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SEISMIC TESTING OF LARGE SCALE STRUCTURES WITH DISSIPATOR DEVICES

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Abstract. *Seismic testing of large-size models is nowadays possible thanks to the pseudo-dynamic (PsD) method, which resembles a quasi-static method with the application of slowly varying forces to the test structure. Low testing velocity may change the behaviour of the materials with respect to their behaviour at real velocity due to strain rate effect (SRE). The SRE during a PsD test is not relevant for the classical construction materials. However, it can be very important for some new materials, such as rubber or silicon, mostly used in isolators or energy dissipative devices. Silicone fluid viscous dampers are an example of these dissipative devices, and they will be the subject of this paper. It is possible to extend the PsD method range of application to structures equipped with dissipative devices by introducing a correction technique (CT) developed by the European Laboratory for Structural Assessment (European Commission) in Ispra, Italy. This technique consists of an on-line linear modification of the restoring measured forces. In this paper, two new procedures of CT are proposed. The first procedure consists of a linear filter where the output is the corrected force and the inputs are the measured forces and displacements. The second procedure is based on neural networks, using the same input but adding the test velocity rate. First, the most appropriate scheme of the algorithms was selected and calibrated. This is based on experimental data obtained by dynamically testing the dissipation devices with a displacement pattern, which was specifically designed for this purpose, at different frequencies and test velocities. Then, the capability of the obtained filter/net is tested using experimental data. Additionally, the most appropriate frequency for the training tests was studied. Outcomes were successful. Both algorithms outperform the previous linear CT, the net-based one being the most accurate and versatile. It was found that the first natural frequency of the unprotected structure is an adequate reference for the training tests.*

1 INTRODUCTION

Seismic design is a relatively new concept in the history of engineering. It consists in different strategies for designing earthquake resisting buildings to ensure the health, safety and security of the building occupants and assets. Some of those strategies can be grouped under the name of ***structural protection***, measures taken to enhance the response of a building under a seismic load. Structural protection can be planed during the design of the building, or after it –for example in historical buildings. It can be divided into three main groups: base isolation, passive systems, and active systems. This paper is focused on the passive protection systems, in particular on ***fluid viscous silicon based devices*** (FVD). They have the advantage of being easily implemented in an existent structure and not needing an external power supply.

Normative regarding seismic design and hence structural protection has experienced a fast evolution in the last century. With each new earthquake new codes have been implemented and new philosophies have been developed, from the addition of an equivalent lateral load in the static study to the ***performance based design***. According to the latter tendency, the response of the buildings under an earthquake cannot be *assumed* but needs to be *observed*, and tests get a first line position in the creation of new codes or the validation of new constructive methods.

A well-known method for seismic testing of structures is the shaking table, mainly used for the testing of small-scale models which dimensions are imposed by the inherent limitations of the table in terms of maximum testable model mass and size. Seismic testing of large-size models is nowadays more affordable thanks to the *pseudo-dynamic* (PsD) method in large reaction-wall facilities, such as the European Laboratory for Structural Assessment (ELSA) of the Joint Research Centre of the European Commission. In fact, the alternative of using large shaking tables, when available, for heavy and tall specimens, may also have serious limitations of accuracy in the application of the input and the reproduction of the characteristics of the tested structures. This is mainly due to the dynamic interaction effects between specimens and shaking tables [1]. Moreover, when protection systems are applied to the structure, the scaling of the system with the required accuracy becomes virtually impossible.

On the other hand, the PsD testing method has to be carried out at a low velocity rate, in order to ensure minimum control errors and power of the actuators. This low testing velocity may change the specimen materials behaviour with respect to their behaviour at real velocity. This alteration is called *strain rate effect* (SRE) and may appear whenever the time scale factor is different from one. In fact, it may also appear, in the opposite sense, in the dynamic test on the shaking table with scaled-down specimens; in this case, due to the dynamic similarity, the time scale factor can be smaller than one.

In a PsD test, the time scale is usually between 10 and 1000, which means having a testing speed from 10 to 1000 times smaller than the actual one. Luckily, this speed variation does not introduce a relevant SRE for the classical construction materials, such as steel or concrete. However, the SRE can be very important for some new materials, such as rubber or silicon, mostly used in isolators or energy dissipative devices, as the before mentioned FVD. In spite of the increment of the testing velocity allowed by the implementation of the continuous PsD method, the SRE on these materials cannot be completely neglected, as their apparent stiffness can be modified in a 10 or a 20%, if not more (see Figure 1).

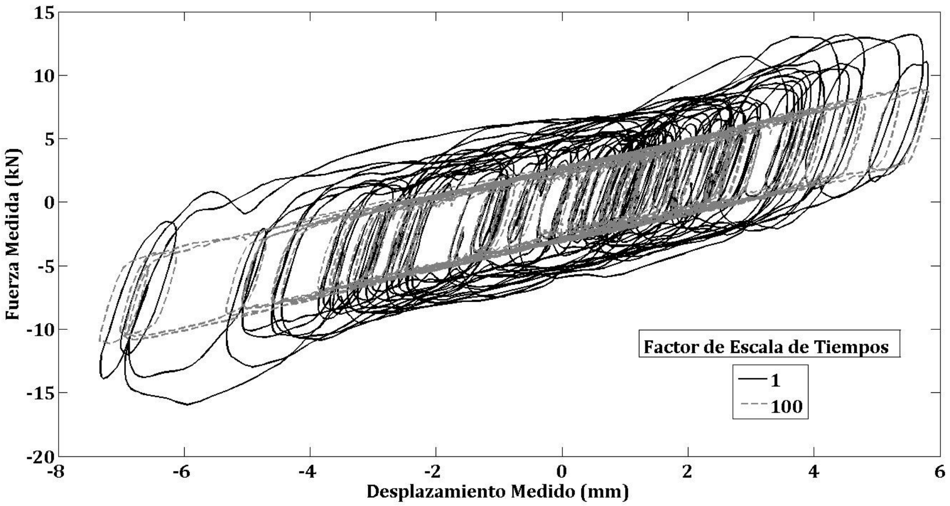

Figure 1: SR Effect: force-displacement cycle at real speed (black) and for a speed 100 times smaller (grey)

It is possible to extend the PsD range of application to cases with SRE by introducing a *correction technique*. In the case of buildings protected by means of FVD, this technique is based on the observation of the devices behaviour in relation with the strain rate change. The principal alteration consists of an attenuation of the measured force amplitude, while the shape of the force-deformation cycle remains mostly invariable. Consequently, the simplest version of the correction consists of a *Simple Linear Method* (SLM), an on-line modification of the restoring measured forces. The corrected force is obtained by simply multiplying the measured force by a coefficient, which is a function of the velocity rate [2].

In the present paper, two new methods are proposed, both consisting in a correction of the restoring forces carried out numerically in the analytical part of the PsD method, after the measuring of the forces and before the calculation of the next step displacement.

The first new method is an improved version of the SLM, called *Filter Method* and it consists in a linear filter where the output is the corrected force and the inputs are to be determined. The second method represents a completely different approach, based on artificial intelligence, using the same input variables as the first method and adding the velocity rate λ, enhancing the method with the possibility of changing the velocity rate during the test. This approach will be referred to as *Neural Network-based Method*. Both methods will be further described later.

2 EXPERIMENTAL PART

2.1 Specimen

The specimen used for the test described in this paper is a 1-storey bolted steel structure of one degree of freedom with overall dimensions of 3x3x3 meters. The top of the structure is formed by a reinforced concrete slab. The structure is complemented by two inverted V braces, which are used as a support for the FVD (see figures 1 and 2). This structure has a double function in this study. On the one hand, it was used as characterization bench when determining the devices behaviour. On the other hand, it was used as testing specimen during the PsD tests.

The displacements of the structure were measured from a no loaded reference frame on the top angles of the structure, using digital encoders Heidenhain. The relative displacements of the devices were measured via four potentiometric transducers Gefran. Forces were measured using piezoelectric load cells, one on each piston (Interface) and one on each dissipation device (Laumas).

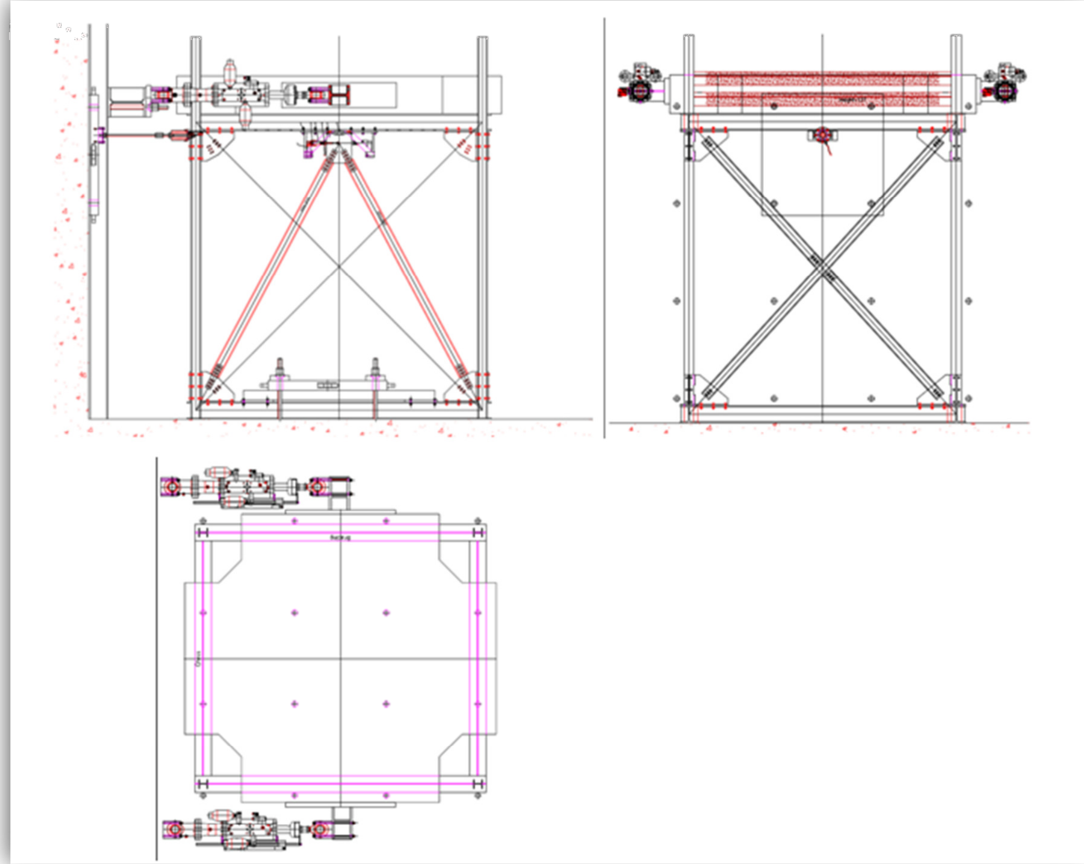

Figure 2: Specimen layout.

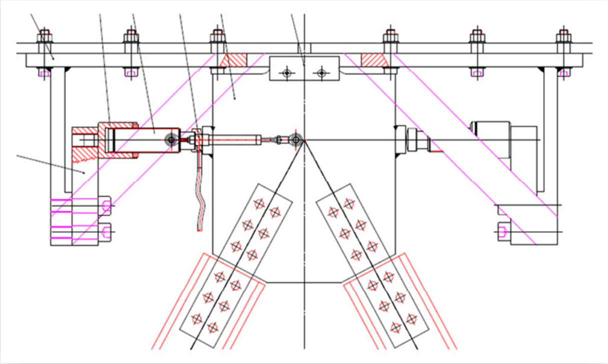

Figure 3: Seismic protection system FVD.

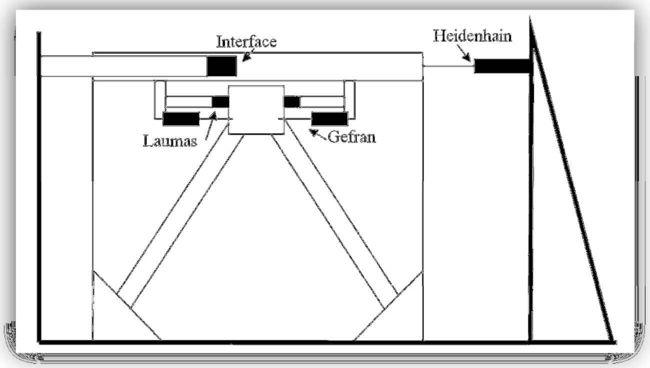

Figure 4: Specimen instrumentation.

2.2 Experimental characterization

First of all, the characterization tests were carried out. The input for these experiments was a displacement history, composed of a series of semi cycles of sinusoidal shape and different amplitudes, connected in such a way that the discontinuities in the slope were avoided. The design of the input signal was based on two aspects: the simplicity, because it should be easily performed on different types of devices; and universality, meaning that the response of the devices to the input should be as complete as possible, both in displacements and velocities.

The characterization tests were carried out under displacement control and at different velocity rates (λ=1, 75, 100, 250 and 500) with respective different frequencies of the input signal (2, 2.5, 3, 3.5, 4, 4.5 and 5 Hz). The signals obtained were pre-processed in order to remove discordances in both amplitude and phase.

The natural frequency of the structure was around 2.5 Hz.

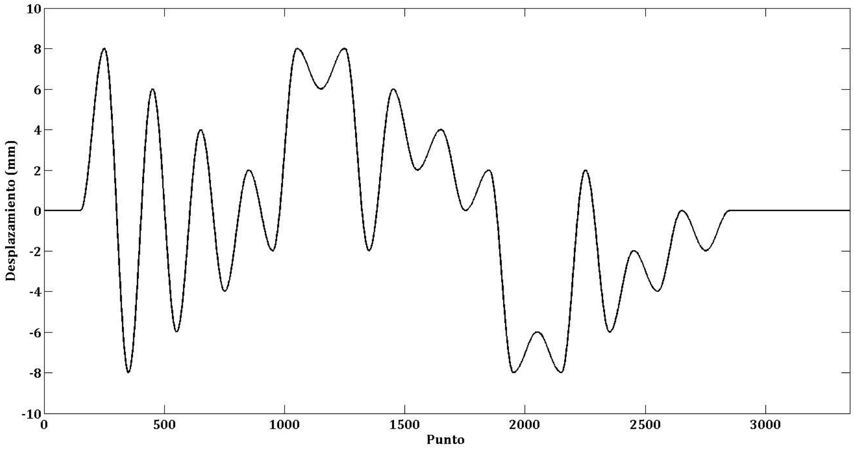

Figure 5: Characterization displacement history, 2.5Hz.

The results of these experiments, measured forces and displacements, formed the experimental database. The data measured during the test at real speed (λ=1) represent the set of ***objective values***.

3 CORRECTION METHODS

PsD tests are carried out step by step. At each step, the restoring forces are measured on the tested structure. The current value of these forces, along with the acceleration history, are used to predict the displacement to be applied to the structure in the next step. Due to the presence of FVD in the structure, SRE will appear, and the measured forces will be different from the forces measured on a real speed test. The proposed correction takes place at the analytical part of the PsD method, i.e., when the displacements of the new step are calculated.

The base of both correction methods is the same: the comparison between two different signals, obtained from two tests carried out in the same structure with identical input data but different deformation rates. The correction methods are tuned in order to minimise the difference between the measured and the predicted values of the restoring force.

The process followed with both methods is very similar. First, a database of experimental data is generated (characterization tests). The objective values have to be present in this database. Afterwards, a preliminary structure is selected for the algorithms (inputs and orders for the filter, inputs and number of neurons for the neural network) and then the algorithms are trained. This step is repeated with several possible configurations, until the optimal structure is reached. Then, the resultant filter/net is verified, using new data as input and checking the error (*Mean Square Error* or MSE) of the obtained correction.

3.1 Filter method

The first new method is called the *Filter Method*. It is a linear filter where the output is the corrected force and the inputs are to be determined. To do this, the filter has to be trained with experimental data and different inputs and orders. The analysis of these tests reveals that the optimal results of the filter method are reached when using as input the measured forces and displacements and their first derivatives in time, which corresponds with order zero for the output variable and order one for the input variables of the filter. This solution constitutes a trade-off between accuracy of the predictions and time of processing. It takes to the following mathematical form:

$$\hat{f}^{(1)}(t) = b_1^{(\lambda)} \cdot f^{(\lambda)}(t) + b_2^{(\lambda)} \cdot f^{(\lambda)}(t-1) + b_3^{(\lambda)} \cdot d^{(\lambda)}(t) + b_4^{(\lambda)} \cdot d^{(\lambda)}(t-1) \tag{1}$$

where $\hat{f}^{(1)}(t)$ is the predicted force and λ is the speed of the test. Thus, what needs to be defined are the four coefficients that multiply the measured force f and displacement d at the time instants t and $t-1$.

3.2 Neural Network-based Method

The second method is based on artificial intelligence, using the same input variables as the first method and adding the velocity rate λ, enhancing the method with the possibility of changing the velocity rate during the test. Neural networks need to be trained with experimental data also, so that their parameters can be adjusted. This process is carried out in two phases. First, the derivatives of the error function (difference between the objective values and the generated values) are obtained. In a second phase the net parameters are optimized, minimizing the error. For these phases, the *Back-Propagation* algorithm and the *Scaled Conjugate Gradient* method are used.

Using the characterization test data as input, it was stated that the appropriate numbers of neurons were 5 input neurons, 1 internal layer of 4 neurons and 1 output neuron.

3.3 Application

Later on, a different set of data was used in order to check the methods. It consisted of the displacements and forces gathered during a group of quasi-static tests, run with a seismic displacement history as input signal. This set is called *Seismic Application* in this study, as it is the use of the already trained algorithms on seismic data. The new methods, applied to the seismic signals, provided good results in terms of NMS error (**3.16%** and **2.74%** resp.), the second one being the most accurate and versatile. Both algorithms outperform the Simple Linear Method in all the analyzed cases, which presented a NMSE of **6.36%**.

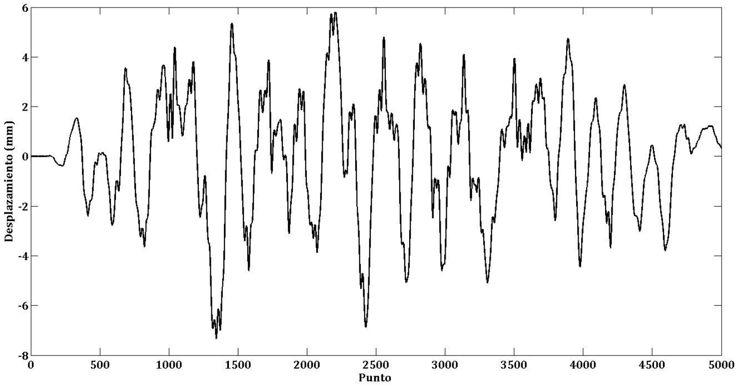

Figure 6: Seismic real speed test measured displacement.

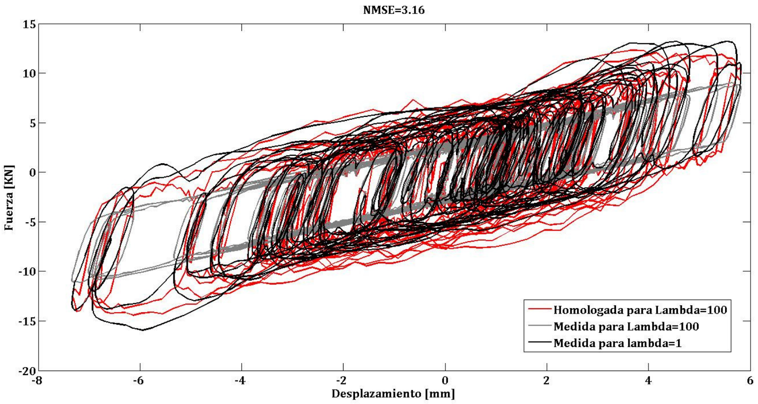

Figure 7: Force-displacement cycle, filter method. In black, data from real speed tests ($\lambda=1$), in grey, data from PsD test with $\lambda=100$, in red the corrected data for that test using the filter method

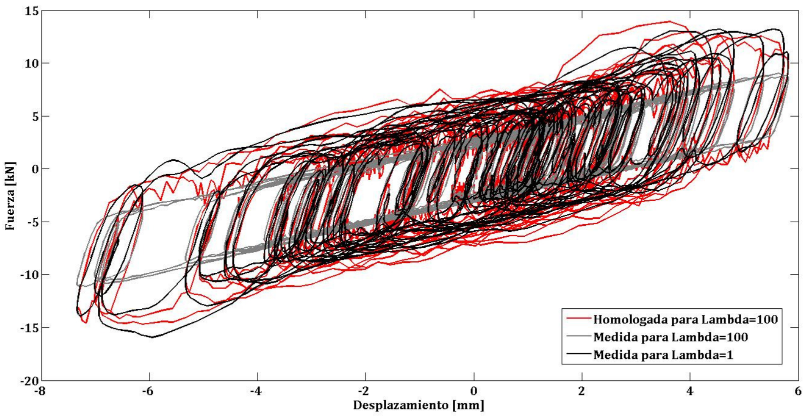

Figure 8: Force-displacement cycle, neural networks method. In black, data from real speed tests (λ=1), in grey, data from PsD test with λ=100, in red the corrected data for that test using the method based in neural networks.

4 COMPLEMENTARY STUDIES

4.1 Neural network based on seismic data

Using the seismic data described in the previous paragraph, a further verification was followed on the Neural Network-based Method. A new net was trained using the first half of these data, while the second part of the data was used in the application phase. It is important to remark that this procedure is possible only as an academic study and not in a real case, because it includes the realization of dynamic seismic testing on the studied structure, which is exactly what is trying to be avoid. The application error obtained with this net (1.3% approx.) is, as expected, lower than the error provided by the previous net. Nevertheless, the differences are not high, demonstrating that the characterization data base is enough for a proper training and that the selected pattern provides a good characterization of the system.

4.2 Selection of the characterization input data frequency

As has been seen before, there were 7 different characterization input signals, identical in shape but with different frequency. Looking at the results of the Seismic Application, it was found that the first natural frequency 2.5 Hz of the corresponding unprotected (without fluid viscous dampers) structure constitutes an appropriate frequency for the proposed time-history displacement pattern to test the dampers. This value can be easily estimated in the design stage through numerical models or obtained by modal testing of the actual unprotected structure.

5 CONCLUSIONS

A methodology intended to make PsD tests applicable to structures seismically protected by means of fluid-viscous dampers has been developed in this paper. It consists of the on-line correction of the measured restoring forces as a function of the forces and displacements experimented by the dampers and the speed of the test.

For this purpose, two different procedures have been developed. The first one is formulated as a linear filter algorithm in which the outputs are the corrected forces, while the measured forces and displacements at the dampers act as inputs. The second one uses the same inputs and outputs, but adding the test velocity factor as a new input variable. In this case, these variables are functionally interpolated by means of a neural network.

These algorithms are calibrated on the basis of data obtained via an experimental procedure. This procedure consists of the dynamical application of a time-story pattern of displacement, designed ad hoc for the characterization of the dampers, and its cyclic reproduction at four different velocity rates.

The performance of the proposed procedures has been evaluated through cyclic tests carried out with different velocity factors. The input employed for these tests was the displacement time-history measured during a seismic event.

The analysis of the results allows the following conclusions to be drawn:

- Removing systematic errors from the experimental data is essential to obtain an accurate calibration of the correction algorithms.
- The first natural frequency of the corresponding unprotected (without fluid viscous dampers) structure constitutes an appropriate frequency for the proposed time-history displacement pattern to test the dampers. Its value can be easily estimated in the design stage through numerical models or obtained by modal testing on the actual unprotected structure.
- It is shown that order zero for the output variable and order one for the input variables is the appropriate configuration for the filter algorithm. This solution constitutes a trade-off between accuracy of the predictions and time of processing. Concerning the algorithm based on neural networks, the appropriate number of neurons of the hidden layer is found to be four.
- The application of the trained algorithms to seismic experimental data reveals that both the proposed algorithms outperform the simple linear homologation in all the analysed cases. The best fitting is always achieved with the neural network algorithm. Moreover, as this algorithm includes the velocity factor as an input, it can be used for any testing velocity within the training range, and it even allows the change of this parameter during the test.

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