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Dissipations in reinforced concrete components: Static and dynamic experimental identification strategy

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ABSTRACT

Despite their now well documented drawbacks, viscous damping based models to describe the dissipations occurring in reinforced concrete (RC) structures during seismic events are popular among structural engineers. Their computational efficiency and their convenient implementation and identification are indeed attractive. Of course, the choice of a viscous damping model is, most of the time, reasonable, but some questions still arise when it comes to calibrate its parameters: how do these parameters evolve through the nonlinear time-history analysis? How do they interact when several eigenmodes are involved? To address these questions, the IDEFIX experimental campaign (French acronym for *Identification of damping/dissipations in RC structural elements*) has been carried out on RC beams set up on the *Azalée* shaking table of the TAMARIS experimental facility operated by the French Alternative Energies and Atomic Energy Commission (CEA). First, this experimental campaign is positioned within an overview of related experimental campaigns in the literature. Second, the IDEFIX experimental campaign is presented. In particular, noticeable results are given by examples of first post-treatments, including an improved so-called "areas method", which lead to very different identified damping ratio depending on the method used.

1. Introduction

The numerous structural constitutive laws which have been developed since the second part of the 20th century laws now allow to provide realistic and reliable results on the nonlinear behavior of reinforced concrete (RC) structures. The more complex is the model, the more precise is the required knowledge of the material properties – a knowledge which is not obvious for engineers when the studied structure is still at the design state. Moreover, the variability of these parameters may lead to a necessary extensive numerical study to assess its influence on the structural behavior and the numerical cost of the associated nonlinear simulations is a strong counterpart that designers and engineers are not always prone to pay for. In addition, no model is precise enough to account for every single dissipation phenomenon occurring in a RC structure during a seismic loading.

For these reasons, the common practice is to consider a simpler structural model associated to an additional viscous damping to account for the dissipations not explicitly modeled. Especially, energy dissipation appears even in the linear domain of the material behaviors [12]. The origins of these dissipations may be multiple: soil-structure interaction, nonstructural elements dissipation, friction in joints, friction, etc. Rayleigh-based damping models – including Caughey's series [8] – are convenient and popular in the earthquake engineering community since they allow a fuzzy description of these sources through a viscous force field. Classical Rayleigh-damping models come with now well-known drawbacks [29,30], depending on which version of the model is chosen (mass proportional, initial stiffness proportional, tangent stiffness proportional, or Caughey's series). Additional viscous damping should be considered carefully when used in combination with a hysteretic model as emphasized in [9,21]. Indeed, the viscous contribution should be reduced progressively once in the nonlinear domain [12], otherwise the total dissipated energy may be overestimated thus leading to a non-conservative result.

For this reason, the amount of dissipated energy is a strong concern to calibrate whatever the chosen model is. Let us consider a (nonlinear) single degree of freedom (SDOF) oscillator of constant mass m and angular eigenfrequency ω_0 excited by a sinusoidal displacement of angular frequency ω. Jacobsen [27,28] has shown that a linear viscous damping force of the form of Eq. (1), where c is the viscous damping coefficient and $\dot{u}$ is the oscillator velocity, is able to represent with an

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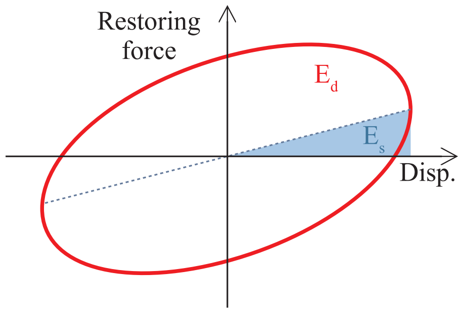


Fig. 1. Principle of Jacobsen's areas method [28] applied on a linear viscous SDOF oscillator response.

acceptable accuracy the dissipations of a more general nonlinear viscous damping force.

$$F_d(t) = -c\cdot\dot{u}(t) \tag{1}$$

His method can be graphically summarized on Fig. 1 for a linear viscous SDOF oscillator response. The restoring force versus displacement plot allows for a quick estimation of both the energy dissipated during one oscillation E_d, corresponding to the area enclosed in the red curve, and the maximum energy stored energy during this cycle E_s corresponding to the area under the straight line between the origin and the point of maximum displacement (since the oscillator is linear). Then, the equivalent viscous damping ratio (EVDR) defined as the ratio of the actual damping coefficient c over the so-called critical damping $c_c = 2\cdot m\cdot\omega_0$ corresponding to the damping coefficient below which oscillations exist if the SDOF is relieved from an out-of-equilibrium state. Then the following equations arise:

$$\xi = \frac{c}{c_c} = \frac{c}{2\cdot m\cdot\omega_0} \tag{2}$$

and

$$\xi = \frac{1}{4\cdot\pi}\cdot\frac{\omega_0}{\omega}\cdot\frac{E_d}{E_s} \tag{3}$$

Eq. (3) being the one proposed by Jacobsen [28] and further discussed for nonlinear cases in Section 4.3. Basically, the EVDR can be seen as proportional to the ratio of energy dissipated during one cycle over the energy storage capacity of the SDOF.

This method stays reliable up to a certain extent whether viscous [1] or nonviscous phenomena are involved [2]. Consequently, a N-degrees of freedom (N-DOF) oscillator would require N equivalent viscous damping coefficients. From this point arises challenging problems regarding the equivalent viscous damping coefficients values associated to each eigenmode, their evolution throughout the inelastic time history analysis, and the possible existing couplings between modal dampings.

Two goals have driven the development of the experimental campaign in order to address the aforementioned issues:

– it should allow for a mode-per-mode as well as mode-coupled dissipations identification;
– the tests must be driven by the degradation level in order to identify the influence of this parameter on energy dissipations. The sensitivity studies regarding other parameters such as material properties should not be corrupted by an uncontrolled evolution of the structural state.

This paper will firstly give an overview of existing experimental campaigns. This will then help to introduce the experimental campaign design for this work. Finally, the relevance of the design is supported by the presentation of noticeable post-treated results.

2. An overview of experimental campaigns

2.1. Quasi-static tests

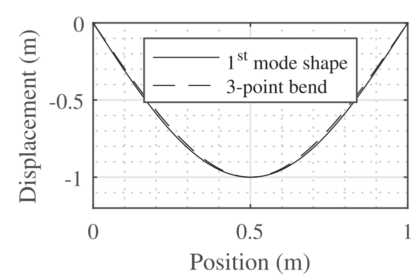
Quasi-static tests are generally easier to setup, and allow for cancelling inertial effects that are inherent to seismic loadings. This characteristic makes them more convenient to identify dissipations which are independent on the velocity or on the acceleration, since both are negligible. However, there is an information loss regarding the dependency of the damping on the excitation frequency. According to Jacobsen [28], the approximation of structural damping by an equivalent viscous damping (i.e. proportional to the velocity) is realistic enough for structures exhibiting light to moderate nonlinear phenomena. In fact, the EVDR ξ_{eq} identified by Jacobsen's method dissipates the right amount of energy when the SDOF system is excited exclusively at the associated eigenfrequency and when loops in the force-displacement curve are complete.

The tests carried out by Crambuer [13] on RC beams subjected to quasi-static cyclic reverse three-point bend (3 PB) loadings aimed to evaluate the EVDR for different damage levels and cycle amplitudes (force-controlled). The underlying hypothesis is that the recorded quasi-static response is the one of the associated SDOF in dynamics. However, because of inertial effects, the flexural mode shape of the beam is sinusoidal while the deformed shape during the 3 PB test is a third degree polynomial function. This observation challenges the validity of the aforementioned hypothesis, but the difference remains small as shown in Fig. 2. The local error criterion used in Fig. 2b is defined in Eq. (4), with x the position along the beam, u the 3 PB deformed shape normalized by the mid-span displacement and ϕ_1 the first mode shape also normalized by its mid-span value. The global error criterion expressed in Eq. (5) (with L the beam span) indicates the good accordance of the 3 PB deformed shape with the first mode shape.

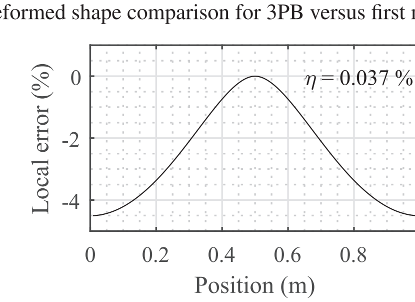
$$e(x) = \frac{u(x)-\phi_1(x)}{\Phi_1(x)} \tag{4}$$

$$\eta = \frac{\int_0^L |u(x)-\phi_1(x)|\cdot dx}{\int_0^L |\phi_1(x)|\cdot dx} \tag{5}$$

Another experimental campaign consisting in quasi-static tests has been carried out by Rodrigues et al. [45] and focused on the assessment



(a) Deformed shape comparison for 3PB versus first mode shape



(b) Local error $e(x)$ between 3PB and first mode shape

Fig. 2. Comparison between 3-point bend deformed shape and first mode shape of the beam.