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ON THE COMPUTATION OF SEISMIC ENERGY DISSIPATION IN REINFORCED CONCRETE FRAME ELEMENTS

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ABSTRACT

Computing energy dissipation in structures under seismic loading is motivated by at least three statements:

1. Commonly used strategy to model the nonlinear behavior of structures consists in choosing some internal variables and then computing their evolution. In this framework, computation of energy dissipation is straightforward and the more refined the nonlinear analysis is, the more precise the energy dissipation computation is. Precise nonlinear analysis of structures until collapse is a keypoint to fully benefit from the new design procedures such as performance-based design: to predict the residual capacity of a structure, elastic analysis is not reliable and this is obvious in the definition of the criteria defined to meet the required performance level. For instance, when a linear analysis is used to predict the demand of the structural elements, the acceptance criteria are sometimes reduced by the significant factor of 0.75 [1].

2. Computing seismic energy dissipation would also be of great interest in the modeling of damping in Earthquake Engineering. Damping is commonly introduced at structural level in the equation of motion of the structure using Rayleigh's method. This approach reduces damping to two sources with poor physical meaning: i) the material is supposed to be elastic viscous and ii) the whole structure is considered as if it moved in a viscous fluid [2].

3. We feel that energy is a quantity that has not been enough exploited in Earthquake Engineering and which could lead to the definition of more consistent acceptance criteria. Indeed it seems natural to compare the seismic energy imparted to the building with the energy which can be dissipated by the structure instead of comparing forces or displacements. For instance, still widely used design procedures rely on the elastic computation of the maximum seismic force increased by the so-called behavior factor $q \geq 1$ defined according to the ductility of the structure; then the resisting force is compared to the seismic action. However, it has been experimentaly shown that low-cycle fatigue plays an important role: concrete sections can highly damage even if the maximum admissible force is never reached during the loading history [3].

Computing energy dissipation is not an easy task. Firstly because many dissipative phenomena occur at different scales in structures under seismic loading, *e.g.* radiations in the soil at structural scale, macrocracks at structural element scale, microcracks at material scale. All these phenomena have to be modeled at the appropriate scale in an appropriate physical and computational framework. Secondly because some dissipative phenomena are very likely unknown and others are difficult to grasp when looking for computational efficiency (dowel effect, steel-concrete interaction). The objective of this contribution is to present a multi-scale methodology to grasp as much dissipative phenomena as possible in RC frame structural elements while keeping reasonable computational efficiency.

Global phenomenological approaches to model the nonlinear response of RC sections can be used. However, one of the rare papers which compare seismic input energy and energy dissipated by the model shows that such approaches only present poor predictive capabilities [4]. We thus prefer to use fiber elements and therefore distinguish between concrete, steel and concrete-steel interface. Indeed, these three components have different dissipative behavior which might need different internal variables to be described. We give a formulation for fiber elements in a general thermodynamicaly and variationaly consistent multi-scale framework. The frame structure is discretized into several beam elements with the finite elements method (FEM) and then, each of these elements is considered as a substructure and is discretized a second time with the FEM into fibers. The multi-scale computational procedure provides strong coupling between the scales [5]. The formulation is based on the partition of the potential energy between the fibers.

Another key issue is the development of local constitutive laws capable of representing most of the material dissipation phenomena but nevertheless robust and not too much time consuming. To that end, we developed a constitutive model for concrete under cyclic loading which couples plasticity and damage, represents strain softening and the appearance of hysteresis loops during unloading-loading cycles. When using linear hardening and softening laws, no local iteration is required [6].

We are convinced that Earthquake Engineering should benefit from deeper interactions between structural analysis and material science and we hope that this work is a step towards this achievement.

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