of the coupling tensor has to be implemented in the element formulation, leading potentially to the significant increase of material parameters which should be calibrated for successful solving of the realistic problems. Further attention has to be paid to the fact that the realistic piezoelectric materials are essentially anisotropic [8]. because of more stress, strain, electric field and electric displacement components.

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ON ADAPTIVE PHASE-FIELD MODELING OF FRACTURE

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Keywords: fracture, phase-field, adaptive remeshing, free vibration

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ABSTRACT

Engineering structures are prone to various types of failures, and those failures can usually be described as brittle fracture, ductile fracture or failure due to fatigue. The most versatile and promising method to model those types of failures is found in the phase-field (P-F) method for fracture which is based on the approximate crack description and variational approach to fracture. The P-F method resolves elegantly various problems, such as complex crack topology problems, but comes with the drawback of large computational costs due to the requirement of high finite element mesh density around the crack and crack tip. To overcome this problem, efficient solving procedures can be employed. Another approach is by the incorporation of adaptive refinement strategies, which is the main topic of this contribution.

In this contribution, we introduce a simple 3D implementation of a quasi-static brittle phase-field model. In contrast to complex remeshing algorithms found in [1, 2] and simpler ones with structured meshes and hanging nodes found in [3, 4], we use an algorithm based on the tetrahedron bisection. The algorithm is simple and easily implementable. Also, in contrast to complex and mathematically involved error estimates [1-3], we use simpler and more intuitive ones to drive an adaptive process. Precisely, recovery-based error indicators and physical-based refinement criterion are used, similarly to those found in the literature [4, 5]. Recovery-based error indicator counts for displacement field error, while physical-based criterion ensures proper refinement around a crack tip. The proposed algorithm shows significant time savings in comparison to simulation with dense fixed mesh, and results are in agreement with the referent ones.

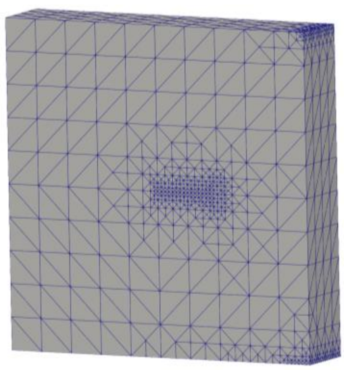

Figure 1. *Example of the refined mesh*

In addition, in this contribution we also perform a short preliminary analysis of free vibration response of the cracked 2D and 3D structures obtained by the proposed adaptive analysis. Thereby, we compare the obtained dynamical responses with those obtained by more conventional modelling techniques, which are usually used in the available literature [6-8], offer some preliminary conclusions and propose potential improvements in the modelling techniques to improve the dynamical responses of the P-F models of cracked structures.

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ON THE NATURAL BOUNDARY CONDITIONS IN THE MIXED COLLOCATION METHODS FOR ELASTICITY PROBLEMS

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Keywords: mixed collocation methods, natural boundary conditions, gradient elasticity, staggered solution.

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ABSTRACT

In the last decade, with the increase of the computing power meshless methods have been utilized for solution of various problems in solid mechanics. This also includes the problems of gradient elasticity, where the material microstructure has a significant impact on the deformation response of the structure. Within the meshless methods nodes are not connected into elements, hence for the approximation of the unknown field variables and the discretization of the geometry only neighbouring nodes are utilized. This lowers the computational effort since no mesh creation process is needed. Furthermore, the problems associated with the element distortion during computations are completely circumvented. However, the most notable negative aspects in meshless methods are the high numerical costs and low accuracy associated with the calculation of high-order derivatives of approximation functions. They are especially present in solution of gradient elasticity problems, which are governed by high-order partial differential equations. These severe setbacks can be alleviated by the application of the collocation method in combination with the mixed meshless approach [1, 2], since such approach requires a lower continuity degree of the approximation functions.

The gradient elasticity theories are used in solution of problems where the classical theories do not provide results of sufficient accuracy. Hence, these theories implicitly take into account the material microstructure and can be described as enhancements of the classical theories, incorporating the higher-order spatial gradients of state variables [3]. The derivation of numerical methods for gradient elasticity is quite a difficult task if the Finite Element Method (FEM) is chosen due to the high order of the governing equations. Therefore, displacement-based FEM formulations often require many degrees of freedom per element, which results in very complex shape functions. For this reason, the formulations are often also rewritten as mixed FEM approaches [4], but there appropriate additional numerical approaches have to be applied in order to ensure the stability of such methods. On the other hand, in the meshless methods shape functions of an arbitrary continuity order can be derived relatively straightforwardly, without increasing the global number of degrees of freedom.

In this paper, two different collocation methods for the solution of gradient elasticity problems are considered, based on the mixed collocation Meshless Local Petrov Galerkin (MLPG) concept [1, 2].

Both of the methods are of the Helmholtz type [5], with only one unknown constitutive parameter. Hence, in these formulations the fourth-order equilibrium equations of gradient elasticity are solved using the strain- and stress-based staggered procedures as uncoupled sequences of the two sets of second-order differential equations [6]. The methods utilize the interpolatory Moving Least Squares (IMLS) function [7] for the approximation of the unknown field variables. Since the applied approximations possess the interpolatory property at the nodes, the essential boundary conditions (essential BCs) are imposed using a simple procedure analogous to classical FEM. The natural boundary conditions (natural BCs) can be enforced in a simple manner using the direct collocation method at the discretization nodes. Since the collocation methods are utilized in all equations, the numerical integration is avoided altogether and the system of discretized equations is obtained in a quick and straightforward manner. Furthermore, the application of the mixed approach results in the collocation methods where only the first derivatives of meshless approximants appear. However, due to the application of different staggered procedures in the strain gradient elasticity problems, different appropriate natural BCs have to be applied for each specific formulation. Hence, the main focus of this paper is the utilization of the appropriate natural BCs within the mixed collocation methods and its influence on the solution of the gradient elasticity problem. In addition, various concepts of the imposition of natural BCs will be considered. The obtained results of all considered concepts will be presented, analyzed and discussed on representative numerical examples, including the description of size effects and the removal of singularities (discontinuities) in the gradient elasticity problems.

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MODELLING CROWD-STRUCTURE INTERACTION ON AN ULTRA-LIGHTWEIGHT FRP FOOTBRIDGE

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ABSTRACT

Conventionally, non-interacting load models have been employed to represent pedestrian actions in design recommendations to assess the vibration serviceability limit state of lightweight footbridges [1, 2]. A low pedestrian-to-structure mass ratio is often assumed in these guidelines, which is valid for structures constructed with traditional construction materials. Since these models neglect human-structure interaction (HSI), an overestimation of the dynamic response of FRP pedestrian structures has been obtained [3]. Moreover, due to the lightweight nature of composite materials, higher harmonics of human actions may excite significantly FRP footbridges [4].

In contrast to concrete or steel footbridges, the pedestrian mass may easily surpass the 30% of the mass associated to a specific vibration mode of an FRP footbridge. This is the case when three pedestrians, whose total mass is 218.8 kg, walk over the structure constructed at the School of Civil Engineering – UPM (see Figure 1). As the laboratory facility presents a natural frequency of 7.62 Hz and modal mass of 405 kg associated to first vertical vibration mode [4], the pedestrian-to-structure ratio is around 54%.

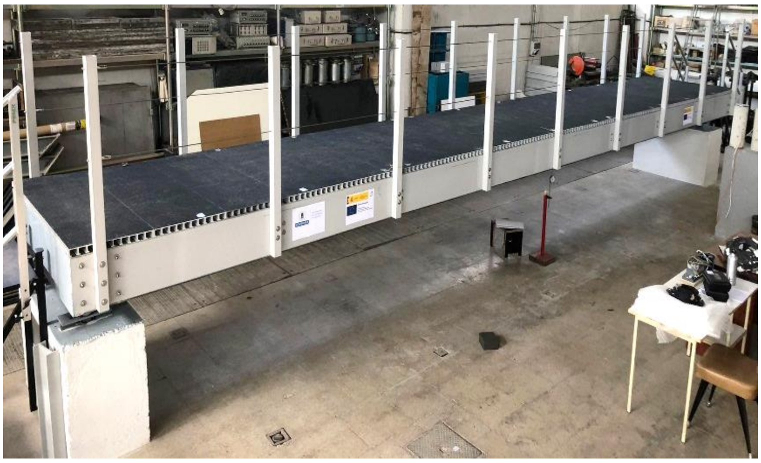

Figure 1. *FRP laboratory footbridge.*

This paper proposes a model to predict the structural response of a simply supported FRP footbridge subjected to weak traffic scenario (0.2 pedestrians/m^2), accounting for HSI and higher harmonics of pedestrians walking. First, experimental results from a test considering three pedestrians walking freely over the bridge deck in a closed-loop path for 5 minutes are presented. During the test, the acceleration response of the FRP footbridge was recorded using a high sensitivity accelerometer attached to the bottom of the central stringer. Figure 2 displays the collected data.

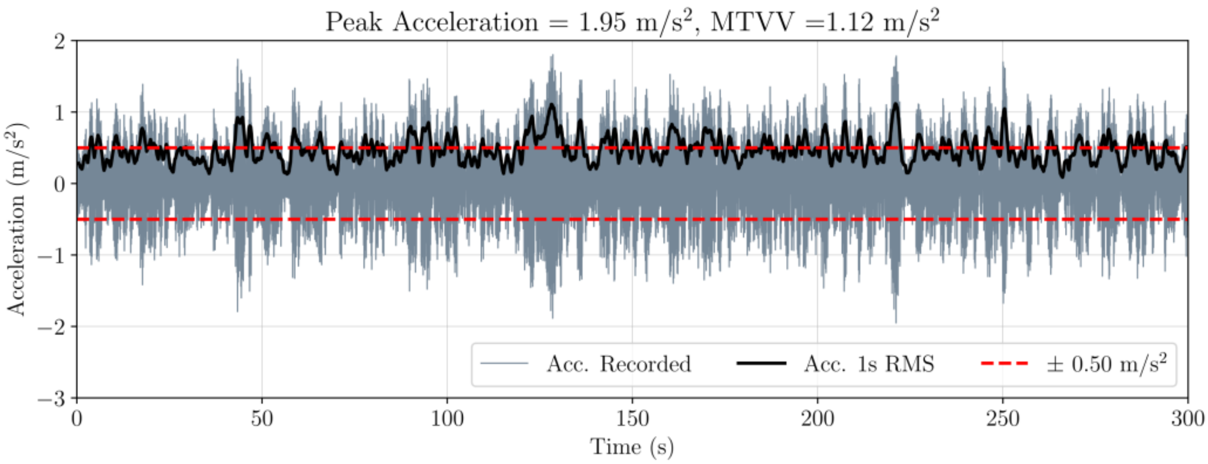

Figure 2. *Response of FRP footbridge at midspan due to three pedestrians walking freely.*

Then, an equivalent time invariant system is constructed considering the dynamic parameters of the structure and the human body (mass, frequency, and damping). To depict the stream of pedestrians walking on the footbridge as a coupled crowd-structure system, a single objective optimization problem is set and solved, minimizing the difference between the experimental and numerical maximum transient vibration values (MTVVs). The identified HSI model may be used as a first approximation to accurately predict the dynamic response of other simply supported lightweight structures subjected to crowd-induced loads.

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VIBRATION DAMPING IN CIVIL STRUCTURES WITH AN ON-OFF SEMI-ACTIVE CONTROL LAW IMPLEMENTED IN LINEAR ELECTRIC MOTOR

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Keywords: *semi-active; Tuned Mass Damper; linear electric motor;* vibration control.

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ABSTRACT

This work proposes a novel approach to implement semi-active control laws in electric motors. The work proposes how to include the model of a real lineal electric motor in a tuned mass damper (TMD). The force generated by the motor depends of a semi-active control law, which is configured as the control laws published in [1]. Figure 1 shows a simple structure model, which is a 1 degree of freedom system (m_s, k_s and c_s) damped with a TMD and a controlled force ($f_a(t)$). The objective of this work is to study the following practical effects when a semi-active control law is implemented: 1) the optimum value of the maximum and minimum force in an on-off control law [1], 2) the influence of real dynamics, comparing force actuators and magnetorheological dampers, and 3) the sampling period. Thus, this work compared the classical semi-active vibration control implementation [1], which uses magnetorheological dampers, with a novel approach based on electric linear motors.

From Figure 1 and considering the variable $x_r(t)=x_t(t)-x_s(t)$, the equation describes the motion of m_t is expressed as:

$$f_t(t) - m_t\ddot{x}_s(t) = m_t\ddot{x}_r(t) + c_t\dot{x}_r(t) + k_t x_r(t), \tag{1}$$

The first control law is $f_t(t) = K\dot{x}_r(t)$, where the parameter K can be K_{min} or K_{max}. Thus, the equation (1) can be used to obtain the value of the force applied by the TMD (denoted as $f_a(t)$) as a function of the base acceleration (see pages 63-65 of [2] for more details). The transfer function between $f_t(t)$ and $\ddot{x}_b$ is expressed as follows:

$$\frac{F_A(s)}{s^2X_s(s)} = -\frac{m_t(c_ts+k_t)}{m_ts^2+(c_t+K)s+k_t} = -m_t\frac{2\hat{\xi}_t\omega_ts+\omega_t^2}{s^2+2\xi_t\omega_ts+\omega_t^2}, \tag{2}$$

where $\omega_t = \sqrt{k_t/m_t}$, $\hat{\xi}_t = c_t/2\sqrt{k_tm_t}$ and $\xi_t = \hat{\xi}_t + K/\left(2\sqrt{k_tm_t}\right)$. The value of K is equal to K_{min} when $\ddot{x}_s(t)\dot{x}_t \leq 0$ (normal functioning) and K_{max} when $\ddot{x}_s(t)\dot{x}_t > 0$ (blocking functioning).

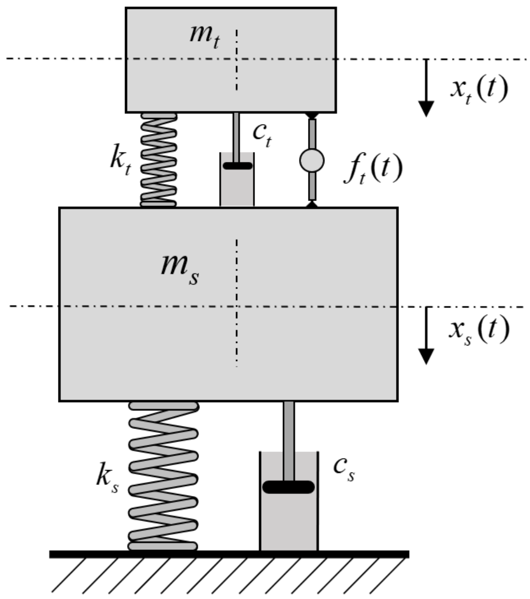

Figure 1: Dynamic system of model of a TMD with a force device.

Based on [3], this work generalizes this common framework in order to design a semi-active control law a feedback system. Thus, the optimization methodology applied in [2] can be extended to this problem in order to study the aforementioned practical implementation problems. In addition, this work shows the advantages of using an electric linear motor as a reaction force device ($f_t(t)$), which emulates the behaviour of a magnetorheological device. These advantages are: i) the problem of maximum damping force imparted by the magnetorheological device can be solved and ii) the control law guarantees the stability of the overall system since a semi-active TMD is passive device from the energy point of view.

This work includes a control example in simulation (Figure 1) in order to illustrate the potential application in practice. The simulation includes models of reals a magnetorheological damper and an electric linear motor. In addition, frequency response functions for different input perturbations are obtained, showing the effect of the nonlinearities (models and control law).

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SENSOR PLACEMENT OPTIMIZATION USING CONVEX L_0 NORM RELAXATIONS

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Keywords: sensor placement, sensor selection, mixed L1/L2 norm, convex optimization.

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ABSTRACT

Sensor placement optimization problem, or closely related sensor selection problem in the setting where possible sensors locations are prescribed, has attracted significant interest in the last decades -- it is certainly one of the most fundamental problems in vibration measurement, modal testing, structural health monitoring, energy harvesting, or virtually any measurement procedure which requires sensors placement and sensors number selection. Another motivation for this topic is perhaps its inherent difficulty – for instance, a problem of selecting *p* sensors among *n* possible locations has ( ) solutions and is known to be *NP*-hard. As the result, many different approaches for tackling this important problem have been proposed [1], with a wide plethora of methods ranging from purely heuristic to the solutions of the (computationally tractable) approximations of the original problem [2].

In this paper, we present the algorithm for optimal sensor placement based on a series of the convex optimizations of the original problem. Generally speaking, each iteration in our approach requires simultaneous minimization of some performance criteria of the dynamical system under the consideration (e.q. measurement error) and sparsity-inducing term [3]. In the existing algorithms [4], [3], the non-convex sparsity inducing L_0 norm is replaced by a series of weighted L_1 relaxations [5]. This introduces sparsity, up to the desired level, into the matrix which determines which system states (or variables) have a sensor attached. In other words, sensors are (optimally) distributed to measure some of the system states.

In the actual sensor placement optimization setting, where the sensor locations are often determined by more than one spatial coordinate (e.q. three coordinates in three dimensional space), this approach appears to be overly restrictive. It effectively eliminates some spatial directions from some locations, thus forcing the sensors directions to “align” with the certain coordinates corresponding to spatial directions. To overcome this difficulty, we generalize the existing approach by introducing mixed L_1/L_2 norm relaxations. This effectively groups coordinates that correspond to the spatial sensor locations and eliminates (or selects) sensor locations as the entire variable groups.

We illustrate the efficiency our approach on a numerical example concerning the displacement and velocity sensors placement on the finite element model of a structural element. We discuss

optimization algorithm parameters (e.q. weights choice) and address the numerical efficiency and convergence rates with respect to the existing algorithms.

Furthermore, as a concluding remark in this paper, we point out that our algorithm falls into the broader category of sparsity-inducing optimization algorithms [6], which play significant role in other research areas such as signal processing, statistics and machine learning. We discuss this connection, bridging the gap between other research areas and providing the insights into possible future research.

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Calibration of human-structure interaction model parameters on an ultra-lightweight FRP lab footbridge

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Keywords: human-structure interaction, dynamic load factor, serviceability, FRP footbridge.

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ABSTRACT

Structural applications using fibre-reinforced polymers (FRPs) have many benefits: not only to lead to sustainable and environmentally-friendly bridge projects, slender and lighter structure designs are increasingly being found. However, these designs have less damping, but they also have less mass and it is easy for high accelerations to be achieved when pedestrians pass through a structure. In addition, in this type of lightweight structures, the effect of human-structure interaction (HSI) influences the dynamic response of the structure, so it is no longer an effect that can be ignored. The effect of HSI is currently being a widely investigated effect [1]. The model used in this work is the one developed by Jimenez-Alonso et al. [2]. This pedestrian model consists of modelling the pedestrian as a Single Degree of Freedom (SDOF) using Mass-Spring-Damper (MSD) system (see Figure 1). The coefficients of the first two harmonics of the Vertical Dynamic Load Factors (VDLF) of this model have been calibrated, as well as the mass, stiffness and damping of the pedestrian SDOF.

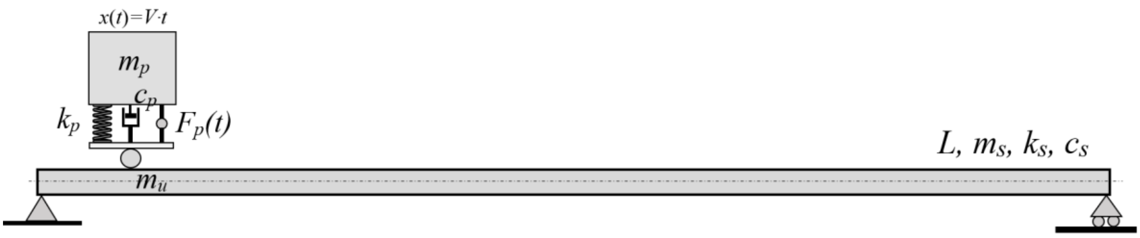

Figure 1. Mass-Spring-Damper system for Human-Structure interaction model.

The structure analysed in this research is a 10-meter span FRP laboratory pedestrian footbridge presented in [3] (see Figure 2). The frequency of the first mode of vibration of this structure is 7.6 Hz, with a damping ratio of 1.5% and a modal mass of only 400 kg. This frequency, 7.6 Hz, is a high value and does not allow to use the already calibrated coefficients of the HSI model mentioned above.

Therefore, HSI model used requires the calibration of the third and fourth harmonic coefficients (walking at 2.5 Hz and 1.9 Hz respectively) for the pedestrian VDLF. In addition, it has also been necessary to calibrate the mass distribution, stiffness and damping of the MSD SDOF system used for the HSI behaviour.

Figure 2. FRP footbridge.

The adjustment of the third and fourth VDLF coefficients for the HSI model has been carried out by minimizing the error between the spectra in the frequency domain of the model curve and the responses of the structure obtained experimentally. This procedure for adjusting coefficients and minimizing error has already been used before in [4].

The results obtained show that in such light structures, high accelerations can be achieved despite the effect of the HSI, which includes damping of the structure, and although the pedestrian excitation load is exerted using the third or fourth harmonic. The modal parameters of the structure can change and it is important to study and know why they vary in order to be able to predict accelerations with certainty and to be able to successfully design passive and semi-active inertial actuator solutions.

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EXPERIMENTAL MODE CHARACTERIZATION OF A TYMPANIC MEMBRANE FROM TIME DOMAIN HIGH SPEED DIGITAL HOLOGRAPHIC TESTS

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Keywords: Tympanic membrane, High-speed digital holographic, finite element model, mode shape

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ABSTRACT

This works is part of a research line focused on the generation of a finite element numerical model of the tympanic membrane (TM) based on experiments carried out on a cadaveric human temporal bone. A high-speed digital holographic (HDH) system was used to obtain the acoustically-induce transient displacement of TM surface of eight specimens during a transient test in the Eaton-Peabody Laboratory.

We are developing a methodology to generate the complete model of the TM system by validation of numerical and experimental data. This study will help to better understand the mechanisms of transmission of sound in the ear, where TM plays an important role in the transmission of sound energy to the inner ear through the excitation of the ossicular chain.

Displacement measurements were obtained by an HDH method based on correlation interferometry capable of measuring almost instantaneously the full field of view of the displacements of the visible face of the TM (>200.000 points at 67.200 camera frame rate) [1–3]. The shape measurement is based on the Multiple Wavelength Holographic Interferometry (MWHI) system, by means of lighting variations with a constant optical path length (OPL) [4,5].

Based on the experimental data, the shape of the outer wall of the TM and the damping values are evaluated. Other parameters (Young modulus, thickness, etc.) will be obtain by numerical-experimental validation between test data and an iterative series of transient numerical simulations with ANSYS software. There is very little numerical work on the time-domain response of the human auditory system [6] and no one referred to a specific specimen. However, the authors have experience in harmonic and modal simulations of these mechanisms, which is a starting point in this study [7–9].

In this work, preliminary methodology for the determination of mode shapes obtained by experimental data is presented. A new routine is programmed based on the post-processing of transient data of full external face of TM during the test. The main objective is to have an accurate approximation of main frequencies and shape modes that we can use further in the numerical-experimental validation.

In this sense, the time response of the system is processed in two different ways. Fast Fourier Transform is applied to obtain the Frequency Response Function with different weighting window, one centred on the initial impulse function applied and another one centred on the long-term response of the system. In the first case, the FRFs shown the spectral distribution of the incident pressure wave. On the second case, the whole modal response of the system can be identified, and natural frequencies and mode shape can be estimated as well as damping values.

The methodology presented shows that we can obtained important information to characterize dynamic properties of the system directly from this kind of transient experiment. In addition, sets a range of starting values for some material properties that reduces the number of iterations in subsequent numerical transient simulations.

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HYSTERETIC DEVICE FOR VIBRATION CONTROL

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Keywords: Passive control, yielding-based device, design optimization, non-linear dynamic analysis.

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ABSTRACT

In the field of seismic passive protection of structures an important role is played by hysteretic devices since they can reduce the energy entering the building thanks to the plastic behaviour of the material. More in detail, metallic devices show a stable behaviour under cyclic loads, producing a wide hysteresis cycle which depends on the yielding limit of the material. An example of these devices is represented by steel panels subjected to shear force. Usually, such devices possess a wide dissipative capacity related to their dimensions. The limit of these kinds of Energy Dissipating Devices is that the dissipation capacity is activated only after they sustain large excursions in the inelastic field. As consequence, the devices are ineffective for vibrations smaller than the inter-story drift that produces the yielding of the material composing the device.

To reduce the displacement in correspondence of which the hysteresis cycles of the dissipators are activated, devices made with ordinary aluminium alloys activated by a shear behaviour have been proposed [1-4]. The use of hysteretic devices has been investigated considering both far-field and near-field earthquakes [5-8].

In the present paper the optimal design of a shear panel made of aluminium and steel and the results of quasi static tests are shown. The geometrical configuration of the device is chosen in accordance with a parametric analysis performed in order to optimise the hysteretic behaviour of the device. The aim of the procedure is to maximize the plastic strain energy in the aluminium plate. Figure 1 shows the main geometrical parameters needed to define the device configuration. Quasi-static tests have also been carried out on a prototype of the dissipative device in order to characterize it. Figure 2 shows the prototype utilized for the characterization tests.

By mean of the interpolation of the experimental results, some analytical expressions of the applied shear load and the maximum displacement at the top of the panel have been determined for the device. The optimal response obtained from the characterization tests exhibits a good dissipative behaviour of the device, highlighted by a wide enough hysteresis cycle.

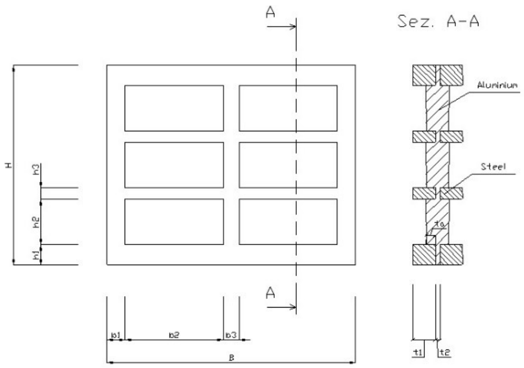

Figure 1. *Geometrical parameters of the aluminium- steel shear panel*

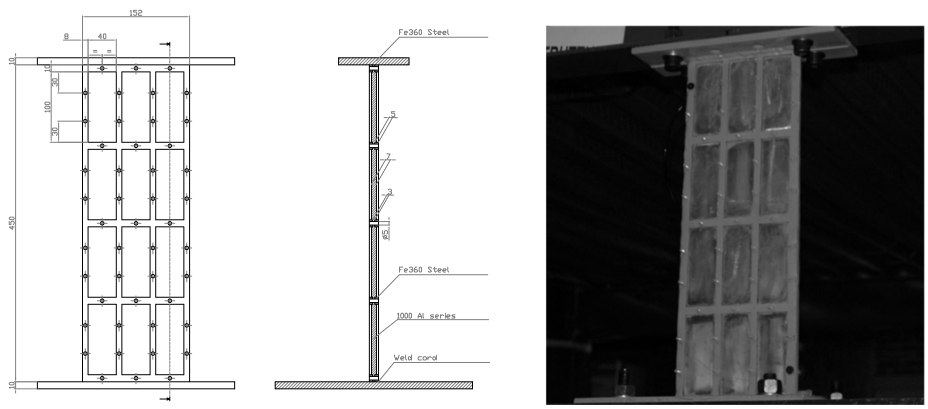

Figure 2. *Prototype of the aluminium-steel dissipater.*

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EXTENDING THE FATIGUE LIFE OF SLENDER STEEL FOOTBRIDGES WITH TUNED MASS DAMPERS

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Keywords: fatigue assessment; human-induced vibrations; footbridges; pedestrian traffic; tuned mass dampers.

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ABSTRACT

During the last decades of the previous century, the urban development of the main European cities made necessary the construction of circumferential highways to both improve the vehicle circulation and avoid traffic congestions in these urban areas. Despite the benefits, which these transportation channels have provided for the habitability and evolution of these cities, they may constitute a barrier for the remaining urban transport means [1] since these ring roads divided every urban area into two sub-regions: (i) an inner; and (ii) an outer one. For the particular case of the pedestrian mobility, multiple footbridges have been built, during the last twenty years, in order to guarantee an adequate permeability between the mentioned sub-regions.

Some common characteristics can be observed in these footbridges [2]: (i) their main span, due to the geometrical constraints generated by the lower highway, is around 40-50 m (so it is expected that their first vertical natural frequency is inside the range that characterizes the pedestrian step frequency [3]); (ii) their typology is simple with few supplementary elements (so low damping ratios are expected [3]); and (iii) their dynamic behaviour is not analysed in detail (neither numerically during their design phase nor experimentally after their construction) since high pedestrian densities are not expected on these footbridges due to their localization [3].

There are few events, reported in literature, in which these structures have shown service or failure problems. However, similarly as it has happened with other civil engineering infrastructures [4], the traffic demand on them has increased gradually during the last years, due to the great expansion experienced by the abovementioned cities (their urban centres have exceeded the peripheral barrier generated by the ring road). Thus, this changing scenario makes necessary to assess the dynamic behaviour of these footbridges under these new traffic conditions.

As one of the main failures, that the increase of the traffic demand has originated in other civil engineering structures (for instance in steel bridges subjected to road or train loads [4]), is the fatigue damage, both the fatigue assessment of these existing footbridges under pedestrian action and the

improvement of their behaviour via cost-efficient interventions [5] are interesting challenges to be tackled in the coming years.

In order to shed some light to this problem, two feasibility analysis have been performed herein. First, the possibility of the occurrence of a fatigue failure in an existing steel footbridge has been assessed via a numerical case-study in which the fatigue damage of a benchmark footbridge (as Fig. 1 shows) has been computed in terms of different pedestrian intensities [6]. The uncertainty, associated with the modification of the modal properties of the footbridge during its lifecycle, has been simulated via a fuzzy approach. Subsequently, the possibility of extending the lifetime of existing steel footbridges via the installation of tuned mass dampers (TMDs) has been assessed. For this purpose, a TMD has been designed, according to the motion-based design method [7], to guarantee the absence of fatigue failure in the benchmark footbridge subjected to different pedestrian flows. Finally, some concluding remarks have been included to close the manuscript.

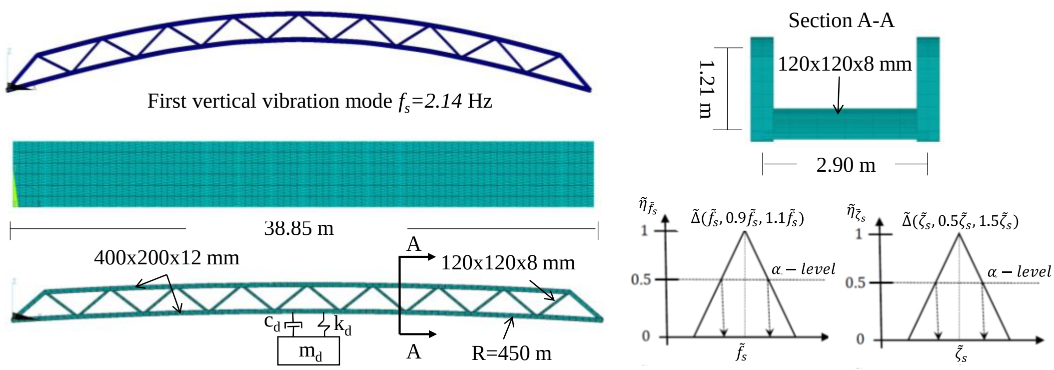

Figure 1. *Description of the benchmark footbridge, first vertical vibration mode and triangular membership functions, $\tilde{\Delta}$, of the two fuzzy variables (where $\tilde{f}_s$ is the first vertical natural frequency and $\tilde{\zeta}_s$ is the associated damping ratio) considered to simulate the uncertain conditions.*

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CRACK GROWTH AND DETECTION IN CNT-COMPOSITES BASED ON INDUCED RESISTIVITY CHANGES

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Keywords: Crack detection, crack growth, X-FEM, piezoresistive composites, nanocomposites, damage identification

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The field of multifunctional materials and structural systems has been the focus of numerous researchers in recent years [1]. In this area, smart structural systems and self-sensing materials are of great interest due to their potential applications in the continuous monitoring of structural integrity. In this context, the piezoresistive behaviour exhibited by carbon nanotube-reinforced composites allows their use as strain sensors in new structural health monitoring (SHM) applications, by measuring the change in electrical resistivity of the composite structure [1].

This work presents a numerical framework based on the extended finite element method (XFEM) to calculate the changes in electrical resistance caused, not only by the presence of a crack, but also by its growth (see more details in [2]). Using the commercial finite element program ANSYS, the continuous virtual monitoring of the structure is solved in two steps. First, the crack growth and the deformation response of the cracked composite domain are computed ---assuming non-permeable crack conditions electrically--- by the XFEM. In a second step, the electrical conductivity of the piezoresistive elements located in the domain is updated according to the state of deformation. Fracture assessment is accomplished by comparison with the electric resistance for the undamaged structure.

As an example of the capabilities of this formulation, Fig. 1 (a) shows a plate of a MWCNT/epoxy piezoresistive composite material, subjected to uniform tension, and which has the distribution of the electrodes shown in Fig. 1 (b). After measuring the electrical resistance relative to the plate without damaging it, in Fig. 2 we can see how we obtain different electrical resistance values depending on the crack size (L/a) and the crack orientation (α).

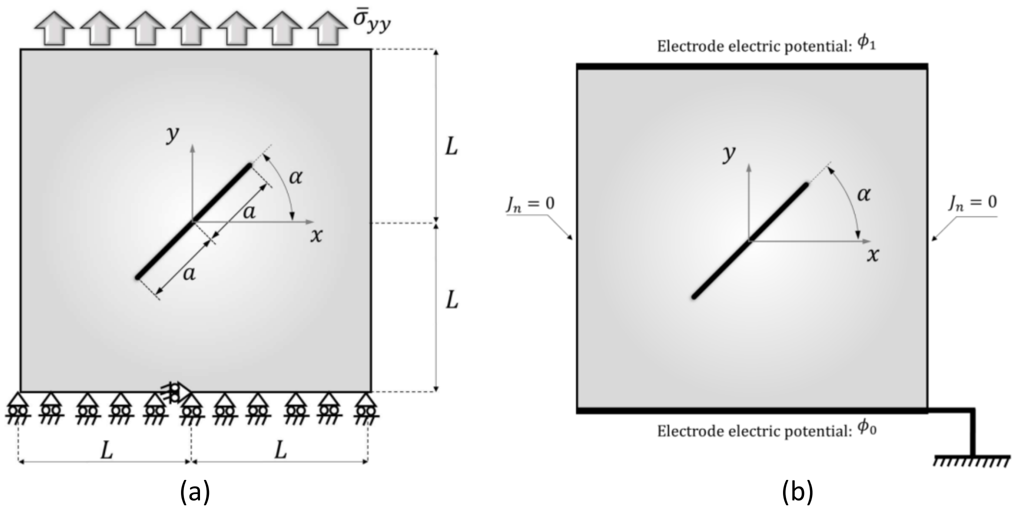

Figure 1. *(a) Cracked plate of MWCNT/epoxy composite material subjected to uniform tension. (b) Position of the electrodes on the plate.*

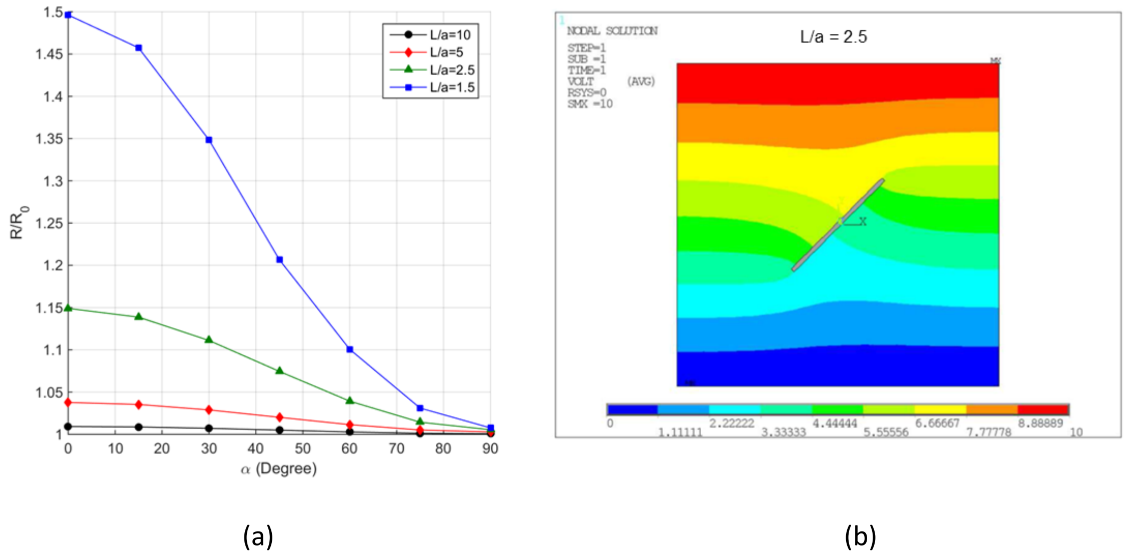

Figure 2. *(a) Influence of crack size (L/a) and crack orientation (α) on changes in electrical resistance. (b) Distribution of the electric potential in the plate for the case of a crack size of L a = 2.5 and a crack orientation* $\alpha = 45^o$.

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NUMERICAL ANALYSIS OF ALUMINIUM LATTICE STRUCTURE WITH K-JOINTS

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Keywords: aluminium, lattice structure, FEM analysis, K-joint, welds.

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ABSTRACT

In the engineering practice, aluminium is more and more used as main structural material not only for industrial buildings, antenna towers, electrical line towers, platforms, bridges, structures in areas with extremely low temperatures etc, but also in various types of public buildings, particularly in spectacle buildings. That is mainly because of aluminium high strength and high resistance to different environmental conditions ("wear-and-tear"), as well as its aesthetics quality. Further advantages of typical aluminium structures – planar (2D) and spatial (3D) lattice structures – are light weight, low costs of transport and maintenance, as well as fast assembling. Among these structures, lattice structures made of circular hollow section (CHS) profiles have prominent role. Connections represent not only important, but possibly critical issue in the design and construction of any type of structures, particularly those of aluminium. Beside the structural design problems, joints also influence the costs of the structure.

In this paper, spatial aluminium lattice structure made of CHS profiles with uniplanar K-joints, subjected to static load, is analysed (Fig. 1). Considered K-joints are formed by direct welding of narrower CHS profiles (brace elements, having smaller radius), to the outer surface of wider CHS profiles (chord elements, with bigger radius). High stress concentration located exactly in the weld, due to discontinuous stiffness in this region, makes the joint highly critical part of the lattice structure and causes common fracture that often occurs on the surface of the chord tube. That is why special attention is devoted to adequate analysis of joints in this work.

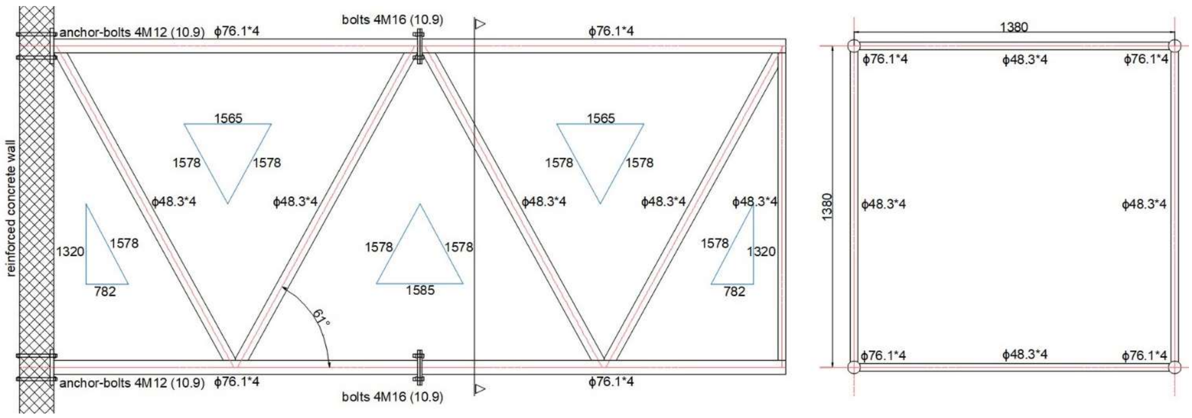

Figure 1. *General geometry of analysed spatial aluminium lattice structure made of CHS profiles with uniplanar K-joints.*

Detailed numerical analysis of the lattice structure as the whole has been conducted in order to obtain the comprehensive results (Fig. 2). Finite elements method (FEM) has been employed, by means of ANSYS software, with a variation of different relevant parameters, so to enlarge the insight into the static behaviour of the structure, as well as to provide a better ground basis for its design.

It has been observed that force-deflection curves demonstrate a similar overall performance for various FE types. The FE size variation, and consequently their quantity variation, in case of a single FE layer per CHS wall thickness, has barely influenced the results of analysis. FEM meshes were also made with two FE layers within CHS wall thickness. Some trials with more than two FE layers were performed and commented as well. Finer mesh provides more comprehensive information. However, it is not desirable from the aspect of time consumption and computer preferences. For the high-quality FEM analysis, it is necessary to include the welds in detailed model of considered joint, because of the heat affected zone (HAZ), which is very important for aluminium as material. The HAZ is thoroughly analysed herein for the most loaded joint (Fig. 3). Finally, the paper aims recommendations for optimal FEM model of K-joint aluminium lattice structure in terms of time consumption vs quality and accuracy of results.

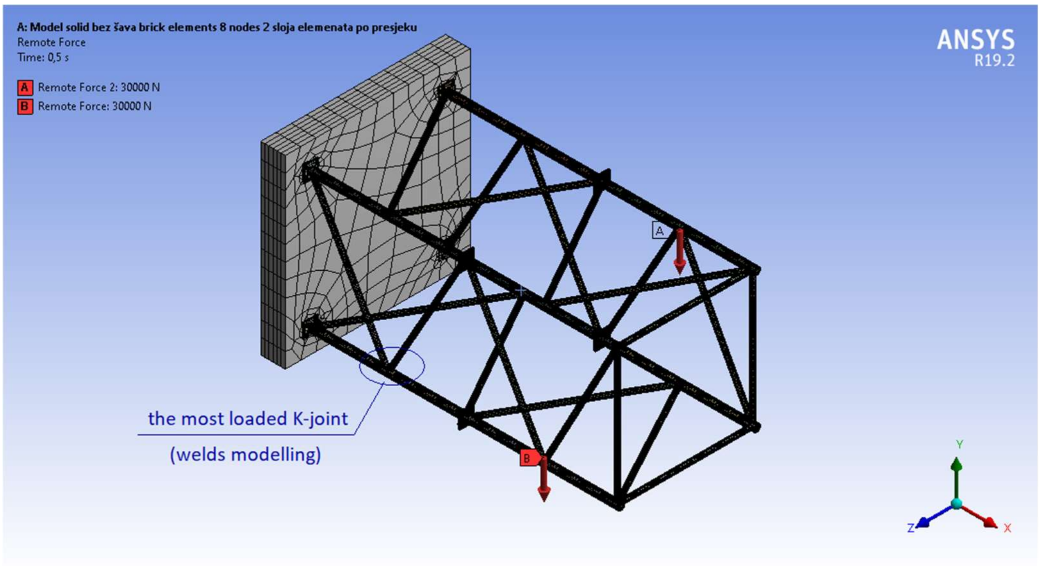

Figure 2. *ANSYS model of analysed spatial lattice structure.*

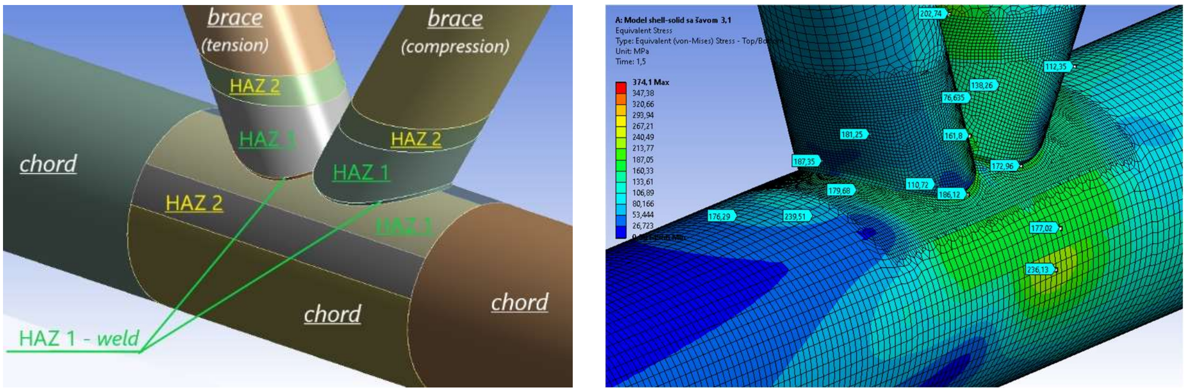

Figure 3. *a/ Position of aluminium softening zones HAZ 1 and HAZ 2.*
b/ An example of Von Mises equivalent stress in the most loaded K-joint

M_{CR}-L CURVES FOR HOT ROLLED I-SECTIONS

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Keywords: lateral torsional buckling, elastic critical lateral torsional buckling moment, M_{cr}-L curves.

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ABSTRACT

In the draft of the new version of EN 1993-1-1 [1], a more consistent method for determining lateral torsional buckling resistance of members with hot rolled I-sections, in comparison with the existing one [3], is proposed.

The proposed method is based on work made by Taras [2]. By developing a LTB specific Ayrton-Perry formulation for mechanical model and precisely calibrated imperfection factor, better consistency and precision is achieved. According to this new proposed method, reduction factor χ_{LT} should be calculated as follows:

$$\chi_{LT} = \frac{f_m}{\Phi_{LT} + \sqrt{{\Phi_{LT}}^2 - f_m {\bar{\lambda}_{LT}}^2}} \tag{1}$$

with

$$\Phi_{LT} = 0{,}5\left(1 + f_m\left(\left(\frac{\bar{\lambda}_{LT}}{\bar{\lambda}_{LT}}\right)^2 \alpha_{LT}(\bar{\lambda}_z - 0{,}2) + {\bar{\lambda}_{LT}}^2\right)\right) \tag{2}$$

where f_m is factor which takes into account the shape of bending moment between lateral restraints.

Like the method present in the current version of EN 1993-1-1 [3], for its practical use, in order to determine the relative slenderness $\bar{\lambda}_{LT}$, it is necessary to calculate elastic critical lateral torsional buckling moment M_{cr}. If calculation is done by hand, this task can be rather time consuming and tricky.

The determination of M_{cr} may be simplified by introducing graphical approach. The idea is to derive and use appropriate M_{cr}-L curves, for a specific length of a member L and specific load case, that would enable easier determination of M_{cr} in engineering practice.

In this paper, M_{cr}-L curves are derived for all IPE, HEA and HEB sections with the length from 4m up to 12m, under uniform load, as Fig.1 illustrates.

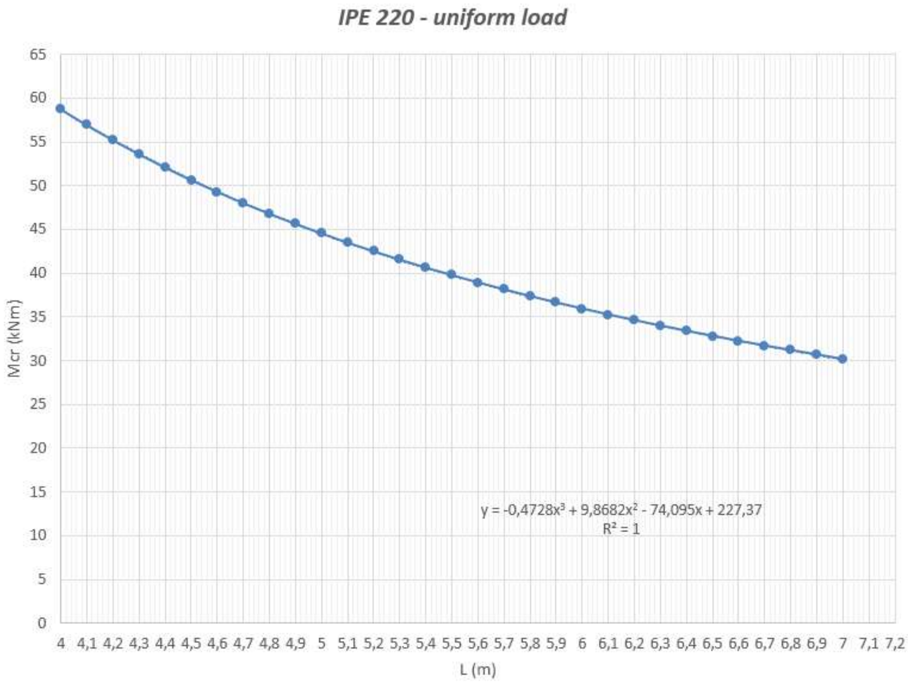

Figure 1. *M_{cr}-L curve for IPE 220, with L = 4-7m, under uniform load.*

The underlying method for calculating M_{cr} used for deriving M_{cr}-L curves is that proposed by Kolekova and Balaž [4].

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MECHANICAL THIN INTERPHASES IN LEAD-FREE PRINTABLE PIEZOCOMPOSITES

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Keywords: Interface spring model; interfacial damage; lead-free piezocomposites; finite element analysis, effective properties.

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ABSTRACT

3D printable lead-free piezocomposites offer scalable and eco-friendly solutions in many engineering applications. Typically, the composite system consists in polymeric matrices reinforced with active polycrystalline particles. The presence of interfacial inclusion/matrix damage in such composites may alter their capability to act as functional smart materials. From the mechanical point of view, an interfacial imperfection refers to displacement jump, due to, for instance, debonding or slippage. In this work, a thin interphase model to account the matrix-inclusion interfacial imperfections is presented. Thus, based on a periodic unit cell, the influence of interfacial damage on the effective mechanical properties is studied. The proposed computational framework is based on the works [1] and [2]. Comparison with the theoretical interface spring model proposed by Lee et al. in [3] and [4] is also presented.

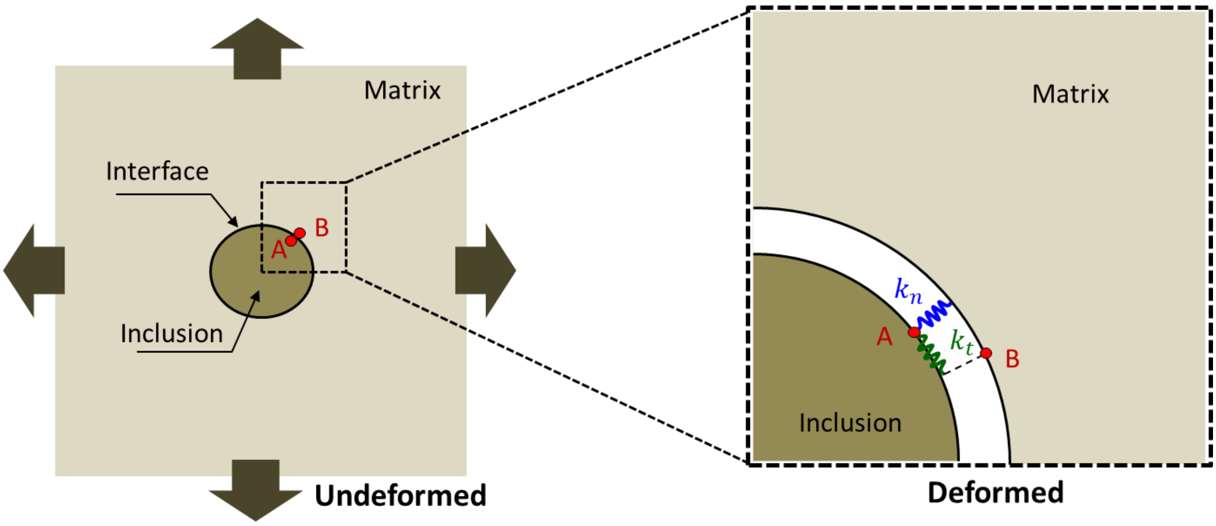

Figure 1. *Scheme of the matrix-inclusion interface spring model proposed in [3, 4].*

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A FAST APPROACH TO STUDY THE DYNAMIC RESPONSE OF RAILWAY BRIDGES ACCOUNTING FOR SOIL-STRUCTURE INTERACTION

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Keywords: Railway bridge dynamics, Bridge soil-structure interaction, Non-proportional damping, SSI Perfectly Matched Layers

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ABSTRACT

The response of railway bridges is strongly affected by soil-structure interaction (SSI), especially under resonance conditions. Radiation and material soil damping influence the modal parameters and usually mitigate the structural vibration levels. However, the interaction between the sub-structure and the soil is seldom considered in numerical models when solving the dynamic problem. In order to predict realistically the vibrational response of bridges under railway traffic, or to assess the structural integrity for new operational situations, SSI should be considered. In the design of new structures this may lead to optimized alternatives and in the case of existing ones, it will permit to assess the bridge performance when facing operational challenges (e.g. increase in the speed or capacity of services) and improve model calibration procedures.

In this paper a general approach is proposed to solve the SSI problem in railway bridges applying modal superposition. A sub-structuring approach involving PML permits the modelling of arbitrary foundation geometries. First, the problem is decoupled into i) the soil-foundation problem, and, ii) the soil-foundation-bridge interaction problem. In the first, the equivalent frequency dependent dynamic stiffness and damping characteristics of the soil-foundation system are computed using the FE-PML method. In the second, the dynamic response of the structure under railway traffic is computed using a FE model that includes spring/dashpot elements at the supports, where the equivalent properties at the bridge-foundation connection points are extracted from the first problem. This soil-foundation-bridge model is solved by modal superposition considering the equivalent dynamic stiffness and damping of the soil-foundation corresponding to each natural frequency. To do so, a model updating procedure is implemented. As the model presents non-proportional damping, the complex eigenvalue problem is solved in order to compute the natural frequencies and mode shapes.

The study considers the vertical force transmission between the deck and the foundation, as the aim of the investigation is to develop and present the methodology. Nevertheless, the approach could easily be extended to more complex bridge-foundation-soil systems.

From the analyses performed the following is concluded:

i. The proposed approach can be used to obtain the dynamic response of railway bridges under running trains considering SSI, with minimal computational effort. However, it is remarked that soil-foundation impedances should be previously calculated.
ii. Resonance and cancellation phenomena, which are often responsible for the maximum bridge acceleration, are accurately reproduced.
iii. Using the proposed approach, it is possible to solve the dynamic problem taking into account high modal contributions of the structure, with minimal computational cost.
iv. Using the proposed model, the experimental response of a real beam-type bridge under train loading is reproduced, capturing the frequency contributions of the first structural bending mode and the loading frequency contributions.

ACKNOWLEDGEMENTS

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EFFICIENT METHODS IN HYBRID SIMULATION OF STRUCTURES EQUIPPED WITH ACTIVE VIBRATION DAMPERS SUBJECTED TO INERTIAL MOVING LOADS

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Keywords: Real-time Hybrid Simulation, Inertial Moving Load, Vibration Control Devices, Proof-mass Actuator, Active Vibration Control.

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ABSTRACT

Real-time hybrid simulation has been proven to be a reliable technique to analyze the behavior of complicated structural systems. In real-time hybrid simulation, the parts of the structure whose behavior is well known are simulated numerically, very often by means of finite element models, whereas the parts of the structure whose response entails more uncertainty are physically tested [1]. The hybrid test proceeds as the numerical and the physical subdomains exchange information in terms of kinematic and dynamic magnitudes. A typical workflow would include the following steps: (i) the numerical model calculates the displacements at the interface of the physical domain, (ii) these displacements are imposed by means of actuators of diverse nature and (iii) the forces exerted by the physical domain on the actuators are read and fed back to the numerical model which calculates the displacements to impose to the physical system in the next time step. Therefore, it is clear that the success of the hybrid simulation scheme strongly depends on the accuracy of both the numerical model and the actuator control system.

The inertial moving load problem is not trivial. The numerical approaches consisting in lumping the moving mass proportionally to the distance of the neighbor nodes only work appropriately for low velocities and care must be taken to properly differentiate the position of the moving mass [2,3]. On the other hand, the control system in charge of governing the motion of the actuator must be accurate enough so as not to cause significant delays which would lead to overall system instability [4].

In this paper, a hybrid simulation test set-up consisting of an Euler-Bernoulli beam equipped with an active vibration absorber and traversed by an inertial moving particle is investigated by means of numerical simulations. Firstly, the proposed hybrid test set-up is explained in detail. Later on, the procedure described in [2] is followed to derive the modified mass, damping and stiffness matrices and force vector adequate for the inertial moving load problem, which will be later integrated by means of a Newmark scheme. The goodness of the obtained numerical model is assessed by means of a semi-analytical method. The active vibration absorber device and its control algorithm are covered next; an

ideal direct velocity feedback control approach will be employed in this study. Finally, the model of the hydraulic actuator employed as the interface between the numerical and physical subdomains and its control system are dealt with and some guidelines for the actuation system sizing are given.

Numerical simulations indicate that the results obtained with the hybrid scheme faithfully represent the actual set-up constituted by the structure, the active vibration absorber and the moving inertial load, provided that certain conditions on the mesh of the beam and on the control system accuracy are fulfilled. The proposed approach might be of interest for researchers to develop hybrid tests to obtain quality estimates of the behavior of structures and vibration absorbers when the former are subjected to moving loads.

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PARAMETRIC ANALYSIS OF SERVICEABILITY LIMIT STATE VERIFICATIONS IN REINFORCED CONCRETE ELEMENTS SUBJECTED TO BENDING

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Keywords: concrete, stress limitations, cracking, deflections, parametric analysis.

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ABSTRACT

For the design of structural concrete elements, the different standards establish the verifications to be carried out both at failure (ULS) and in service (SLS). It is usual in reinforced concrete to start by designing steel amounts to comply with ULS and, subsequently, to verify the different SLS's, introducing corrections in case of non-compliance. In relation to the SLS, existing literature has been reviewed [1]–[4] and it has been found that most cases focus on the verification of cracking and vertical deformations. However, the stress limitations of concrete and steel seem to be secondary or even recommended to be literally omitted in reinforced concrete structures [5].

This paper first presents a case centered on a suspended beam for a building, with 7.5 m spans, designed for category A according to Eurocode 1 [6]. Maintaining a rectangular section with a constant depth of 50 cm, designs with different section widths (15, 20, and 30 cm) and two strength grades (C20/25 and C30/37) were studied. The ULS design was carried out for a linear analysis with redistribution of moments according to Eurocode 2 [7], using $\delta = 0.8$. Regarding the SLS's, the crack widths and minimum cross-sectional depth limitations for vertical deformations (deemed-to-satisfy type verification in the 2010 Model Code [8]) were satisfied in all six cases analyzed. However, the short-term concrete compressive stresses in service reached values between 80% and 140% of the characteristic strength under the quasi-permanent combination (in the case of the characteristic combination the values exceeded 170% in some cases).

Given this particular result, a massive parametric analysis was performed in MATLAB to design and check structural solutions of more than 1.5 million reinforced concrete beams by varying 12 parameters directly involved in their design: (1) characteristic concrete strength (f_{ck}); (2) aggregate type; (3) ambient relative humidity; (4) yield strength of the reinforcing steel (f_{yk}); (5) beam span; cross-sectional depth (6) and width (7); (8) tributary width of the slab supported by the beam; (9) slab depth, directly affecting its self-weight; (10) occupancy imposed load according to Eurocode 1, with its corresponding combination factor (2); (11) boundary conditions; and (12) redistribution factor δ of moments, used in the structural analysis for ULS. An algorithm was programmed to perform the combinations after removing those that made no sense (e.g., applying redistribution to a statically determinate beam, analyzing beams whose cross-section could not provide sufficient strength

without exceeding unrealistic or excessive amounts of reinforcement). Finally a total of 1,547,808 cases were successfully analyzed. The SLS calculations (stress limitations, crack widths and deflections) were carried out both in the short and long term, taking into account concrete shrinkage and creep – including the non-linear creep model when exceeding 45% of f_{ck}. The vertical deformations were determined by double numerical integration and by applying energy theorems. For each beam, 100 cross-sections were designed and analyzed across the beam ends. The most relevant results of the parametric analysis are summarized in Table 1.

Table 1. Non-compliance of SLS verifications after massive design of RC beams for ULS

Type of SLS verification	Cases that do not satisfy a specific SLS	
	Short term	Long term
80% of the yield strength of the reinforcing steel	19,4 %	25,4 %
Characteristic compressive strength of concrete	35,1 %	----
60% of the characteristic strength of concrete	82,7 %	----
Crack width	7,2 %	8,5 %
Vertical deformation	1,6 %	9,9 %

The 60% f_{ck} limitation is usually set to avoid micro-cracking in compression and also roughly matches 40-50% f_{cm} in the usual strength grades. At higher compressive stresses the concrete deviates from the linear behavior generally assumed in service. Therefore, the results obtained would challenge the general approach in SLS in cases that may occur in practice –which are identified in the full paper– and that would constitute a potential source of pathologies in the medium-long term.

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PARAMETRIC STRUCTURAL ANALYSIS OF REINFORCED LIGHTWEIGHT CONCRETE BEAMS FOR BUILDINGS

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ABSTRACT

In contrast to other fields of engineering where the use of materials that lighten the structure has gradually revolutionised the technology, the use of lightweight concrete in building structures is still a relatively small part of today's construction industry. Despite the fact that lightweight concrete has been known for more than 2,000 years [1] there is a certain lack of awareness of the advantages that its use can offer [2]. One of the possible reasons for this situation is the difficulty in standardising lightweight aggregate concrete (LWAC) when made from natural lightweight aggregates, as these vary enormously from region to region depending on the type of deposits [3]. However, an artificial lightweight aggregate such as light expanded clay aggregate (e.g. LECA) can be manufactured anywhere in the world in the last few decades by means of a specific industrial process that allows its properties to be standardised. Thus, an example of the potential impact of LWAC in structural engineering can be given for floors and beams in buildings: the savings in steel in beams and the savings in concrete volumes in the supports (which would be maintained with conventional concrete) and in the foundations could constitute a significant improvement in terms of sustainability [4], as well as an increase in the quality of housing in terms of sound insulation [5] and safety against earthquakes [6] and fire [7].

This work has addressed some fundamental aspects in the use of LWAC for structural purposes. A massive parametric analysis has been carried out in MATLAB focusing on beams for building floors - both made with LWAC- for spans, depths and conventional building loads. Since the range of cases is infinite, it has been applied firstly to beams with the following parameters: (1) spans between 4 and 7 m; rectangular cross-sections with (2) widths between 25 and 35 cm and (3) depths between 35 and 55 cm; (4) tributary floor widths between 3.5 and 6 m; (5) moment redistribution factor d for ULS between 0.7 and 1; (6) dry oven densities between 2200 and 1000 kg/m^3; (7) characteristic compressive strengths (f_{ck}) of 20, 25 and 30 MPa; and (8) occupancy loads between 2 and 5 kN/m^2. Secondly, this same analysis has also been extended to flat beams with a depth between 35 and 50 cm. The number of cases studied in this parametric analysis reached 1.5 million cases and its objectives were (i) to determine the saving –or additional consumption– of steel in the longitudinal reinforcement of the floor beams, (ii) to calculate the reduction in the loads transmitted to the building supports and foundations, and (iii) to evaluate the impact on cement consumption required

by structural LWAC in order to achieve reach the same strength as conventional concrete, thus allowing sustainability to be included in the study. For the latter purpose, the ACI method [8] was applied for the dosage and compared with the Fanjul method [9], for LWAC densities between 2000 and 1600 kg/m^3. A formulation has been proposed to keep the ratio of sand to coarse aggregate volume constant, thus simplifying the dosing process of concretes with coarse aggregate of two different densities and avoiding trial and error loops or imprecisions in comparing concretes. Fig. 1 summarises the most common situations and concludes that the choice of moment redistribution factor might sometimes have an enormous impact, not always intuitive, on steel savings.

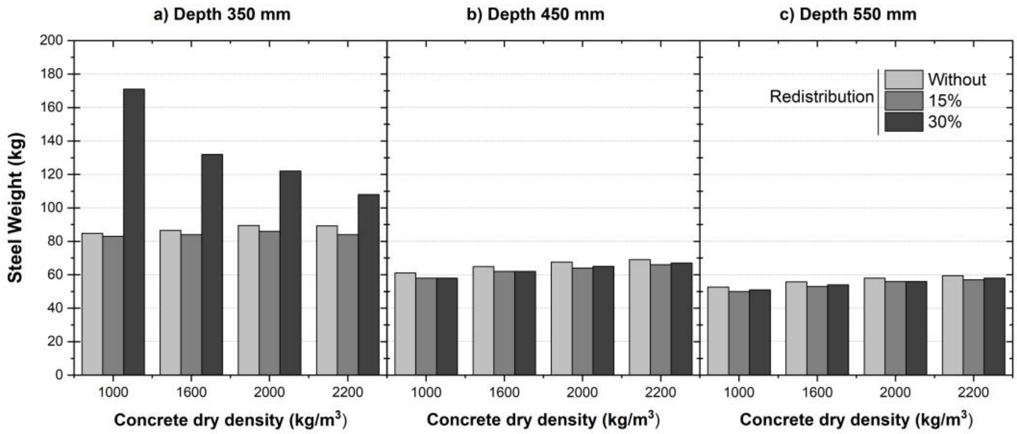

Fig. 1 Effect of concrete density and moment redistribution factor on the longitudinal reinforcement savings for a 5 m two-span continuous beam with f_{ck} = 25 MPa and subjected to an occupancy load of 2 kN/m^2.

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MECHANICAL BEHAVIOUR OF MASONRY PANELS PREVIOUSLY DAMAGED BY HIGH TEMPERATURES

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Keywords: masonry panels, shear strength, high temperature, Textile reinforced mortars (TRM).

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ABSTRACT.

Masonry walls exhibit low tensile strength and high material heterogeneity, which makes them especially vulnerable against accidental loadings. There are a large number of studies, both experimentally and numerically, of the masonry behaviour under accidental loadings such as earthquakes. In this regard, the most relevant research focuses on (1) evaluating the shear strength of masonry with diagonal compression tests, (2) its behavior against in-plane cyclical loadings and (3) TRM-based reinforcement techniques [1]. However, there are very few studies that analyse the behavior of masonry under high temperature exposure, such as those that can occur in a fire.

This paper describes the preliminary results of an experimental tests in which masonry panels (reinforced with TRM and unreinforced) have been tested in diagonal compression, previously damaged by the fire exposure. For this, masonry panels were subjected to different temperature levels, up to a maximum of 600 °C using an electric oven (Figure 1).

In general, the results show that high temperatures causes a decrease in shear strength, as well as the transverse stiffness modulus. However, the walls reinforced with TRM based on carbon fiber were the ones that present the best performance, since their mechanical properties were reduced by a smaller percentage.

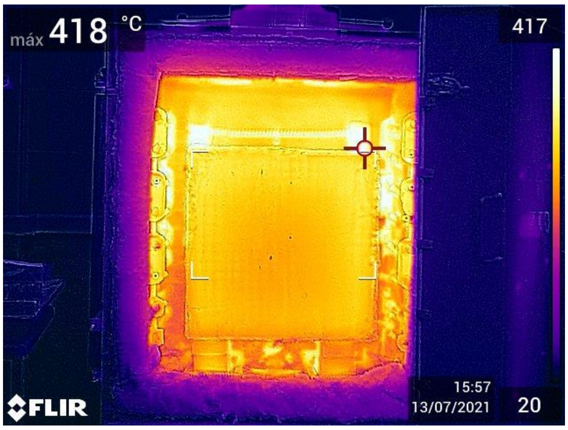

Figure 1. *Masonry panels submitted to high temperature.*

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FORENSIC ANALYSIS TAKEN AFTER THE COLLAPSE OF A HISTORICAL BELL

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Keywords: bell, fatigue failure, cyclic loading, forensic engineering, collapse.

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ABSTRACT

This paper describes the analysis performed after the collapse of the historical *EL JAUME* Bell in the Cathedral of Valencia´s Micalet Bell Tower in Spain (Fig.1). When the bells were being rung during the celebration on Christmas Day 2014, a sudden collapse took place fortunately without any casualties.

After several visits to the bell tower, a forensic study was carried out to determine the causes that had originated the collapse of this historical bell, which dates back to 1429. A fractographic and metallographic analysis of the steel shaft was initially carried out. This study allowed us to know the characteristics and mechanical properties. In a second phase, a fatigue damage analysis was carried out from two points of view. On the one hand, a finite element model of the steel shaft was carried out and the fatigue damage was studied using the Miner´s rule [1]. On the other hand, the remaining fatigue life was also estimated from the Whöler S-N curves for elements subjected to rotational bending [2], obtaining very similar results between both procedures.

Once this analysis was performed, it was concluded that the bell collapse was caused by fatigue damage in steel shaft, which theoretically should have been reached between 300,000 and 400,000 cycles. Specifically, damage propagation occurred due to an incorrect design of the steel shaft that caused a cross section with high stress concentration. Finally, the paper shows the remedial measures proposed in all the bells of the Micalet bell tower, whose steel shafts were designed under the same criteria and therefore, there was uncertainty about their remaining fatigue life.

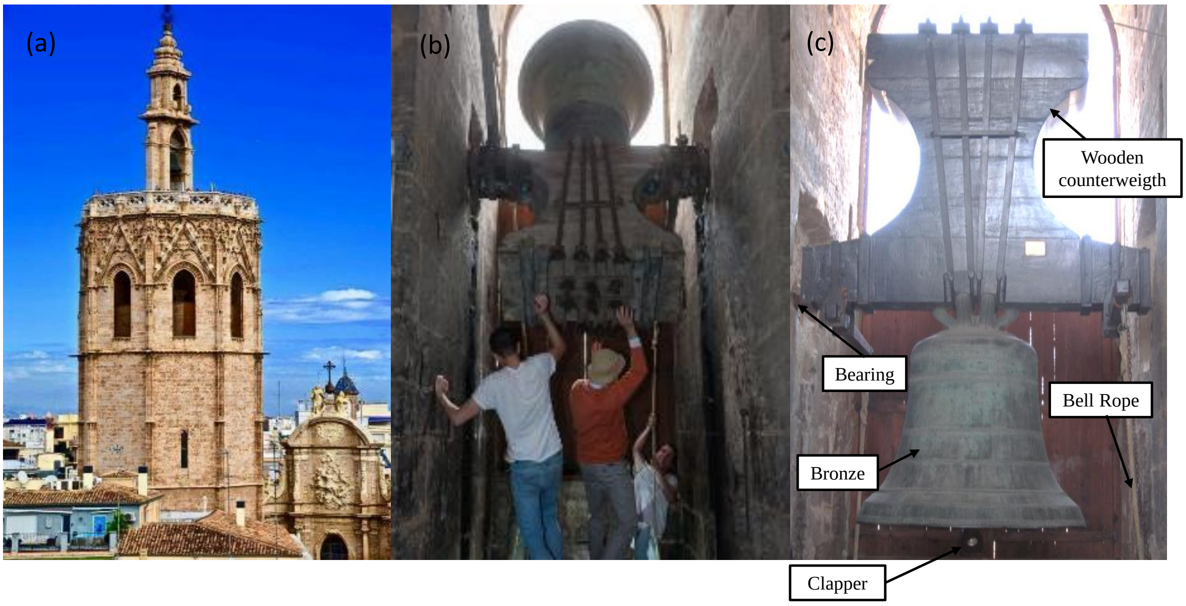

Figure 1. *(a)- El Micalet bell tower. (b)- Bell ringers ringing the bell manually (c)- El Jaume bell before the collapse.*

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STRUCTURAL OPTIMIZATION OF *LIVELY* COMPOSITE FLOORS WITH INTEGRATED CONSTRAINED LAYER DAMPING

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Keywords: Floor vibration, vibration control, damping, Structural Optimization.

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ABSTRACT

Due current architectural trends, contemporary offices are open-plan spaces with much less furniture, dead loads, and partitions than old ones. This has led to a reduction in floors' weight and damping. Consequently, Vibration Serviceability Limit State (VSLS) due to human-induced vibration has become an increasing concern for structural engineers, who occasionally need to stiffen or add mass to certain floor design in order to comply with VSLS.

In most of the cases, this excessive dynamic response of the floor has a resonant nature, so that a slight increase on floor's damping will decrease considerably the vibration level. To provide this damping increase since design stage might allow not increasing floors' mass or stiffness just to meet VSLS. This work has studied how the integration of a damping increase strategy would affect the optimally designed structural layout of a "lively" steel-concrete composite floor. The studied damping technique was firstly proposed by [1] and consists of a thin viscoelastic (VE) layer constrained between the steel member and the concrete slab of a floor's secondary beam (Figure 1). When the beam vibrates in bending modes the VE deforms to shear hysteretically dissipating additional energy. Thus, the treatment is applied for a given proportion of the beam's length near the supports where the longitudinal shear is higher, and hence, it is more effective. However, this region is disconnected to shear, so the experienced damping increase is accompanied by a slight stiffness decrease. This damping strategy is usually known in the literature as Constrained Layer Damping or CLD [2].

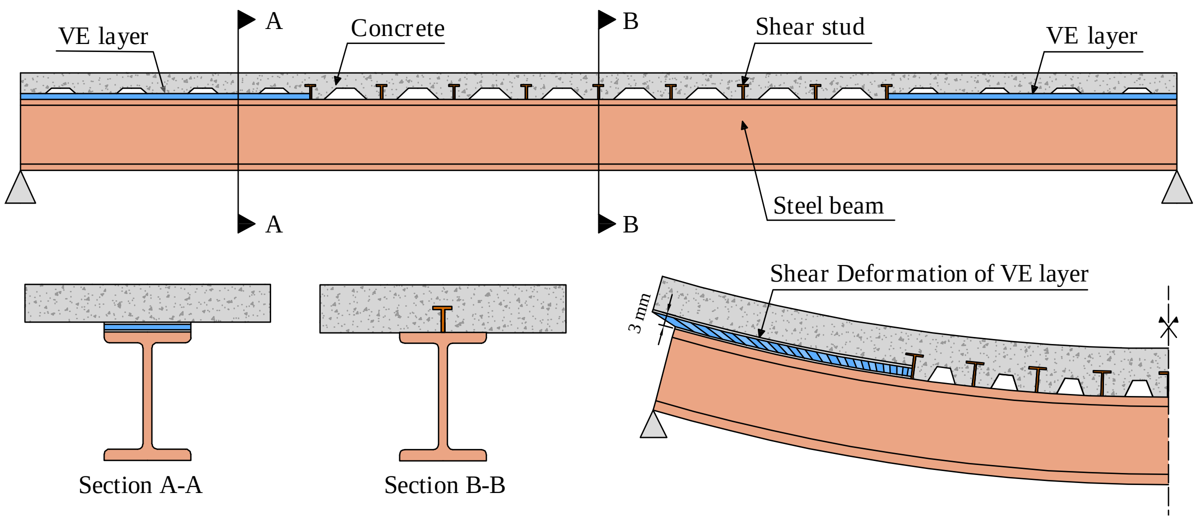

Figure 1. *Studied CLD treatment applied to composite floors.*

In this paper a structural checking methodology has been developed for analysing all the limit states which influence the final sizing of the floor elements, including a detailed analysis of the ELSV, with and without including the studied damping strategy. This methodology has been implemented into an optimization algorithm which finally has found optimal structural designs with and without the viscoelastic layer implemented [3]. Thus, it has been demonstrated that from a structural performance point of view and from the environmental impact of the floor, the integration of this damping strategy may be a really effective solution (Figure 2).

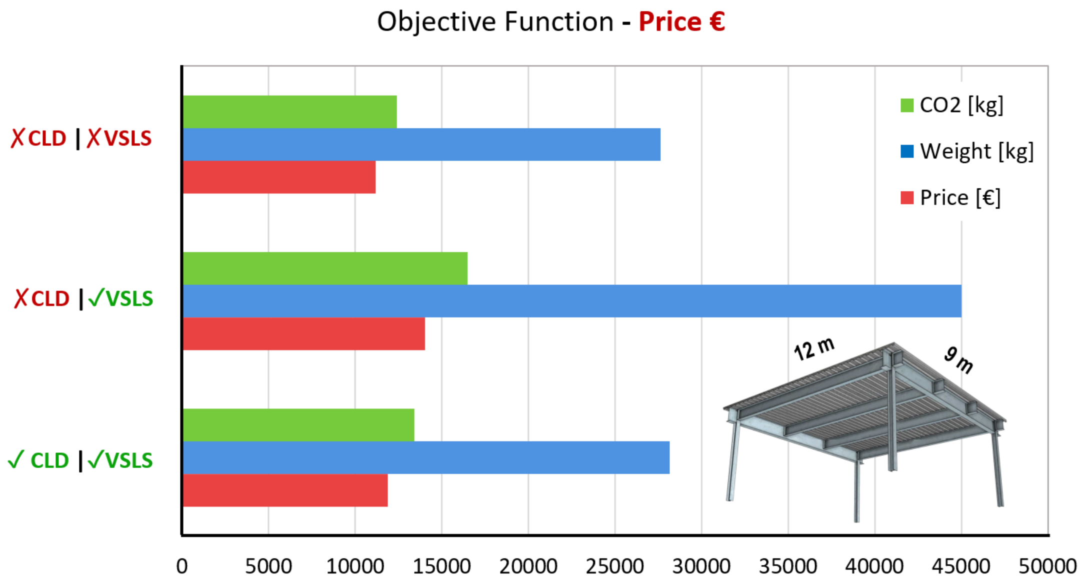

Figure 2. *Structural Optimization Results for a 12m X 9m composite floor with and without checking the VSLS and with and without considering the CLD viscoelastic treatment studied.*

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THE OBSERVED FISHER INFORMATION MATRIX FOR UNCERTAINTY QUANTIFICATION IN OPERATIONAL MODAL ANALYSIS

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Keywords: operational modal analysis, uncertainty quantification of modal parameters, state space model, observed Fisher information matrix.

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ABSTRACT

Operational Modal Analysis is a well-known technique to compute the modal parameters of civil/mechanical systems using in-situ recorded vibrational data, mainly accelerations. There are many different algorithms to estimate the modal parameters, both in time and in frequency domain. For example, the maximum likelihood algorithm obtains the modal parameters at the maximum of the log-likelihood function. In theory, this method gets the modal parameters with the lowest variance [1]. This is important, because scientist and engineers are interested not only in to estimate modal parameters, but also in to quantify the uncertainty of these estimates.

In this sense, the variance of the maximum likelihood parameters can be obtained using the Expected Fisher Information matrix [1], but in complicated models like the state space model is not easy to derive such a matrix [2]. According to large sample theory, another possibility is to use Observed Fisher Information matrix (OIM) [3]. This matrix is simply the (negative) Hessian matrix of the log-likelihood.

In this work we investigate the performance of the OIM for the uncertainty quantification of modal parameters obtained using maximum likelihood and the state space model. We use two different alternatives to compute the OIM:

- using numerical methods: the second-order partial derivatives of the Hessian are approximated by mean of finite differences.

- a more involved way is to find the Hessian taking derivatives of the log-likelihood function. In the case of the state space model, we have used the Kalman filter outputs. Preliminary results can be found in [2].

The purpose of the paper is twofold:

- to compare the numerical and the analytic OIM: speed, precision, ...

- to analyse the performance of OIM for uncertainty quantification of modal parameters: the results obtained with OIM are compared to the results obtained with Montecarlo simulations.

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MECHANICAL ASPECTS OF SHINGLED SOLAR CELLS

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Keywords: shingling technology, Prony series, nonlinear finite element model.

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ABSTRACT

In an effort to reduce the costs of solar modules, the shingling technology seems to be a promising approach to substitute the classical interconnections in a photovoltaic module by more efficient ones. More efficient means that higher power densities and an enhanced energy yield can be achieved. These performance gains can be attributed to lower resistive losses, a more efficient area use, and lower processing and operating temperatures. Several studies on the mechanical aspects [1] as well as on the electrical efficiency [2] point to a bright future of shingled solar cells. A key ingredient is Electrically Conductive Adhesive (ECA) which is used to connect the front of each shingle to the back of the next one. This connection has a double function, first it guarantees the electrical continuity along the string and second, it provides mechanical strength to avoid detachments during the photovoltaic module making process and under operating conditions of the finished solar panel. The shingled solar cells are covered on both sides by a layer of encapsulant material like EVA (ethyl vinyl acetate) which exhibits linear viscoelastic behaviour.

In Figure 1 a cut of the studied design is shown before both EVA layers are compressed.

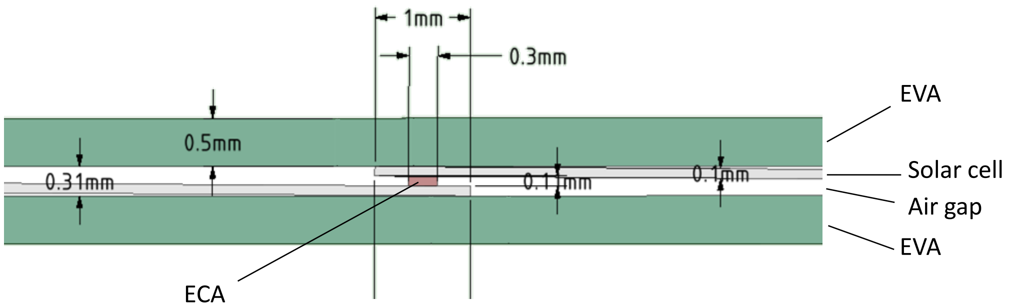

Figure 1. *Cross-sectional view of connection region of two solar cells*

During the production process both EVA layers are compressed and the different components undergo large strains. As a consequence, nonlinear Finite Element models are required to estimate the stresses that are developed.

In Figure 2 the mesh of a Finite Element model is shown that has been used to study different aspects of the compression process.

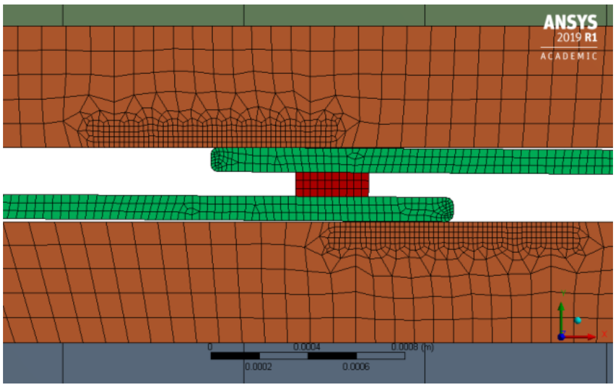

Figure 2. *Finite Element model of solar cells (green), ECA (red) and EVA (brown)*

Several studies have been carried out varying the thickness of the solar cells. Typical results include the stress distribution vs loading-step. At each load step the probability of failure of the solar cells has been calculated using Weibull distributions that have been obtained in earlier studies [3]. As EVA as well as ECA exhibit linear viscoelastic behaviour, this type of analysis permits to study how the loading rate and other aspects influence the probability of failure during the production process.

The model can thus be used to improve the production process in certain respects.

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