Experimental and Numerical Simulation of a Multilevel Structure Behaviour Subjected to Transient Loads

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Abstract: - The paper presents a low-cost experimental setup consisting of a shaking table, a displacement measuring system based on non-contact optical infrared (IR) sensors, along with a standard acceleration measuring system, based on PZT accelerometers and signal conditioners. A 3 level reduced scale model of a lightweight frame structure, subjected at the base by transient seismic loads, is presented in this study. A methodology to obtain good agreement between measurements and 3D finite element method (FEM) computations of a structure subjected to transient loads is presented. It consists in 3 steps. In the first and by applying sinusoidal loads at the base of the structure, a frequency domain study was done. In second step, inducing free vibrations, a time-domain analysis was made. By using FEM as an inverse method to match experimental results, the elastic and damping properties of the structure materials were determined. In the third step, the validation step, transient loads measurements were carried out for both accelerations and displacements. As the excitations loads and the response of the structure are transient, a simple the integration of measured accelerations to obtain displacements is not possible. The measured displacements with low-cost noncontact optical IR sensors showed an acceptable accuracy in the small range of interest. The experimental measurements were compared with FEM computation results, showing good agreement.

Keywords: - transient seismic loads, earthquake engineering, low cost shaking table, low-cost displacement sensors, frame structure

1. INTRODUCTION

Nowadays, more and more civil engineering with metallic structures is being built. In high-rise buildings, the advantage of steel structure is obvious, and owns considerable economic and social benefits [1].

Usually, structures are studied with simplified analytic models subjected to transient loads [2] to evaluate the efficiency of different type of antiseismic devices with hysteretic behaviour. The analytic models are suitable for inverse problems, but they do not consider a precise geometric model of the structure. In FEM the structures are more precisely described geometrically, and often used as good computational power is commonly available.

The laboratory experiments conducted on reduced scale models and numerical FEM are valuable tools for evaluating more precise the behaviour of full-size structures under transient seismic arbitrary loads, through scaling laws applied to the obtained experimental results [3]. These laboratory experiments are done on shake tables. A historical review of shake table is done in [4]. They can be very expensive, millions of dollars, often driven by powerful hydraulic actuators, and need hangar or outdoor open space to use it [5], [6], for large size reduce scale models.

In the last years, low-cost shake tables based on cheap microcontroller boards, cheap stepper motors, and cheap robotics mechanical parts, for small size laboratory models where developed [7], [8], [9],[10].

All these shaking systems need accelerations and displacements measurements at different points of the shaked structure to be compared with FEM results.

Experimentally acceleration is precise and easy to measure, even in full size structures, while FEM results are usually expressed in displacements, and both parameters can give valuable information. The numerical transformation of displacements to accelerations, by derivation, works well enough, and depend on the time step used in FEM computations, while the numerical integration of measured accelerations to obtain measured displacements do not work well, mainly due to the noise in experimental measurements. It can work satisfactory in some cases [11], or on some small portions of the acceleration signal, or when the signal is mainly sinusoidal [13],[14], but not satisfactory in general.

Measuring displacements is a difficult problem. A fixed point of reference is needed. On real structures it is very difficult to do accurate measurements due to the very small ratio between displacements and size of the structure. And in some cases, like offshore structures, it is almost impossible to do such measurements even with the use of GPS, because the signal can be lost, and anyway the accuracy is not good [12]. For large structures with high weight, the influence of the Pull-Wire (PW) potentiometer displacement sensors or Linear Variable Differential Transformer (LVDT) sensors on the accuracy of the displacement measurements is negligible. But on reduced scale lightweight laboratory structure this influence could be significant.

Noncontact measurements of displacements based on low-cost ultrasonic sensors have been used in laboratory shaking systems with satisfactory results [9] or based on very expensive high-speed cameras [14].

So, we chose to do measurements in both accelerations and displacements and compare them to the one obtained with FEM computations. Thus, we used two types of sensors that can lead to results that can be compared with FEM computed results: acceleration sensors and signal conditioners, and noncontact optical IR displacement sensors, that work better than the ultrasonic one.

In this paper a laboratory 3 level structure with 4 vertical steel strips and level 1, 2 and 3 with plexiglass plates is studied. The shaking system was made with a base plate sliding on ball bearings on two parallel rails. The arbitrary load movement is done with a stepper motor and a ball screw, widely used on mass produced for 3D printers and small CNCs. The stepper motor is controlled by an Arduino Mega 2560 board.

The studied structure is similar to the one studied in [15], [16] and [17]. In [15], [16] experimental work was done on a shake table with an eccentric motor, suitable for steady-state frequency measurements and frequency domain FEM computations. In [17] only theoretical comparisons between the laboratory scale and real scale structures subjected to transient loads, were done based on FEM time-domain computations.

To obtain a correct behaviour of such structures under transient seismic loads, correct elastic material parameters must be put in the numerical simulation, as well as correct damping parameters of the supporting steel column strips.

To obtain the precise elastic material parameters and damping parameters of all the structure elements, a 3 steps methodology is presented:

1. Measurements in the frequency domain. The structure was shaked with a sinusoidal signal at the base, at a constant frequency. By sweeping the excitation frequency in the 1Hz-3.3Hz, good measurements on accelerations can be done. As the measurements are sinusoidal, the integration of acceleration to obtain reliable displacements is possible. The measurements are used as target for inverse methods of determining the elastic properties of the materials in the structure. The materials elastic properties existing in Comsol libraries were slightly modified, after an optimization process, to match the frequency-domain (and eigenfrequency) FEM to the measured results.

2. Measurements of free vibrations. With the base kept fixed, a displacement of 2 cm was imposed at the top of the structure, and after a sudden release, it was allowed to vibrate freely. The measurements are done in accelerations. Here also, the measurements are decaying sinusoidal (pseudo-sinusoidal) signals, and here also the integration of acceleration is possible. The measurements were used as target for inverse methods based on FEM, of determining the damping elastic material properties of the structure columns.

3. With the elastic and damping properties obtained, a validation by comparisons of experimental and FEM computations in the transient time domain, was done. Here the displacements cannot be integrated from accelerations. Displacements are measured with low-cost noncontact optical IR sensors, with acceptable accuracy. So, measurements and FEM computations are done in both modes: in displacements and accelerations. Good agreement was obtained between experimental measurements results and FEM computation results.

2. NUMERICAL METHOD

The numerical model used in this paper is the FEM, implemented in the software Comsol 5.6, under the Solid Mechanics module [18]:

$$\rho \frac{\partial^2 u}{\partial t^2} = \nabla \cdot S ,$$

$$S = S_q + C : \varepsilon ,$$

$$\varepsilon = \frac{1}{2}\left[\left(\nabla u \right)^T + \nabla u \right],$$

$$C = C\left(E, \nu \right), \tag{1}$$

$$S_q = \eta_b \dot{\varepsilon}_{vol} + \eta_v \dot{\varepsilon}_{dev} ,$$

$$\varepsilon_{vol} = \varepsilon_{kk} ,$$

$$\varepsilon_{dev} = \sqrt{\frac{2}{3} dev\left(\varepsilon \right)_{ij} dev\left(\varepsilon \right)_{ji}} ,$$

$$dev(\varepsilon)_{ij} = \varepsilon_{ij} - \frac{\varepsilon_{kk}}{3} \delta_{ij} .$$

where u is the displacements vector, S is the stress tensor, ε is the strain tensor, C is the elasticity tensor, ":" stands for the double-dot tensor product, E the Young modulus, ν is the Poisson ratio, ρ the mass density.

S_q denote the viscous damping with two coefficients η_b and η_v representing the bulk and shear viscosity, and ε_{vol} and ε_{dev} are the volumetric and deviatoric parts of the elastic strain tensor.

As the materials are isotropic, the variables that are to be determined are the elastic properties of the materials: the Young modulus E, the Poisson ratio ν, the mass density ρ, and the viscous damping properties by the two coefficients η_b and η_v, the bulk and shear viscosity.

3. EXPERIMENTAL SETUP

The experimental setup (Figure 1, Figure 2) consists of the main components:

1) the shaking system;

2) the measurement system used in two configuration modes:

- accelerations measurements and with Bruel&Kjaer accelerometers and signal conditioners,
- displacements measurements with noncontact optical IR sensors;

3) the analyzed structure.

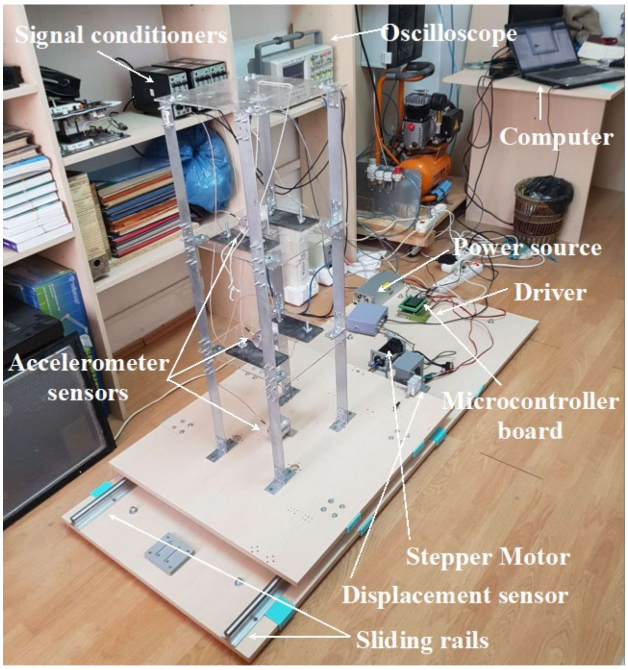

Figure 1. Experimental setup in configuration 1: with accelerometer sensors and signal conditioners.

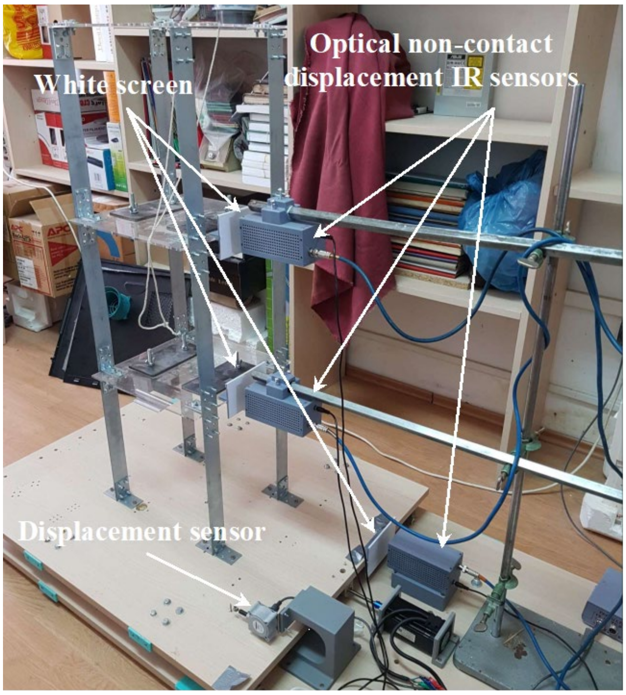

Figure 2. Experimental setup in configuration 2: with displacement noncontact optical IR sensors

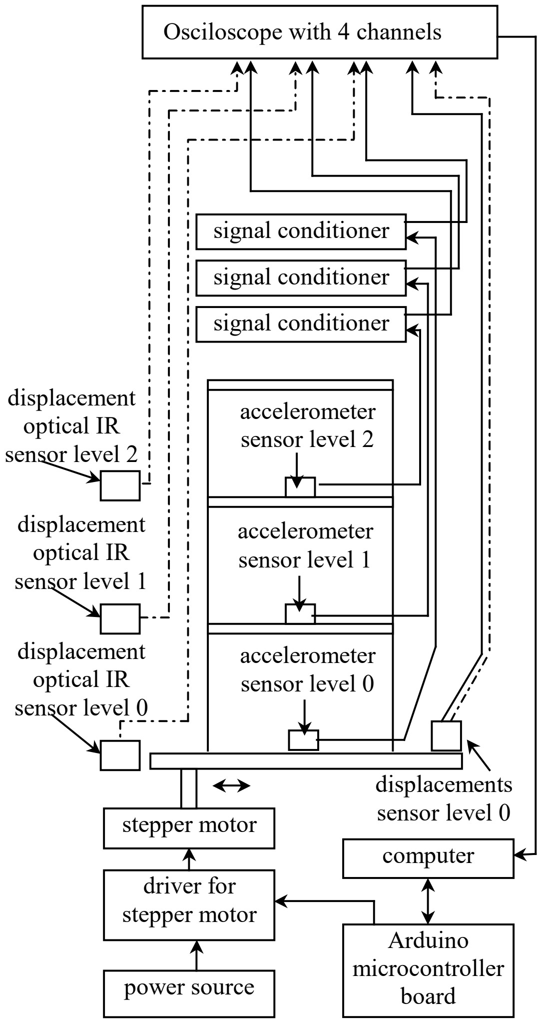

Figure 3. Block diagram of the experimental setup in both configurations.

1) The shaking system is made with a 2 cm base plate sliding on SBR20uu ball bearings on two parallel SBR20 rails bolted on a plate embedded in the floor. (It was found that if the plate is bolted on a table the residual vibrations of the table lead to bad noisy results).

The arbitrary load movements are generated on the sliding plate with attached ball screw that slides on a tapered rod. The linear movement of the plate is generated by a 3Nm stepper motor controlled by an Arduino Mega 2560 board.

As shown in the block diagram (Figure 3) the stepper motor is controlled by a driver capable to deliver large electric currents, and by a microcontroller board that gives short 5μs pulses of low power 5V, followed by a waiting time, at every step of the motor. The Arduino board used can store only an array of 4000 rows, so the step in our actuation was the maximum possible: 10 μm. An algorithm was used to convert a signal variable in amplitude and constant in time, in a signal of constant step amplitude and variable in delay time.

The stepper motor was choused of medium size and power (3Nm). It must have enough force to move the shaking platform in a controlled way, but to have also small internal inertia. And for laboratory scale measurements with about 7 kg weight structure, with reasonable speed of the arbitrary loads (not very violent moves) the system is acceptable.

2) The measurement system consists of displacements and acceleration sensors, signal conditioners and an oscilloscope connected to a computer for data acquisition. One PW displacement sensor of type Celesco SP2-4 was used. It is a potentiometer roulette type sensor, a resistive one. It gives an electrical signal from 0V to 12V between the minimum and maximum limits (0-10 cm;0-4 inches) of the wire length. As it exhibits a not negligible required pulling force, it can not be used for upper levels of the structure, but it was used on the base of the structure of the shaking system, where the actuation force is much bigger than the pulling force of the sensor, as a permanent reference of the displacements measured, and connected to one of the oscilloscope channel's.

The oscilloscope used was an Agilent DSO5014A, with 4 channels, 100MHz bandwidth on 16 bits. The data acquisition sample rate used by us was of 50S/s (1000S for 20s). It was used so, because the data looks too noisy otherwise. A smoothing of the measured data was done by averaging 5 points captured; low-cost noncontact optical IR sensor have a maximum limiting sample rate of 400S/s; the time step in 3D FEM computations would be too small, and simulations would be more time consuming. The fourth channel was used to connect to the PW displacement sensor and used as a reference signal for the others. As the oscilloscope has only 4 channels, the measurement system has been configured in two modes: accelerations measurements and displacement measurements, using 3 channels of the oscilloscope at a time.

For acceleration measurements 3 acceleration sensors, named usually accelerometers, were used to measure the accelerations at 3 levels of the vibrating structure and amplified with signal conditioners (Figure 1). All the 3 accelerometers, are uniaxial charge accelerometers of type HMF KB12, with sensitivities 700pC/m/s^2, made of Aluminium. As the columns of the metalic structure are made of plates, and the shaking table delivers displacements in only one direction, the Ox directions, all the 4 columns have the same deformations. The uniaxial sensors are mounted to capture acceleration in that Ox direction, in the middle of the plexiglass plates, with bolts. The 3 signal conditioners with amplification and integration facilities are Bruel&Kjaer Charge Amplifier type 2635.

For displacement measurements 3 optical IR analog sensors of type Sharp GP2Y0A51SK0F, with range 2cm-15cm, with a good accuracy range of 2cm-10cm, were used at the same 3 levels of the shaked structure, positioned face centered to a 8cm×12cm white screen. They are not linear sensors. They are more accurate to the 2cm range, so the sensors were positioned to catch more accurately displacements around the beginning and the end of the arbitrary movement of the shaked structure (Figure 2).

3) The analyzed structure (Figures 1,2) consists of 3 level frame made of plexiglass supported by steel strips. To ensure a precision mounting of the plexiglass plates, stiffener assemblies made up of L shape angles and bolts were used to attach the plexiglass plates to supporting steel strips.

The plexiglass plates were positioned at the level of 340mm, 670mm and 1000mm height from base. The geometric dimensions of the plexiglass plates are 300mm×300mm×4mm, with different holes for the supporting additional steel plates and accelerometer sensors. Additional steel plates were attached with screws to the plexiglass plates to give a more realistic approach of weight of real existing structures. The steel plates have been manufactured to weight 0.5 kg each, with geometric dimensions of 160mm×80mm×6.2mm. The accelerometer sensors were positioned on the center of the plexiglass plate in the Ox direction, and weighted 225 g. The geometric dimensions of the supporting steel strips are 1.5mm x 50mm x 1000mm.

4. RESULTS

In order to have good realistic behaviour of the structure subjected to arbitrary seismic loads, the elastic properties of the structure's material parameters as well as the correct viscous damping parameters of the structure, a 3 steps methodology was used. The firsts 2 steps determine the elastic and damping properties of the material, and the third step is for validation.

For the FEM simulation of the structure's behaviour a simplified model of the real structure is taken in consideration, as shown in Figure 4. In the FEM simplified model the bolts, that attach the L shape stiffeners to the plexiglass plates and supporting steel strips, were neglected. The stiffeners were considered to be bonded to the structure, as well as the steel blocks. The accelerometer sensors were approximated to a parallelepiped geometric shape and made from aluminum.

As the time-domain analysis require much more computational resources than the eigenfrequency or frequency domain analysis, a mapped mesh (Figure 6) was used, for better computational accuracy, where stress on structure is bigger (on steel plates and angles), and free triangular for the floors, to speed up the computational time.

In the first step of the methodology measurements in the frequency domain were done. The structure was shaked with a sinusoidal signal at the base, at a constant frequency (as described in reference [15]). By sweeping the excitation frequency in the 1Hz-3.3Hz, good measurements on accelerations can be done. As the measurements are sinusoidal, the integration of acceleration to obtain reliable displacements is possible. The measurements were used as target for inverse methods of determining the elastic properties of the materials in the structure. The materials elastic properties existing in Comsol libraries were slightly modified, after an optimization process, to match the frequency-domain (and eigenfrequency) FEM to the measured results, and taken:

- for plexiglass: $E = 3.0\,GPa$, $\nu = 0.4$, $\rho = 1190\,kg/m^3$
- for steel: $E = 211.9\,GPa$, $\nu = 0.288$, $\rho = 7860\,kg/m^3$
- for aluminum: $E = 73.14\,GPa$, $\nu = 0.331$, $\rho = 2780\,kg/m^3$

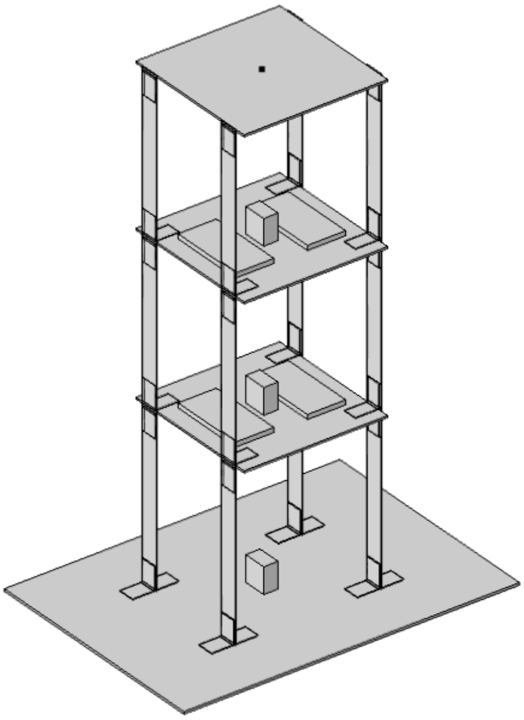

Figure 4. Simplified structure taken in FEM simulations

In the second step of the methodology measurements in free vibrations time domain were done. The base of the structure was kept fixed (0 displacements) and a force was applied to level 2 of the structure until the displacements reached a 2 cm. After a sudden release, it was allowed to vibrate freely. Here also, the measurements are decaying sinusoidal (pseudo-sinusoidal) signals, and here also the integration of acceleration to obtain reliable displacement measurements is possible.

The measurements were used as target for FEM inverse methods of determining the damping material properties of the structure columns, as shown in Figure 7. It can be seen that the resonance frequency, given by the eigenfrequency analysis (Figure 5), and time-domain of the structure's free vibration, approximate reasonably well the measured resonance frequency (2.87 Hz) of the analyzed structure.

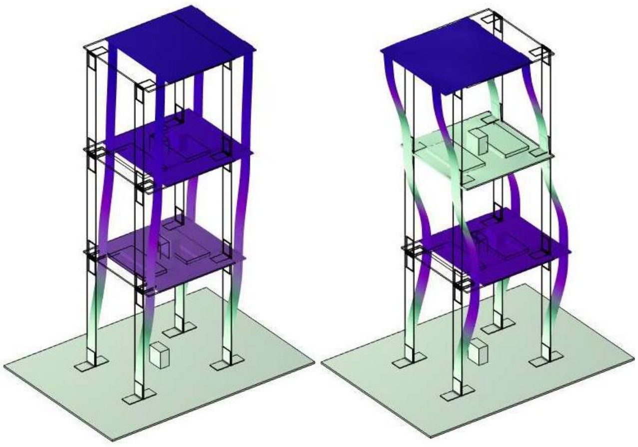

Figure 5. The first and second vibration modes of the structure at 2.87 Hz respectively 8.13 Hz.

The viscous damping coefficient η_v, representing the shear viscosity, was found in FEM by iterative simulations until the simulated logarithmic decay match the experimental one.

The bulk viscosity coefficient η_b was neglected, tacking into account its little influence. The numerical analysis consists of 2 steps, as in experimental measurements: the first one a stationary analysis with a force applied horizontally in the Ox direction to the level 2 of the structure, and a second analysis a time-domain one, simulating the free vibrations of the structure.

As in the experimental measurements and in the computed results the exponential decay had small differences from one sinusoid to another, it was averaged over 10 cycles measured and computed. It was found that shear damping coefficient $\eta_v = 47 \cdot 10^6\ Pa \cdot s$ is the best match for the studied structure.

With these elastic and damping material properties correctly determined from frequency domain and free vibrations analysis, in the third set of the methodology, a time-domain analyses for transient arbitrary loads applied to the base of the structure in the Ox direction were performed and compared to experimental measurements.

The signal used in FEM computations and in experimental measurements, given by the reference PW displacement sensor (about 10s long), is presented in Figure 8.

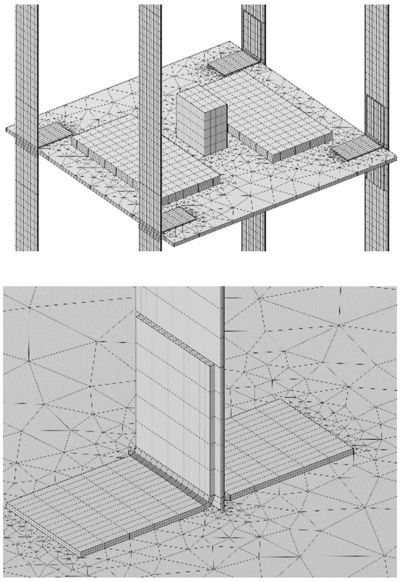

Figure 6. Mapped mesh considered in FEM simulations

The first type of analysis was the comparisons of computed FEM and measured accelerations. The experimental data were obtained at a sampling rate of 50 Samples/s.

As the arbitrary motion of the shaked structure is driven by stepper motors that execute small micro-steps, with accelerations and decelerations, which are measurable with sensitive accelerometers, it is expected that the measurements to be noisier than computed results (Figure 9).

As one can see from Figure 9 a, b, c, the computed FEM accelerations approximate reasonably well the measured ones, especially at the upper levels of the structure.

Even the experimental integration works well in the frequency domain [15], and in free vibration analysis, with sinusoidal or pseudo-sinusoidal motion, it was found to be totally inappropriate for transient loads of the structure: the signal conditioner Bruel&Kjaer Charge Amplifier type 2635 acts as an electronic filter of measured data.

Another step in the analysis was to compare the displacements, at all 3 levels of the structure, obtained from experimental measurements (Figure 2) with noncontact optical IR sensors GP2Y0A51SK0F with computed FEM results.

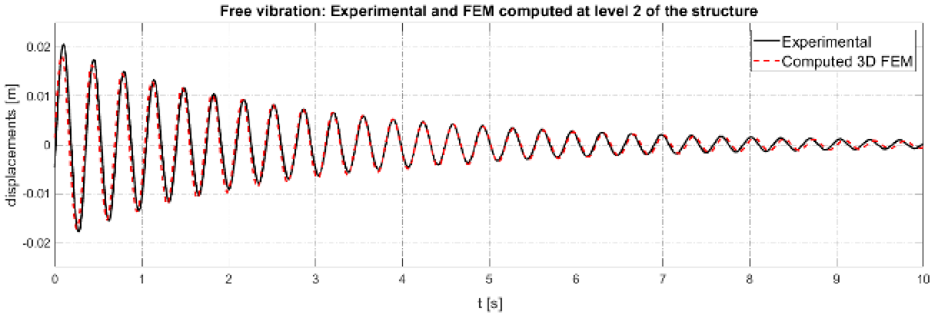

Figure 7. Measured signal during the experimental evaluation of the structural damping on free vibrations.

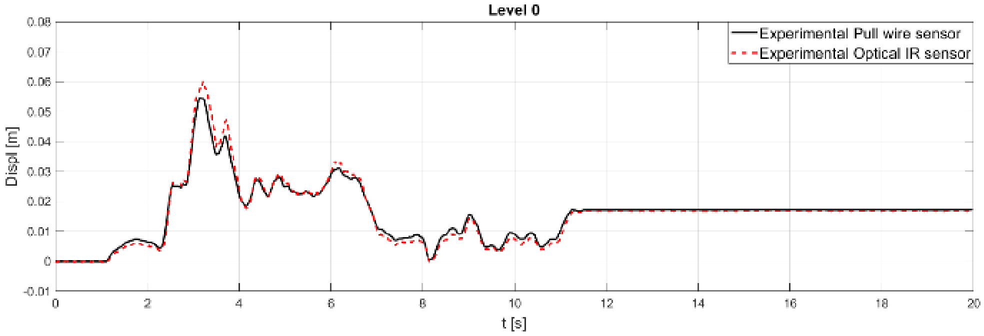

Figure 8. Experimental comparisons between the reference PW displacement sensor on level 0 and the optical IR sensor

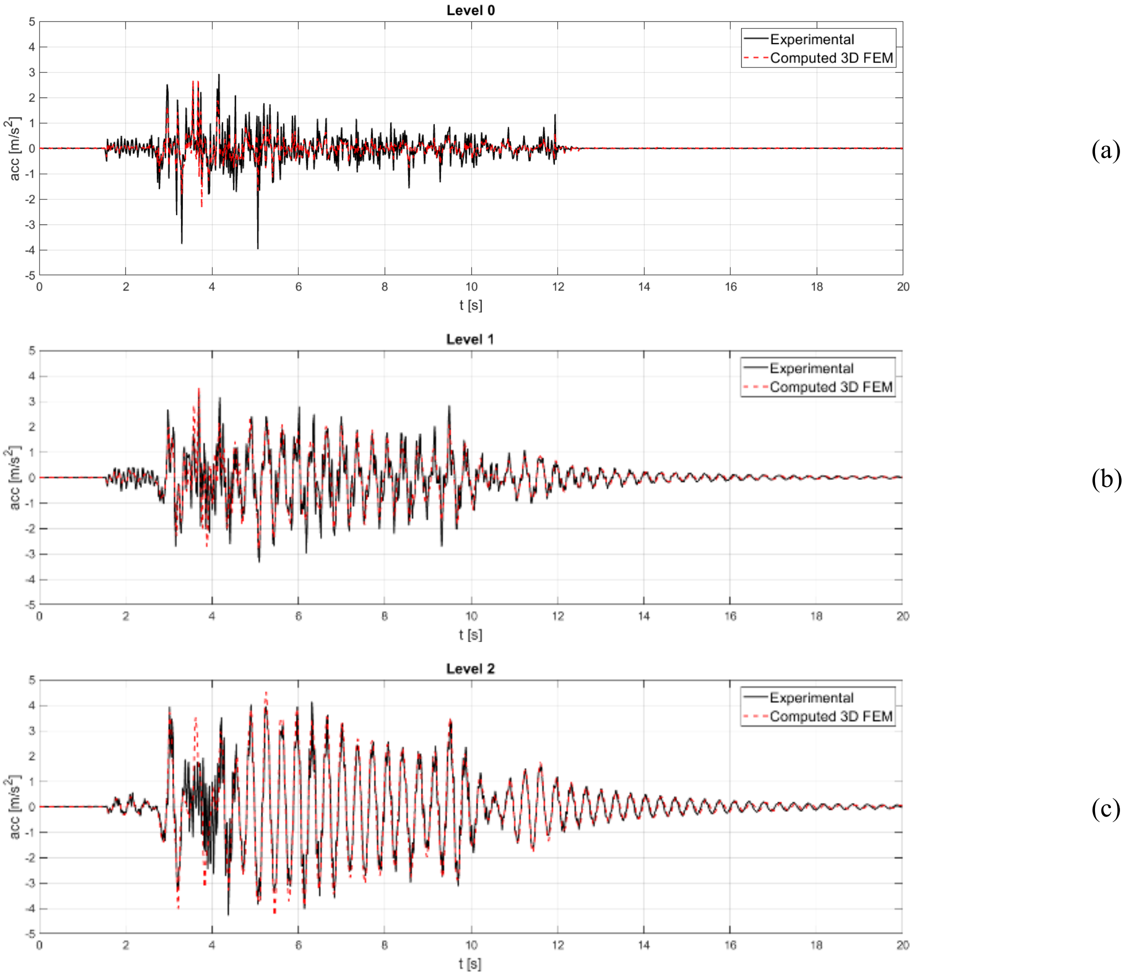

Figure 9. Experimental and numerical FEM accelerations on level 0,1 and 2 of the structure

As a confirmation that this type of sensor works, a comparison of the measured displacements on level 0, with the reference PW displacement sensor and with optical IR sensor was done and presented in Figure 8.

The measured displacements, at level 1 and 2 of the structure, were done with noncontact optical IR sensors instead of PW which would influence the measured results, as the pulling force is not negligible compared with the vibrating forces at upper levels, in measurements on laboratory scale lightweight structures.

A time-domain FEM analysis was done, with elastic and damping parameters determined and described above, along with a displacement transient load given by the reference PW sensor and introduced in computations at the base of the structure.

The comparisons between the measured displacements (Figure 10) and the computed ones (Figure 11), at all 3 levels of the structure, show a reasonable good agreement.

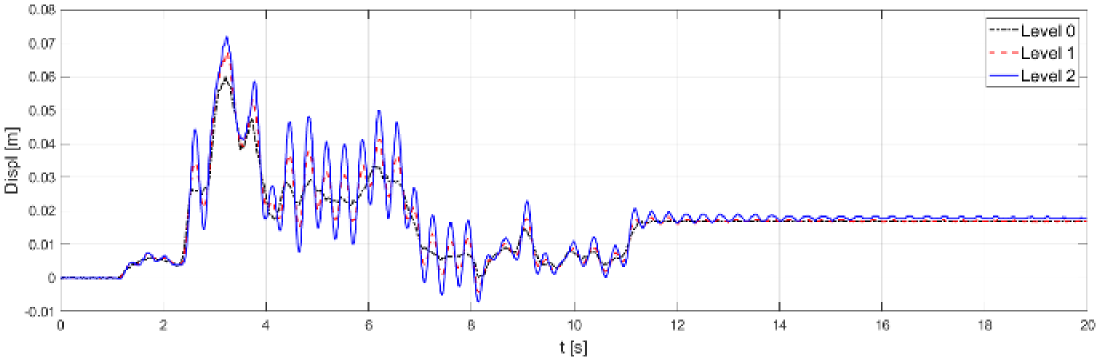

Figure 10. Experimental displacement measurements with optical IR sensors

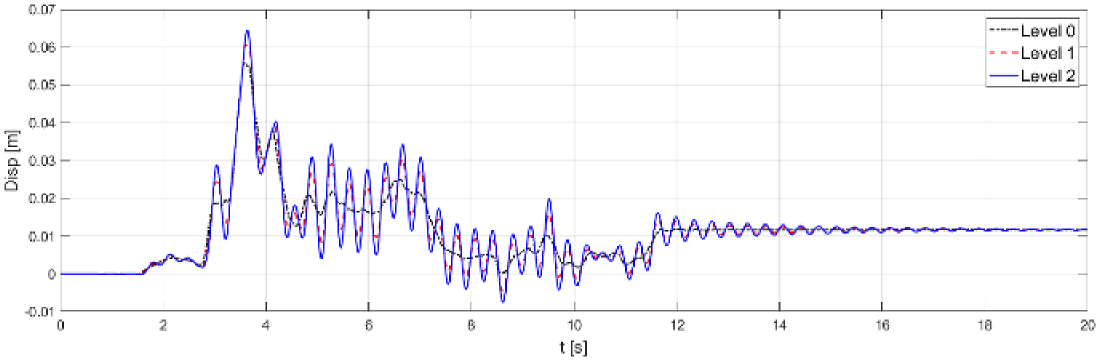

Figure 11. Computed FEM displacements

The frequency spectra of experimental and computed data, both in accelerations and in displacements were plotted in Figure 12-Figure15.

It can be seen that standard measurement equipment in accelerations, being very sensitive, catches correctly the first mode of vibration of the structure, the dominant one, at 2.87 Hz, but also the second mode of vibration at 8.13 Hz, shown in Figure 5. These modes of vibration are also present in the frequency spectrum of time-domain FEM computed results. However some frequency peeks in Figure 12, at around 14 Hz can be observed experimentally but not in computations, due to the not uniform movement induced by the stepper motors.

The low-cost noncontact optical sensors catch experimentally the first mode of vibration, and results are in good agreement with the frequency spectrum of computed FEM results.

5. CONCLUSIONS

A low-cost experimental setup with a low-cost shake table and low-cost noncontact displacements measuring system based on optical IR sensors, along with a standard accelerations measuring system based on accelerometers and signal conditioners was designed and successfully used on a laboratory three level lightweight structure subjected to transient seismic arbitrary loads.

As the excitations loads and the response of the structure are transient, a simple integration of measured accelerations to obtain displacements is not possible. As the structure is lightweight contact PW and LVDT displacement sensor cannot be used

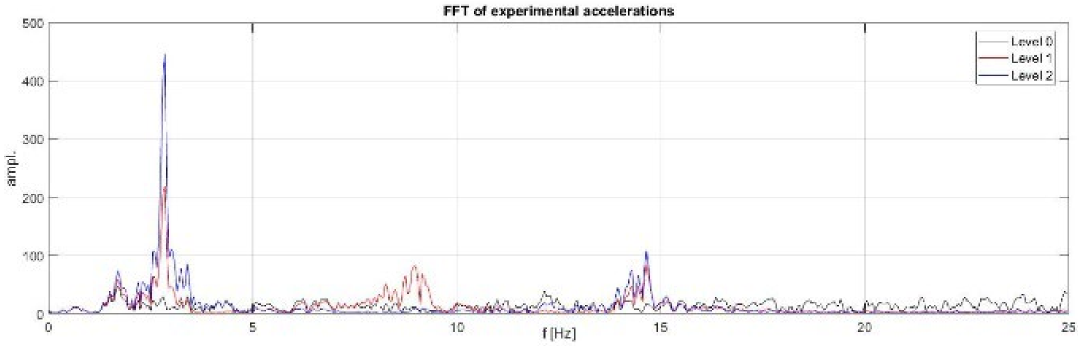

Figure 12. Frequency spectrum of experimental accelerations

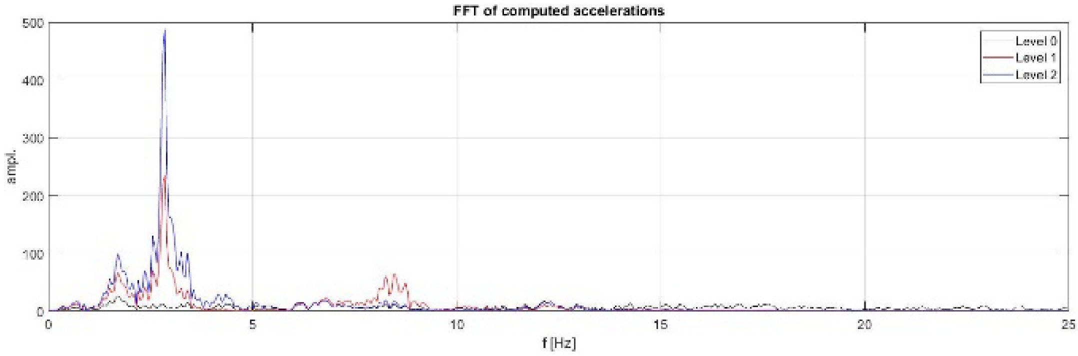

Figure 13. Frequency spectrum of computed accelerations

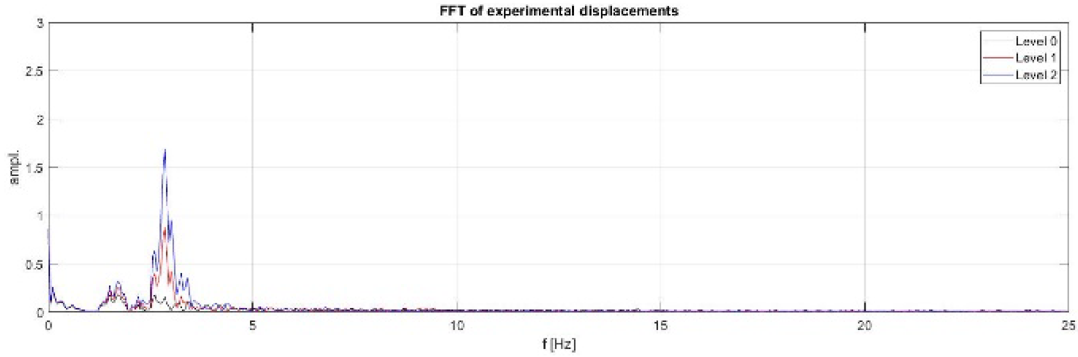

Figure 14. Frequency spectrum of experimental displacements

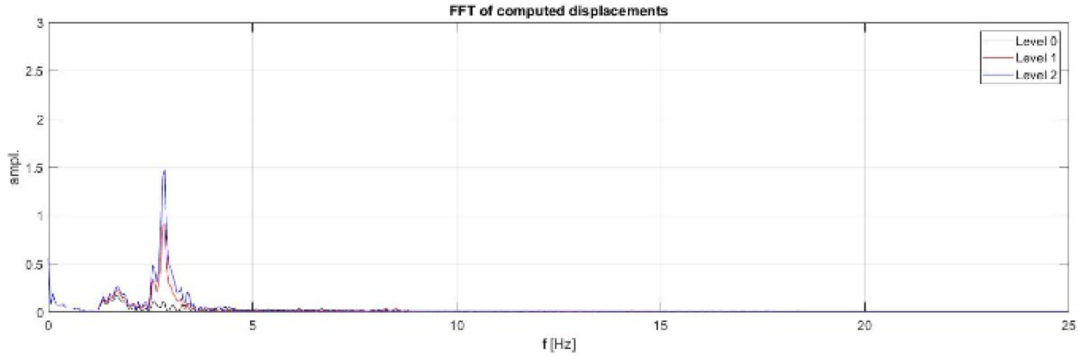

Figure 15. Frequency spectrum of computed displacements

on the upper levels of the structure. The displacements measured with low-cost noncontact optical IR sensors did show an acceptable accuracy in the small range of interest.

A 3 steps methodology to obtain good agreement between measurements and 3D FEM computations in case of transient seismic loads applied to a lightweight laboratory reduced scale structure have been presented. The first 2 steps, frequency-domain and time domain free vibration analysis, uses FEM as an inverse method to correctly determine the elastic and damping properties of materials. In the third step, the validation one, the determined elastic and damping properties of the materials have been used in transient FEM computations.

Comparisons of the computed FEM data with experimental data, in the case of transient loads subjected to a lightweight structure, on both accelerations (with standard accelerometer sensors and signal conditioners), and displacements (with low-cost noncontact optical IR sensors), shows good agreement.

So, the designed low-cost experimental setup with a low-cost shake table, low-cost noncontact optical displacement sensors and standard accelerations measuring system, as well as the methodology based on FEM computations, can be a good starting point of more thorough studies for assessing the efficiency of earthquake antiseismic devices attached to different lightweight laboratory scale frame structures, in future works.

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