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## **Damping capabilities of reinforced concrete components in the beyond design range: from the identification to a critical review of common best-practices**

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### **ABSTRACT**

When attempting to predict the seismic response of reinforced concrete (RC) structures, a trade-off has to be found between a realistic representation of the dissipations through material law and a numerically more efficient modelling with a controlled computational demand such as a Rayleigh-type damping model. Anyway, constitutive laws only describe internal dissipation and actually need a complementary dissipation term often chosen as a proportional damping matrix to take into account external dissipation sources such as interactions with the environment. Decoupling these two contributions in global dissipation measurement from experimental tests is still challenging. To address this problem, a numerical study based on an experimentally identified structural model is here presented. To this end, an experimental campaign has been carried out on RC beams set up on the AZALEE shaking table of the TAMARIS facility operated by the French Alternative Energies and Atomic Energy Commission (CEA). In this paper, the experimental campaign is briefly presented. Then, a parametric model is formulated and identified from the experimental results. Third, numerical dynamic experiments are carried out in order to assess the influence of several parameters on the energy dissipation and on the equivalent viscous damping ratio through two different methods. The validity of these results is assessed on a numerical case where a nonlinear model and an equivalent linear model are compared with each other. Experimental results of dynamic tests are also used as reference in order to estimate the additional viscous damping necessary to take into account the whole energy dissipation.

### **INTRODUCTION**

Despite the increasing accuracy of models for nonlinear behaviour of RC structures, their combination with complex finite element (FE) meshes still leads to high computational cost. In practice, an additional viscous damping is often used to account for dissipations not taken into account by the structural model (Crambuer et al., 2013), particularly in its linear domain (Correia et al., 2013). As shown in (Charney et al., 2008), (Hall et al., 2006), combining both types of dissipations (i.e. hysteretic and viscous damping) can compromise the validity of a study and could require a reduction of the viscous damping in the nonlinear range (Correia et al., 2013). In order to represent this dependency, several evolving Rayleigh-type viscous damping models have been proposed (see (Jehel et al., 2014a) for a study of such models), but experimental evidences on slender buildings tend to show that modal viscous damping can be thought to be an intermediate between constant viscous damping for all modes and stiffness-proportional damping (Cruz et al., 2016). Before performing such a fine analysis, simplified methodologies should be used in order to obtain a first design of a structure. Displacement-based methods have become popular for the past decades,

but they generally require the knowledge of a monotonous force-displacement curve and the value of an equivalent viscous damping. This damping ratio has a key role when assessing maximum structural responses and some studies show it is the second source of uncertainties after the ground motions (Celik et al., 2010). Nevertheless, this assumed equivalence with the energy dissipated hysteretically may be questionable. Indeed, the identification is performed on quasi-static loadings whereas damping ratio is used for seismic loadings. In addition, several studies have emphasized the fact that the viscous damping depends on the response amplitude for RC buildings (Li et al., 2002), (Satake et al., 2003), (Liu et al., 2010), which contradicts the hypothesis of a linear equivalent viscous damping. To verify if the previous observations made on buildings comply with RC components, beams in the present study, and evaluate the influence of different excitation and material parameters, an experimental campaign described in the following section has been carried out and is followed by numerical experiments calibrated on experimental data.

## EXPERIMENTAL CAMPAIGN: THE IDEFIX TEST<sup>1</sup>

An experimental campaign has been set up on RC beams by means of the AZALEE shaking table, as part of the TAMARIS experimental facility operated by CEA. The main objective was to provide reference data through both dynamic and quasi-static tests in order to evaluate the dissipations depending on structural, material and signal characteristics. The measure of damping forces is challenging because their levels are unknown and generally more difficult to investigate than acceleration or restoring forces (Jehel et al., 2014b), they exhibit several sources and evolve along the time-history analysis. In order to quantify and to analyse the dissipation and its evolution during quasi-static and dynamic loadings, a dense network of various sensors type have been mounted on the experimental setup. Furthermore, an important design effort was made on the technological choices for the samples and the boundary conditions. A general view of the experimental setup is presented in figure 1. For an extensive description, please refer to (Heitz et al., 2017a).

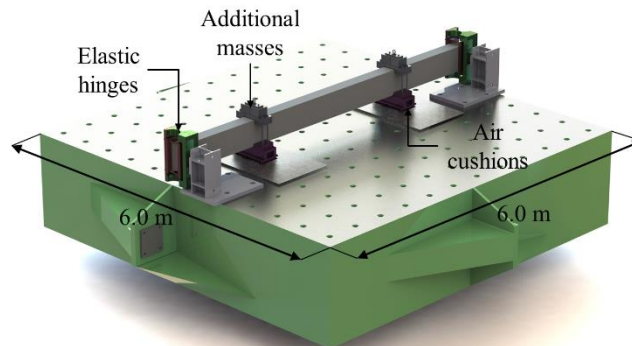


Figure 1. General view of the experimental setup.

## OVERVIEW OF EXISTING EQUIVALENT VISCOUS DAMPING IDENTIFICATION METHODS

### *Energy balance in the expression of the viscous damping ratio*

Considering an ideal system, the expression of the viscous damping ratio will be here below. The notations are defined in figure 2. If the ground motion is an harmonic acceleration  $\ddot{u}_g = -U_g \cos^2 \omega t$ , the steady state displacement and velocity will be given by equations 1 and 2, where  $U$  is the response displacement amplitude,  $\omega$  is the excitation pulsation and  $\phi$  is the phase angle.

$$u(t) = U \cos(\omega t - \phi) \quad (1)$$

<sup>1</sup> IDEFIX: French acronym of the experimental campaign standing for Damping/Damage relationship identification in reinforced concrete components.

$$\dot{u}(t) = -U\omega\sin(\omega t - \phi) \quad (2)$$

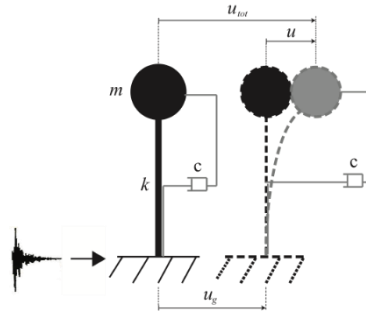


Figure 2. Notations used for the considered mass-spring-damper oscillating system.

The corresponding energy dissipated during one cycle by the damper is  $E_d$  expressed in equation 3, with  $\omega_0$  the natural pulsation of the system.

$$E_d = 2\pi\xi \frac{\omega}{\omega_0} kU^2 \quad (3)$$

For a purely linear spring, the maximum stored elastic energy is:

$$E_s = \frac{1}{2} kU^2 \quad (4)$$

Thus, from equations 4 and 5, we can define the viscous damping ratio as:

$$\xi = \frac{1}{4} \frac{\omega_0}{\omega} \frac{E_d}{E_s} \quad (5)$$

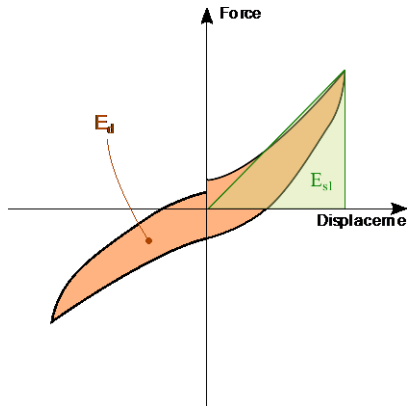
Let us note that the viscous damping ratio of a linear oscillator depends not only on the ratio between dissipated energy over the maximum stored energy, but also on the ratio between the natural pulsation of the oscillator and the excitation pulsation.

### ***Jacobsen's areas method***

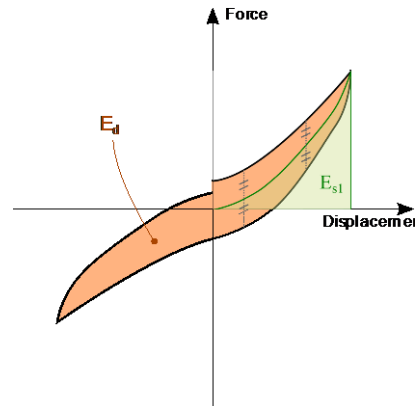
The first option to evaluate an equivalent viscous damping ratio by an energy equivalence approach to estimate hysteretic dissipations has been made by (Jacobsen et al., 1930), (Jacobsen et al., 1960). The method was originally developed to evaluate the equivalent viscous damping ratio (EVDR) for nonlinear frictional system. Some question remain open:

- to overcome the frequency dependency and to ensure the loops continuity, it is assumed that the excitation is harmonic with the same frequency as the natural frequency of the system (see equation 5 with  $\omega = \omega_0$ ). However, it is a common practice to perform a quasi-static cyclic test on the hysteretic damper to evaluate the associated EVDR;
- while the energy dissipated by a linear viscous damper is linearly proportional with respect to the excitation frequency (see equation 3), the energy dissipated by the hysteretic damper to be approximated is not. Hence, for any excitation with a frequency content higher than the oscillator's natural frequency, the viscous damping ratio will be overestimated and vice-versa;
- the stored energy is generally supposed to be square-proportional to the displacement (figure 3a) but this hypothesis is inexact in the case of a nonlinear behaviour which is the case when pinching occurs for example (figure 3b);
- when the loops are not symmetric, there is no actual reason to pick up the maximum relative displacement rather than the minimum one when assessing the stored elastic energy. For this reason, (Kumar et al., 2015) proposed an approach adapted to asymmetric hysteretic behaviours.

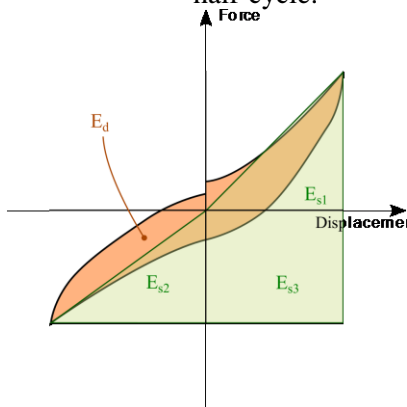
As depicted in figure 3c. A method inspired from this work and more suitable for nonlinear restoring forces is proposed in figure 3d.



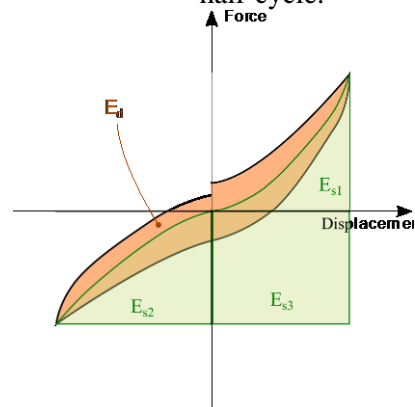
(a) Linearly stored energy evaluated on a half-cycle.



(b) Nonlinearly stored energy evaluated on a half-cycle.



(c) Linearly stored energy evaluated on a full-cycle proposed by (Kumar et al., 2015).



(d) Nonlinearly stored energy evaluated on a full-cycle inspired by (Kumar et al., 2015).

Figure 3. Different ways to apply area method derived from (Jacobsen et al, 1960).

### ***Logarithmic decrement method***

Another way to assess an equivalent viscous damping is to use the so-called logarithmic decrement method. Indeed, it can be shown that, for a linear viscously damped system in free vibrations, the decreasing envelope of the displacement follows an exponential law. If the oscillator is dropped without any initial velocity, its displacement  $u(t)$  is expressed in equation 6, where  $U_0$  is the initial displacement,  $\xi$  is the viscous damping ratio and  $\omega_0$  is the natural pulsation. Two consecutive maxima of the oscillations give the logarithmic decrement  $\delta$  by the equation 7 which is then useful to determine the viscous damping ratio  $\xi$  with equation 8. In the case of a non-viscous damping, the decreasing envelope is different, (e.g. it is linear for Coulomb's friction). Hence, either two different maxima have to be chosen to find the best fitting EVDR for the whole free vibrations regime, either the computation of the EVDR has to be carried out between each couple of successive maxima to determine an EVDR evolution throughout the free vibrations regime.

$$u(t) = U_0 \exp(-\xi \omega_0 t) \cos(\omega_0 \sqrt{1 - \xi^2} t) \quad (6)$$

$$\delta = \ln \left( \frac{U_1}{U_2} \right) \quad (7)$$

$$\xi = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \quad (8)$$

## PARAMETRIC STRUCTURAL MODEL IDENTIFICATION UNDER QUASI-STATIC CONDITION

### *Description of the test*

An application of the previously described method will be presented below. A quasi-static cyclic triangular loading, labelled QSC1, is carried out thanks to two actuators mounted on the additional masses positions with an increasing cycle amplitude centimetre by centimetre, each cycle being repeated three times to stabilize the damage state of the beam. The time-displacement evolution of this loading is given in figure 4. In order to describe the whole response of the beam with a simple degree of freedom oscillator (SDOF), the displacement field is expressed on the first mode shape. From a theoretical point of view, the mode shape is a sinusoid modified by the presence of the additional masses. A full-field measurement based upon an industrial digital image correlation method has been used. This method provides displacement data all along the beam, allowing for a projection to the eigenbasis. The out-coming projection error is useful to detect nonlinearities occurring during the excitation. For a more detailed explanation of this method, please refer to (Heitz et al., 2017a).

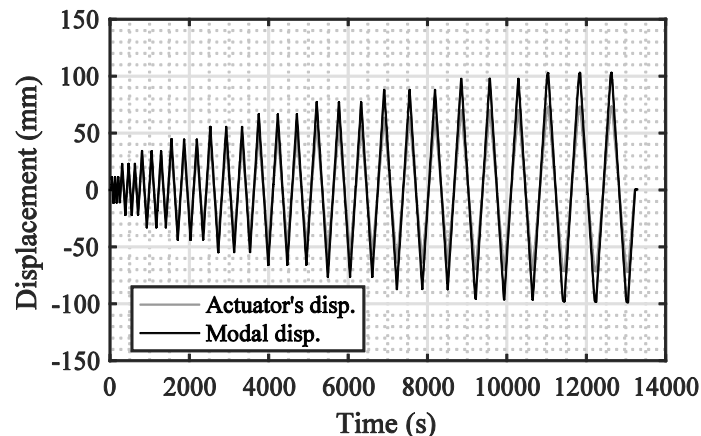


Figure 4. Displacement time evolution and modal displacement time evolution – inputs for the model identification procedure.

### *Short description of the parametric structural model*

The parametric structural model considered in his study is based upon a single degree of freedom oscillator with a restoring force described by a nonlinear function of the displacement. This nonlinear function has been formulated within the framework of irreversible thermodynamic processes. Three phenomena are accounted for: damage (associated with stiffness degradation), friction (hysteretic effects) and pinching (variations of the stiffness around the origin). For the sake of conciseness, the constitutive equation equations are not described in this paper. However, an extensive description of the model can found out from (Heitz et al., 2017b).

### *Identification method*

The identification process is performed by built-in methods of Matlab<sup>®</sup>. In order to limit the risk to fall into a local minimum, the choice of a three steps identification has been made: (i) elastic step, (ii) damaging step and (iii) friction step. The error criterion to minimize is given in equation 9. For each identification

step, only a part of data is used. For the elastic step, only the first displacement points prior to the elastic limit displacement are kept. Then, for the damage step, the capacity curve is deduced by keeping the highest force value associated to each displacement from zero to maximum displacement in the time-history recording. Eventually, the friction parameters are identified within the last stabilized loop, when the dissipations do not evolve anymore and the cyclic displacement amplitude is the highest. It can be seen on figure 5 that the model identification is satisfactory.

$$\eta(t) = \frac{\int_0^t (F(\tau) - F_e(\tau))^2 dt}{\int_0^t F_e(\tau)^2 dt} \quad (9)$$

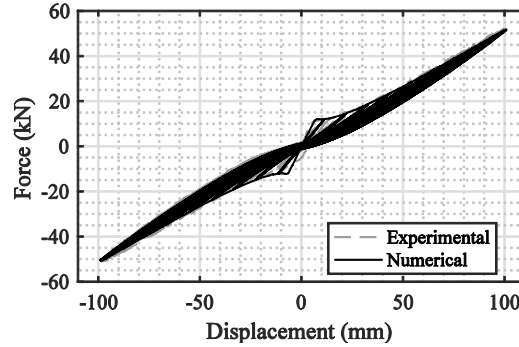


Figure 5. Comparison between the measured and the identified force-displacement response.

## COMPARISON OF SOME METHOD TO ESTIMATE AN EQUIVALENT VISCOUS DAMPING RATIO

### *Equivalent viscous damping ratio evaluation using Jacobsen's method*

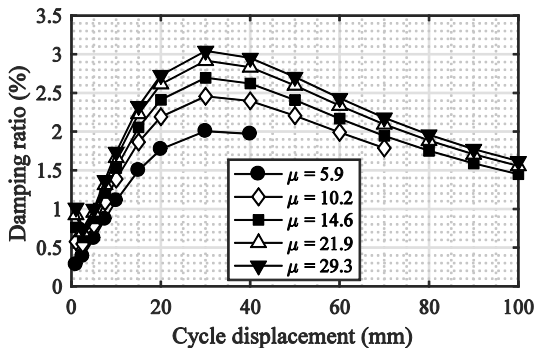
Once the model, it is possible to compare the EVDR obtained from different methods. The main advantage of a virtual experimental study is to avoid spurious dissipation due to external sources. Hence, the validity of the representation of hysteretic dissipation by an equivalent viscous damper is assessed. To assess the influence of the different model's parameters and of the prescribed displacement, an increasing cyclic quasi-static displacement loading has been designed. Each cycle is repeated three times so the hysteretic behaviour in the second and third cycle can be considered as stabilized and the energy dissipation due to damage initiation is not taken into account. It is important to note that the first three cycles are equal to the last three in order to remain at the same ductility level of the beam all along the loading. The definition of this ductility level is:

$$\mu = \frac{\delta_m}{\delta_y} \quad (10)$$

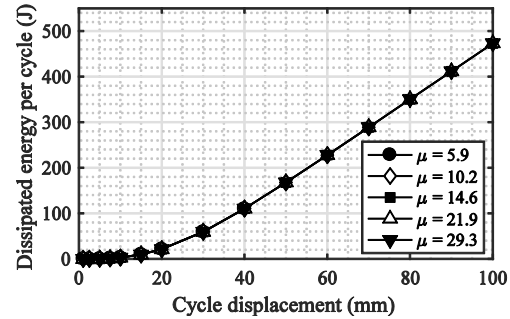
where  $\delta_m$  is the maximum displacement in the time-history analysis and  $\delta_y$  is the elastic limit displacement. The dependency of the EVDR on the ductility level is first addressed. With the identified set of parameters, the EVDR exhibits a strong dependency on the displacement amplitude. Starting from zero, it reaches a maximum and then decreases again asymptotically to zero (more or less quickly depending on the model parameters). After, the influence of the constitutive model parameters is studied considering a constant ductility level of 14.6.

The model including damage mechanisms, the maximum elastic energy storage decreases with the ductility level (figure 6c). The other important observation is that the dissipated energy does not seem to depend on

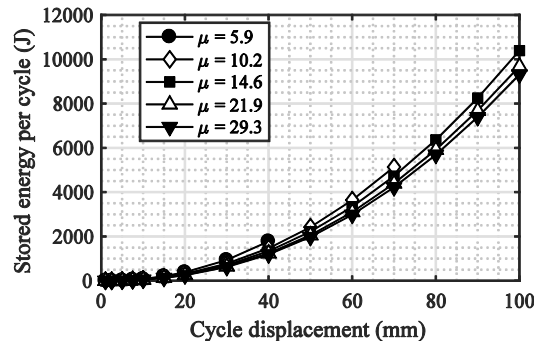
the ductility level of structures for the present nonlinear model. However, since the equivalent viscous damping ratio depends on the ratio of the dissipated energy over the stored one, the EVDR seems to increase with respect to the ductility level (see figure 6a).



(a) Influence of the cycle amplitude on the equivalent viscous damping ratio for different ductility levels.



(b) Influence of the cycle amplitude on the dissipated energy per cycle for different ductility levels.



(c) Influence of the cycle amplitude on the stored energy per cycle for different ductility levels.

Figure 6. Influence of the ductility level over energies and equivalent viscous damping ratio for different cycle amplitudes obtained by Jacobsen's areas method

**Equivalent viscous damping ratio: comparison between Jacobsen's area method and logarithmic decrement method**

A list of displacement levels is arbitrarily defined. The loading and post-process are performed as follows:

- a quasi-static cyclic displacement is prescribed to the oscillator in order to make it reach a given ductility level;
- an initial displacement is prescribed to the beam;
- the beam is dropped off the initial displacement value and its free vibrations are simulated by a Newmark implicit algorithm to assess nonlinearities associated to the hysteretic model;
- the logarithmic decrement method is applied between each consecutive maxima of displacement;
- perform the previous steps for all displacement levels chosen.

From the different ductility levels, an EVDR is associated to a cycle amplitude of displacement and to a given period (deduced from a measured pseudo-period estimated by means of the time between the two consecutive maxima and the corresponding EVDR). The data obtained are plotted on figures 7 and 8. The dependency of the period on the cycle amplitude seen on figure 8b is directly due to the pinching effect: the beam stiffness reduction in the neighbourhood of the zero-displacement point i.e. when the cycle amplitude is lower than the closure displacement) is accompanied by a period increase. As shown by quasi-static tests using Jacobsen's areas method, the EVDR increases with the ductility level. The value of the amplitude of displacement progressively decreases in free vibrations regime because of the energy



dissipation. For each pseudo-cycle, the first maximum of displacement is considered to define the amplitude (alternatively, the second maximum or the mean of the two maxima could have been chosen).

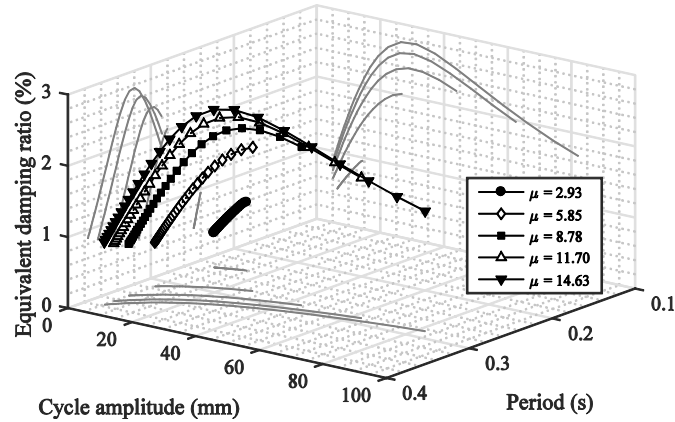


Figure 7. Equivalent viscous damping ratio versus cycle amplitude and measured cycle period for several ductility levels.

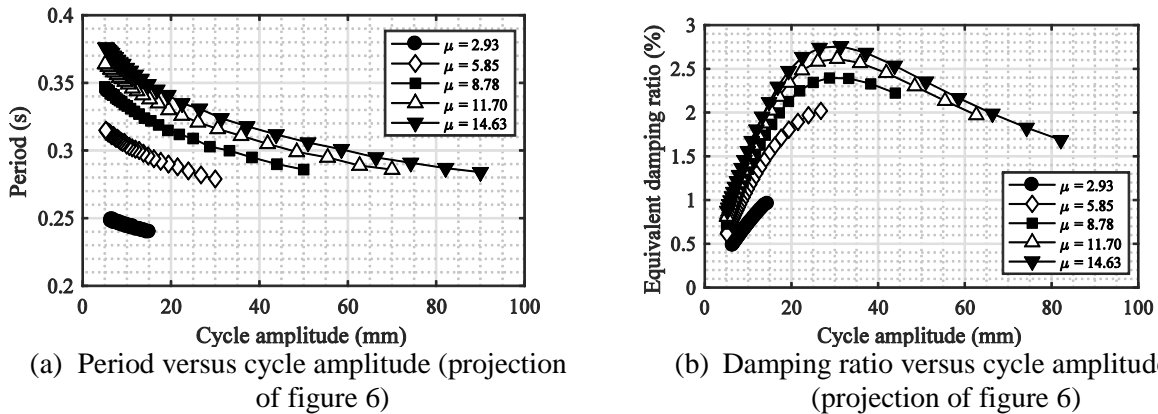


Figure 8. Comparison between the measured and the identified force-displacement response.

The values obtained for the same ductility level  $\mu = 14.6$  for both the quasi-static test analysed by means of the Jacobsen's areas method and the present free vibration test by the logarithmic decrement method are in good agreement as depicted in figure 9. It can be argued that the areas method gives higher estimates of the EVDR than logarithmic decrement, however the relative difference remains reasonable at the maximum damping ratio (+3% of relative difference) and also in mean on the studied cycle amplitude range (+10% of relative difference).

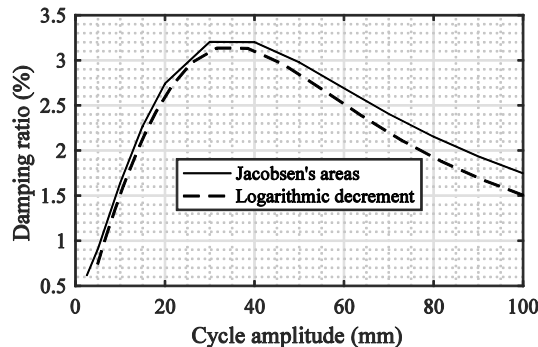


Figure 9. Comparison of the equivalent viscous damping ratio values obtained by Jacobsen's area method in quasi-static and the logarithmic decrement method in dynamics

## CONCLUDING REMARKS

A major experimental campaign has been carried out. In order to model the nonlinear phenomena such as pinching effect, a thermodynamic-based model has been proposed. Moreover, full-field measurements make possible the projection of beam displacements on the theoretical mode shapes which constitute an innovative post-treatment method and can be considered as a so-called *modal filter*. Once the model parameters calibration has been performed through a Matlab<sup>®</sup> built-in identification procedure, numerical simulations of quasi-static cyclic reverse tests and dynamic free vibration tests on the nonlinear oscillator associated to the beam are carried out. The comparison of the EVDR values obtained with each method did not show major differences, thus suggesting that the dynamic characteristic of the loading does not influence significantly the result, even when comparing a logarithmic decrement post-treatment method with the Jacobsen's method. The parametric study has shown the influence of the various model parameters on the equivalent viscous damping ratio. Mostly, the ductility level and the cycle amplitude seem to have a major impact on the EVDR. Furthermore, **a direct interpretation of the damping ratio as an energy dissipation indicator is a misunderstanding: the ductility level here only decreases the maximum stored energy and does not modify the energy dissipation, yet the EVDR increases with respect to the ductility level.** Several studies are ongoing, such as the modal combination influence on the damping, velocity effects or structural and material changes influence on the dissipated energy.

## ACKNOWLEDGEMENTS

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## REFERENCES

- Celik, O. C., & Ellingwood, B. R. (2010). Seismic fragilities for non-ductile reinforced concrete frames—Role of aleatoric and epistemic uncertainties. *Structural Safety*, 32(1), 1-12.
- Charney, F. A. (2008). Unintended consequences of modeling damping in structures. *Journal of structural engineering*, 134(4), 581-592.
- Correia, A. A., Almeida, J. P., & Pinho, R. (2013). Seismic energy dissipation in inelastic frames: understanding state-of-the-practice damping models. *Structural Engineering International*, 23(2), 148-158.
- Crambuer, R., Richard, B., Ile, N., & Ragueneau, F. (2013). Experimental characterization and modeling of energy dissipation in reinforced concrete beams subjected to cyclic loading. *Engineering Structures*, 56, 919-934.
- Cruz, C., & Miranda, E. (2016). Evaluation of Damping Ratios for the Seismic Analysis of Tall Buildings. *Journal of Structural Engineering*, 143(1), 04016144.
- Hall, J. F. (2006). Problems encountered from the use (or misuse) of Rayleigh damping. *Earthquake engineering & structural dynamics*, 35(5), 525-545.
- Heitz, T., Richard, B., Giry, C., and Ragueneau, F. (2017a). Damping identification and quantification experimental evidences and first numerical results. *Proceedings of the 16<sup>th</sup> World Conference on Earthquake Engineering. Paper number 1960*.
- Heitz, T., Giry, C., Richard, B., and Ragueneau, F. (2017b). How are the equivalent damping ratios modified by nonlinear engineering demand parameters? *Proceedings of the 6<sup>th</sup> International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*.
- Jacobsen, L. S. (1930). Steady forced vibrations as influenced by damping. *Trans. ASME*, 52(15), 169-181.
- Jacobsen, L. S. (1960). Damping in composite structures. In *Proceedings of the 2nd world conference on earthquake engineering* (Vol. 2, pp. 1029-1044).

- Jehel, P., Léger, P., & Ibrahimbegovic, A. (2014a). Initial versus tangent stiffness-based Rayleigh damping in inelastic time history seismic analyses. *Earthquake Engineering & Structural Dynamics*, 43(3), 467-484.
- Jehel, P. (2014b). A critical look into Rayleigh damping forces for seismic performance assessment of inelastic structures. *Engineering Structures*, 78, 28-40.
- Kumar, S. S., Krishna, A. M., & Dey, A. (2015). Cyclic response of sand using stress controlled cyclic triaxial tests. In *Proc. 50th India Geotech. Conf.(Pune, Maharashtra, India)*.
- Li, Q. S., Yang, K., Zhang, N., Wong, C. K., & Jeary, A. P. (2002). Field measurements of amplitude-dependent damping in a 79-storey tall building and its effects on the structural dynamic responses. *The Structural Design of Tall and Special Buildings*, 11(2), 129-153.
- Liu, K. S., & Tsai, Y. B. (2010). Observed natural frequencies, damping ratios, and mode shapes of vibration of a 30-story building excited by a major earthquake and typhoon. *Earthquake Spectra*, 26(2), 371-397.
- Satake, N., Suda, K. I., Arakawa, T., Sasaki, A., & Tamura, Y. (2003). Damping evaluation using full-scale data of buildings in Japan. *Journal of structural engineering*, 129(4), 470-477.