COMPDYN 2011
ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis, V. Plevris (eds.)
Corfu, Greece, 25-28 May 2011

MODELING ENERGY DISSIPATION: A PARADIGM FOR PERFORMANCE-BASED ENGINEERING OF RC MOMENT-RESISTING FRAME IN SEISMIC LOADING

Pierre Jehel[1], **Pierre Léger**[2], **and Adnan Ibrahimbegovic**[3]

[1] École Centrale Paris, Laboratory of Soil, Structures and Materials Mechanics
Grande Voie des Vignes, 92295 Châtenay-Malabry Cedex, France
pierre.jehel[at]ecp.fr

[2] École Polytechnique of Montreal, Department of Civil Engineering
University of Montreal Campus, P.O. Box 6079, Station CV Montreal, PQ, Canada H3C 3A7
pierre.leger[at]polymtl.ca

[3] LMT-Cachan (ENS Cachan/CNRS/UPMC/PRES UniverSud Paris)
61 av. du Président Wilson, 94235 Cachan Cedex, France
ai[at]lmt.ens-cachan.fr

Keywords: Earthquake Engineering, Damping, Energy Dissipation, Performance-based Engineering, Moment-resisting Frame, Reinforced concrete.

Abstract. *Inelastic structural models used for performance-based design intrinsically dissipate a part of the total amount of the seismic energy imparted to the structure. To take into account the energy dissipation sources not considered in the structural model but that nevertheless exist, damping generally is added. Given an inelastic structural model, state-of-the-practice documents thus advocate to add a portion of damping that is consistent with the inelastic structural model used. The main purpose of this contribution is to investigate whether it is* a priori *straightforward for practitioners to consistently add damping or not. There is indeed no clear theoretical framework for adding damping. This investigation is based on a reinforced concrete moment-resisting frame tested on the shaking table of the École Polytechnique of Montreal. Numerical analyses were carried out with ten different combinations of inelastic structural models and added viscous damping models. The main conclusion of this investigation is that it is a complex task to add viscous damping in a way that is consistent with the capacity of the inelastic structural model to dissipate imparted seismic energy. In the context of RC moment-resisting frame structures in seismic loading, without considering any interaction with the surrounding environment, computing energy dissipation quantities can serve as an indicator for assessing the consistency looked for and appears as a paradigm for performance-based engineering.*

1 INTRODUCTION

The theoretical formalism we use to derive the set of equilibrium equations that governs the motion of a civil engineering structure in dynamic loading is inherited from the mathematical works achieved at the end of the 17^{th} century and during the 18^{th}. Mechanics was at that time a branch of mathematics and the development of infinitesimal calculus and variational calculus has been motivated by the need to rationally describe the world as human beings can perceive it. The world was in particular assumed to be perfect in the sense that it was conservative: no energy dissipation source was considered.

The first introduction of a source of energy dissipation in the formulation of a mechanical problem is attributed to Sir John William Strutt, better known as Lord Rayleigh. His analytical method, along with modal damping, is nowadays still widely used to model the damping phenomenon observed in the response of elastic mechanical systems. It is also common practice, *e.g.* in earthquake engineering, to introduce Rayleigh's damping in the simulation of inelastic systems. Although Lord Rayleigh himself mentioned that his theory lacks physical insight, it is suitable for correctly representing the behavior of a structure as far as i) it remains in its elastic range and ii) there is no need for a microscopic description of the internal mechanisms that generate damping.

When the assumption of elasticity is discarded, *e.g.* for performance-based engineering, there are two main reasons why an explicit description of internal mechanisms becomes necessary. First, internal mechanisms cause irreversible modifications in the structure that have to be accurately described to assess its performance level. For instance, strength and stiffness degradations of structural elements are key indicators to assess residual structural capacity. Second, they dissipate part of the imparted seismic energy and thus participate to the global damping characteristics observed in the structural response. It is however not realistic to explicitly model each internal energy dissipative mechanism, but the most important should be modeled.

Combining explicitly modeled energy dissipation sources with added viscous damping, such as Rayleigh's damping, is common practice in performance-based earthquake engineering [1]. This will be shown in the next section where we will first present the definitions we adopted for damping and finally introduce the concept of *consistent added damping*. As mentioned in recent building rules [2], the portion of added damping should be consistent with the inelastic structural model. As far as performance-based engineering is concerned, the main purpose of this contribution is to investigate whether it is *a priori* straightforward to consistently add damping or not. To this end, the third section is dedicated to the numerical modeling of a reinforced concrete moment-resisting frame tested on the shaking table of the École Polytechnique of Montreal [3]. Ten numerical simulations are carried out according to different combinations of inelastic structural models and Rayleigh's damping models. An analyses of the results is provided an its main conclusion, expressed in the context of RC moment-resisting frame in seismic loading, is that the proportion of seismic energy that is dissipated by the added viscous damping model E_D, even when associated to small critical damping ratios, can become preponderant with respect to the proportion of seismic energy that is dissipated by the inelastic structural model E_H. This sounds not physical. Modeling a portion of added damping that is consistent with a given inelastic structural model thus appears as a complex task. According to this conclusion, in this particular context of RC moment-resisting frame structure in seismic loading and without considering any interaction between the structure and its surrounding environment, computing the E_D/E_H ratio could *a posteriori* be used as an indicator of consistency.

2 CONSISTENT ADDED DAMPING

2.1 Definitions for damping

The definition of damping might somehow be ambiguous. The definition we adopted in this paper needs thus to be clarified. First, in [2], the following definitions are proposed:

- Inherent damping: damping due to inherent dissipation of energy by elements of the structure.
- Additional viscous damping: damping added in the simulation to take into account inherent energy dissipation sources not explicitly considered in the inelastic structural model.

In the numerical simulations, there are thus two sources of damping: damping that comes from the inelastic structural model and additional viscous damping.

Then, in [4], in the context of inelastic structural analysis, damping is defined as ”*the portion of energy dissipation that is not captured in the hysteretic response of components that have been included in the model*”. According to this definition, it is also suggested in [4] to use ”*un-modeled energy dissipation*” as a more appropriate terminology for damping.

In this contribution, we adopt the following definitions:

- Hysteretic damping: energy dissipation due to the inelastic response of the structural elements included in the model.
- Added damping: damping added in the simulation, for instance Rayleigh's damping, to take into account energy dissipation sources not explicitly modeled in the inelastic structural model.

On the contrary to what is suggested in [4], we decided to also qualify the hysteretic energy dissipation as damping. Indeed, in experimental investigations, measured damping is due to all the energy dissipative phenomena; then, in the numerical simulations, hysteretic energy dissipation sources also participate to the damping characteristics of the structure. In what follows, all the energy dissipation sources, that is total damping, is thus split into an explicitly modeled part (hysteretic damping) and an additional part (added damping). This latter part is introduced in the simulations to take into account the energy dissipation sources not explicitly modeled in the inelastic structural model.

2.2 Some words on the state of the practice

Section 2.4 in [4] is a very useful and detailed presentation of damping in the buildings in the context of nonlinear structural analysis. We provide here a very short summary of it.

Experimental evidence concerning $1/3$ to $1/2$ scale reinforced concrete frame systems are presented. The critical damping ratios in the first mode versus level of damage measured from 7 shaking table tests are shown and it is concluded that:

- In the initial or undamaged condition, the critical damping ratio ranges from 1% to 3%.
- In structures that have undergone modest levels of shaking (less than 1% drift) and sustained slight damage (*i.e.* hairline cracking, minor spalling), damping values increase to about 4%.
- Following significant damage, damping increases beyond 5% up to a maximum measured value of 11% of critical.

Inelastic structural models cannot represent all the energy dissipation mechanisms involved in the measured damping. It is mentioned in [2] section 6.4.4 that "*most of the structural damping [should] be modeled directly in the analysis through hysteretic response of the structural components*". And then, "*depending on the type and characteristics of the nonlinear model, additional viscous damping may be used to simulate the portion of energy dissipation arising from both structural and nonstructural components (*e.g. *cladding, partitions) that is not otherwise incorporated in the model*".

Concerning now the choice of the critical damping ratios to be considered for adding viscous damping, the general principle to be appealed for is expressed in the following terms in [2] section 6.4.4: "*When used, viscous damping should be consistent with the inherent damping in the structure that is not already captured by the nonlinear hysteretic response that is directly simulated in the model*". It is stated in [4] that "*many of the currently available guidelines on damping are intended for use with elastic dynamic analysis*". Nevertheless, the value of 5% of critical damping is presented as common practice for nonlinear studies of low to mid-rise buildings. In [5], the dynamic behavior of steel-concrete composite structures is modeled and the authors conclude that the two critical damping ratios of 1% and 5% "*can be viewed as reasonable lower and upper bounds when energy dissipation due to material hysteretic behavior is already modeled explicitly*". In works developed with the finite element computer program *Vector* [6], it is advocated not to add damping and thus to use the inelastic structural model as the sole source of seismic energy dissipation.

2.3 Adding viscous damping

The inelastic earthquake response of RC structures is computed according to the following discrete equations of motion:

$$\mathbf{M}\ddot{\mathbf{U}}(t) + \mathbf{C}(t)\dot{\mathbf{U}}(t) + \mathbf{R}(t) = \mathbf{F}^{sta} - \mathbf{M}\boldsymbol{\Delta}\ddot{\mathbf{U}}_g(t) \tag{1}$$

where $\mathbf{M}$, $\mathbf{C}(t)$ are the mass and damping matrices and $\mathbf{R}(t)$ is the nonlinear restoring forces vector; $\mathbf{F}^{sta}$ is the applied static forces, and $-\mathbf{M}\boldsymbol{\Delta}\ddot{\mathbf{U}}_g(t)$ represents the applied seismic forces with $\boldsymbol{\Delta}$ the matrix indicating the active dynamic degrees of freedom for directional mass and $\ddot{\mathbf{U}}_g(t)$ the applied ground acceleration.

There are several methods for introducing added viscous damping ($\mathbf{C}(t)\dot{\mathbf{U}}(t)$) in numerical simulations: the so-called Rayleigh's or Caughey's methods or modal damping. We only present here Rayleigh's methods that will be used for the numerical simulations presented in the next section:

$$\mathbf{C}_{[i]}(t) = (a_M\mathbf{M} + b_K\mathbf{K}_0)_{[1]}\ ,\ (a_M\mathbf{M} + b_K\mathbf{K}_{tan}(t))_{[2]}\ \text{or}\ (a_M(t)\mathbf{M} + b_K(t)\mathbf{K}_{tan}(t))_{[3]} \tag{2}$$

where $\mathbf{K}_0$ and $\mathbf{K}_{tan}(t)$ are the initial and tangent stiffness matrices. The coefficients a_M and b_K determine the critical damping ratio for two chosen structural frequencies.

Although all of these methods have clear significance and computational benefits in elastic simulations, they might be inappropriate in inelastic analyses and thus have to be handled with care. Several researchers presented seismic analyses of nonlinear structural systems using different damping models from Eqs. (2) [7, 8, 9, 10]. It was concluded that $\mathbf{C}_{[3]}(t)$ was the best model to maintain a constant value of added viscous damping throughout the analysis and avoid spurious internal damping forces. However, the update of parameters $a_M(t)$ and $b_K(t)$ with the progress of the solution is not practical from a computational aspect and damping models $\mathbf{C}_{[1]}$ or $\mathbf{C}_{[2]}(t)$ are generally preferred. The coefficients a_M and b_K are most often computed from the initial dynamic properties of the structures, but pushover analysis (or other approximations) could also be used to predict the secant stiffness at the target ductility to estimate an elongated natural period of vibration in the computation of a_M and b_K.

The purpose of the following section is to investigate how far such commonly used added viscous Rayleigh's damping models can be considered as consistent with the hysteretic damping coming from the inelastic structural model. Then, to *a posteriori* quantify this consistency, an indicator based on energy quantities is suggested.

3 ENERGY AS AN INDICATOR OF CONSISTENCY FOR ADDED DAMPING

In this section, numerical inelastic seismic analyses of a RC moment-resisting frame tested on a shaking table are compared. Different computer programs available to practitioners and researchers are used to combine different RC inelastic and added viscous damping models, and to compare their relative amount of energy dissipated during the seismic time-history.

3.1 Description of the RC frame structure and ground motions

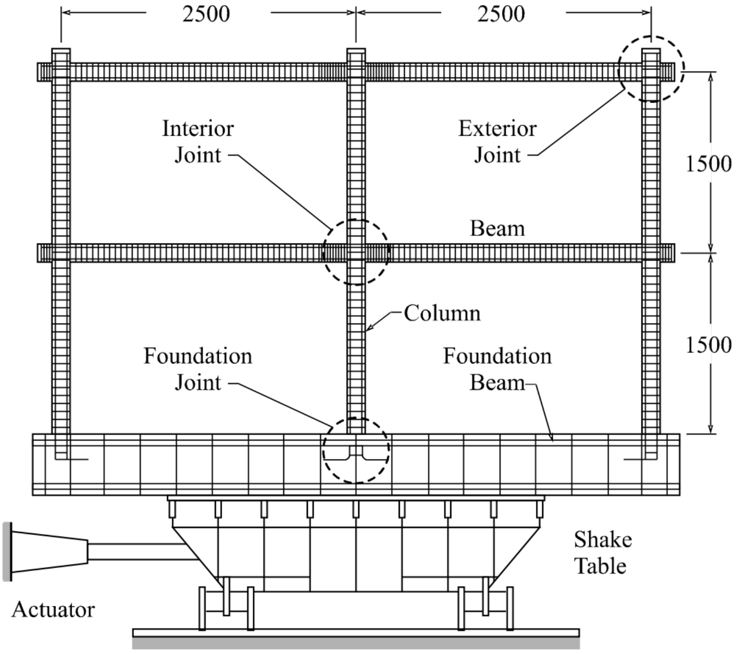

Figure 1: RC frame tested on a shaking table.

Fig. 1 shows the geometry and reinforcing steel of the half scale RC moment-resisting frame that was tested on a shaking table some years ago by Filiatrault *et al.* [3] at École Polytechnique of Montreal. The structure was designed according to the Canadian National Building Codes CNBC 1995 for a global displacement ductility demand $R = 2$. A detailed description of the frame is given in [3]. The two bays, two stories frame is 5 m wide, 3 m high with rectangular cross-sections of 15x16 cm and 14x15 cm for the 1$^{\text{st}}$ and 2$^{\text{nd}}$ floor beams, 17x13 cm and 18x13 cm for the external and internal columns. Resulting properties of RC are as follows: concrete Young's modulus 25,200 MPa, compressive strength 31 MPa and Poisson's ratio 0.17; the longitudinal steel Young's modulus 224,600 MPa with a yield strength 438 MPa and the ultimate strength 601 MPa. Four inverted U shape concrete blocks attached in each span of the beams were used to simulate concentrated gravity loads from framing joints. The centers of gravity of the added masses were computed such that they coincide with the center of gravity of the beams. Service cracks were induced by the added masses. The total weight of the frame was 95 kN. The fundamental period was measured at 0.36 s in a free-vibration test with a first modal damping ratio of 3.3%. Mode 1 is preponderant.

The ground motion record that was selected for the test program corresponds to the N04W component of the accelerogram recorded in Olympia, Washington (April 13, 1949). Fig. 2 presents the feedback record measured on the shaking table during the test initially scaled to a peak ground acceleration PGA = 0.21 g, as well as the corresponding response spectrum.

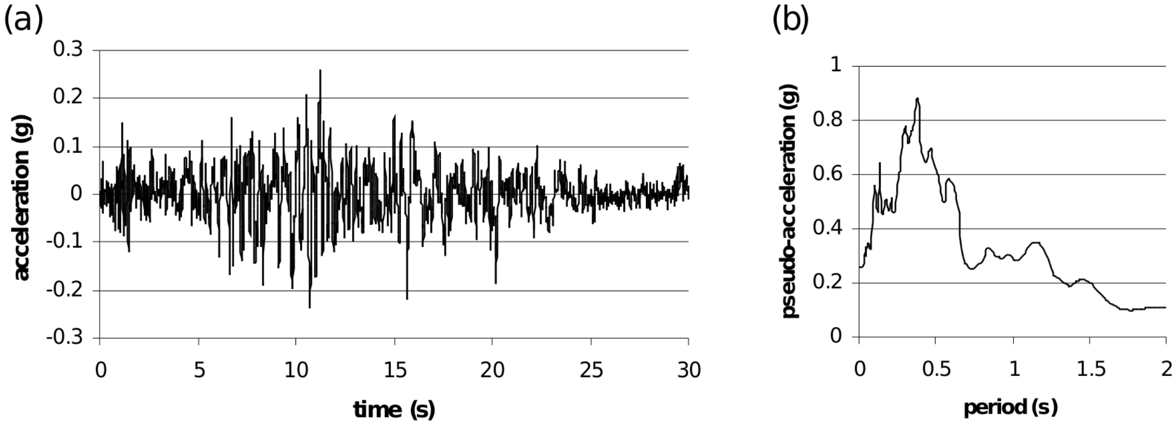

Figure 2: Seismic input motion: (a) shaking table acceleration, (b) response spectrum (5% critical damping ratio).

The frame structure was designed according to the CNBC 1995. The structural response observed during the shaking table test, expressed in terms of displacements, shear forces and plastic hinges positions, is in accordance with the building code.

3.2 Structural models

It is well known that all the inelastic analyses do not provide identical results and it is not realistic to aim at modeling all the energy dissipative phenomena that can occur during seismic time-history. However, as mentioned in [11], there are ”*phenomena that affect the behavior at or near collapse and that cannot be detected and evaluated by means of conventional elastic analysis techniques*”; among others, the author focuses on i) structure P-delta effects, ii) deterioration in strength and stiffness and, for moment-resisting frame structures, iii) the capacity design strong column–weak girder concept for which excessive plastic hinging in columns should be avoided. The inelastic structural models used thus have to be at least capable of reproducing these key issues.

The model developed with the computer program *Ruaumoko* [12] (Fig. 3a) is based on beam-column elements with plastic hinges lumped at the member ends. The Q-HYST degrading rule version of the modified Takeda model (Fig. 3b) was used to represent the inelastic moment-rotation behavior in plastic hinges. The backbone of the hysteretic curve was obtained from a plane section analysis program. At each node the connection was modeled using rigid end beam and column offsets (infinitely stiff zones whose length is equal to the depth of the adjacent beam or column) and plastic hinges whose lengths are equal to half the height inside the stirrups. *Ruaumoko* allows using the damping models $\mathbf{C}_{[1]}$ or $\mathbf{C}_{[2]}(t)$ defined in Eqs. 2.

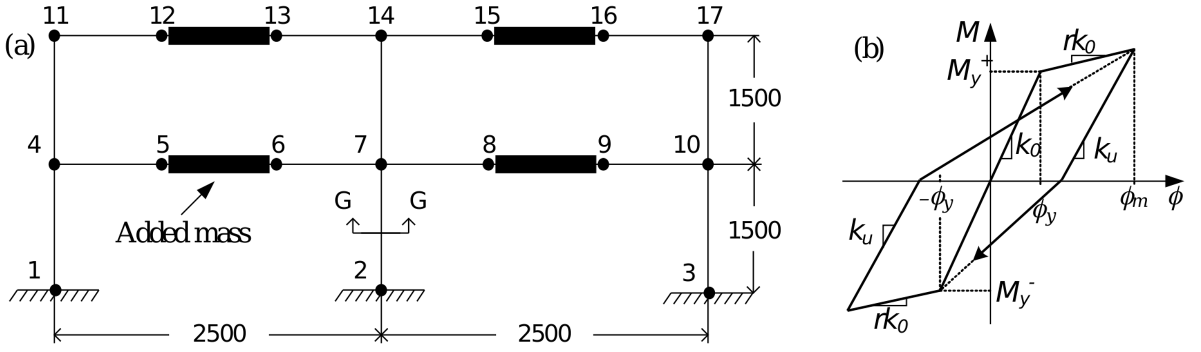

Figure 3: Ruaumoko lumped plasticity model: (a) geometry; (b) modified Takeda hysteretic model.

We also used the computer program *Perform3D* [13] allowing for the discretisation of the various frame cross-sections into fibers. A division of the sections into 6 concrete and steel layers for the columns and 8 layers for the beams was used. A 1D behavior law was associated to each material; Fig. 4a shows the stress-strain behavior of the concrete material models. The mesh is the same as in Fig. 3a. For the structural model referred to as Perform3D_1, unconfined concrete material was assigned to each concrete fiber and 5 numerical integration points (NIPs) per element were considered. For the structural model Perform3D_2, the concrete material was defined as confined concrete inside the stirrup and as unconfined outside (Fig. 4b), and only 2 NIPs per element were considered. Connections at each node were modeled by using rigid end beam and column offsets, that is, for *Perform3D* program, zones whose length is equal to the depth of the adjacent beam or column and whose stiffness is 10 times those of the element. In *Perform3D*, Rayleigh's damping models are not exactly defined as in Eqs. 2. We consequently define both $\mathbf{C}_{[F1]}$ as a Rayleigh's damping model computed according to the initial stiffness, as for model $\mathbf{C}_{[1]}$, and $\mathbf{C}_{[F2]}$ as a Rayleigh's damping model computed according to the reduced stiffness associated to a global displacement ductility $R = 2$, in the spirit of model $\mathbf{C}_{[2]}$. To this, the methodology is described in [13].

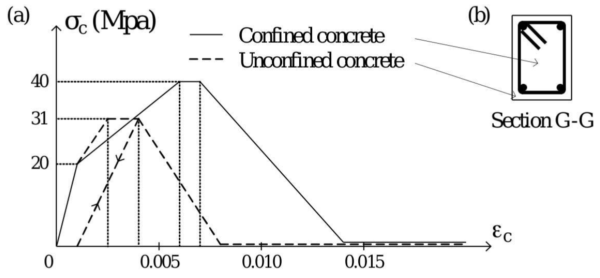

Figure 4: Perform3D fiber element model: (a) concrete model, (b) confined and unconfined fibers. Stiffness degradation is modeled and there is no strength in tension.

Degradations, and thus energy dissipation phenomena, were observed in the beam-column joints during the test. For more detailed structural models, rigid end zones should thus be replaced by inelastic connections.

3.3 Results analysis

The total weight of the structure P and the fundamental elastic period T^{ela} are first indicated in Tab. 1. *A posteriori*, with the experimental results at hand, the values obtained for T^{ela} can be validated as follows. Because of the dead load, there is significant initial damage in the structure and the experimental fundamental period that is initially measured ($T_{FV}^{ini,exp} = 0.36$ s) is longer than the elastic one. The elastic dynamic properties of the mock-up are thus not known. For *Perform3D*, we evaluate the initial fundamental period by weakly exciting the structure after the dead load has been applied, letting it return to rest in free vibrations and measuring T_{FV}^{ini} (mode 1 is predominant). Then, the maximum top-displacement d_{max} is indicated. The quantities E_T, E_D and E_H correspond to the total seismic energy dissipated by the numerical model, the energy dissipated by the added viscous damping model and by the inelastic structural model. Finally, the fundamental period T_{FV}^{fin} is computed when the structure returns to rest at the end of the seismic motion.

	Exp.	Ruaumoko					Perform3D_1			Perform3D_2	
Damping model	/	/ (1)	$[C]_{[1]}$	$[C]_{[2]}$	$[C]_{[1]}$	$[C]_{[2]}$	$[C]_{[F1]}$	$[C]_{[F1]}$	$[C]_{[F2]}$	$[C]_{[F1]}$	$[C]_{[F2]}$
$\xi_{1,2}$ (%)	/	0.0	1.5	1.5	3.3	3.3	0.1	1.5	1.5	1.5	1.5
P (kN)	95	93.8					94.8				
T^{ela} (s)	NA (2)	0.28					0.26				
T_{FV}^{ini} (s) (3)	0.36	0.44					0.38				
d_{max} (mm)	48.9	47.1	44.1	45.8	42.2	42.2	46.4	45.5	46.1	43.6	43.8
E_T (N.m)	/	3735	3307	3442	2861	3089	2782	3534	3557	2698	2620
E_D/E_T (%)	/	0.0	23.7	22.2	46.2	43.3	8.2	60.2	55.9	83.0	81.7
E_H/E_T (%)	/	100.0	76.3	77.8	53.8	56.7	89.8	38.2	42.4	20.4	18.3
T_{FV}^{fin} (s)	0.55	0.46	0.45	0.45	0.46	0.45	0.51	0.49	0.50	0.40	0.40

(1) No added damping introduced in the model.
(2) NA: Not Available.
(3) FV: Free Vibrations.

Table 1: Earthquake response analyses of a RC moment-resisting frame using different inelastic structural and added viscous damping models (excerpt of the results).

Our purpose here is to show that it is somehow difficult to *a priori* assess that an added damping model is consistent with the inelastic structural model. Indeed, even for Rayleigh's damping models defined with small critical damping ratios, E_D can become very larger than E_H. This sounds not acceptable for most of the performance-based analyses. One can hope that this non-realistic behavior would be avoided with a "good" inelastic structural model. However, there is *a priori* no reason not to check whether added damping is consistently modeled or not and the computation of the amounts of energy dissipated all along the seismic time-history seems to provide a pertinent indicator for this.

The following tendencies can be observed from Tab. 1:

- The $E_{H/D}/E_T$ ratio is affected by the choice of a structural model. 1) For the lumped plasticity models (*Ruaumoko*), hysteretic energy is preponderant, which is no more the case for the *Perform3D* fiber element models; this is illustrated in Fig. 5. 2) For *Perform3D* models, the assumptions made on the concrete behavior law also significantly affect the energy ratios.

- For a given computer program, the larger the E_H/E_T ratio is, the larger and closer to the experimental response is the maximum top-displacement. This observation supports some researchers' opinion, who advocate not to introduce added damping in inelastic simulations [6].

- For both *Ruaumoko* and *Perform3D* models, the energy repartition is not significantly affected by the choice of a Rayleigh's damping model of the $\mathbf{C}_{[(F)1]}$ or $\mathbf{C}_{[(F)2]}$ kind. Defining added viscous damping according to a reduced stiffness matrix with respect to the initial one nevertheless leads to a slight reduction of the E_D/E_T ratio.

- For both *Ruaumoko* and *Perform3D* models, the energy ratios are sensitive to $\xi_{1,2}$, the critical damping ratio attributed to modes 1 and 2.

- For all *Ruaumoko* models, the final fundamental structural frequency is roughly $T_{FV}^{fin} = 0.45$ s. This indicates that the global structural stiffness degradation is independent from the E_H/E_T ratio. On the contrary, for *Perform3D* models, there is a clear correlation between the amount of energy dissipated by the model and the degradation of the global stiffness. Considering *Perform3D* models only, the best approximation is obtained when there is almost no added damping.

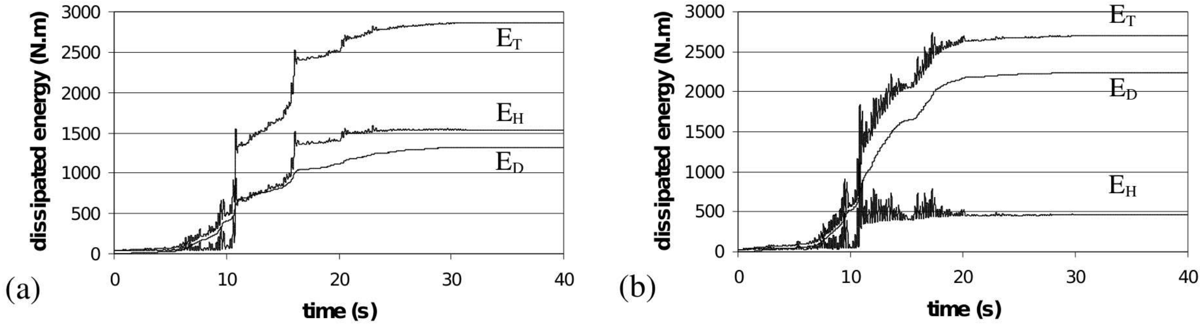

Figure 5: Energy dissipation sources: (a) Ruaumoko $\mathbf{C}_{[1]}$-3.3%, (b) Perform3D_2 $\mathbf{C}_{[F2]}$-1.5%.

Besides, computing energy quantities allows to compare the relative importance of the inelastic mechanisms accounted for in the structural model. For instance, for detailed material constitutive models developed in the theoretical frameworks of continuum mechanics and thermodynamics with interval variables, it is often difficult, in the context of seismic inelastic time-history analysis, to assess whether enriching the model with new local mechanism is meaningful or not. However, for this kind of models, it is often straightforward to compute the energy dissipated by each local phenomenon such as plasticity or damage [14], and it is thus possible to quantify the relative importance of each local phenomena.

4 CONCLUSIONS

In the particular context of RC moment-resisting frame structure in seismic loading, and without considering any interaction between the structure and its surrounding environment:

- **Facts.** The seismic energy imparted to a structure is dissipated consequently to inelastic mechanisms, that are irreversible modifications, in the structure.
- **Issue.** Performance-based methods ideally require that the irreversible modifications in the structure are predicted. One of the main issues related to performance-based engineering thus is: how to model the energy dissipation mechanisms in the structure?
- **Methodological aspects.** The need for modeling internal energy dissipation provides methodological indications for the development of inelastic analyses. Energy dissipation in a structural numerical model should be mostly hysteretic to predict the internal modifications. However, it is not always satisfied for inelastic numerical simulations, even when added viscous damping is associated to a small critical damping ratio. Therefore, developments should be oriented towards both increasing the capacity of inelastic structural models to reproduce the physical mechanisms that dissipate the imparted energy and reducing the portion of added damping.
- **Results interpretation.** Results of inelastic time-history analyses can be better interpreted according to energetic quantities, which indicate whether the energy dissipation is, as expected, mostly hysteretic or not. In the case most of the energy is dissipated by added damping, it can be inferred that the numerical simulation failed to predict the internal modifications in the structure (strength and stiffness loss, drift, etc.). Elastic simulations are an extreme case: all the seismic energy is dissipated by added damping and, consequently, the structure after the earthquake is the same as before. Computing the portion of the total energy dissipated by a particular nonlinear mechanism during the seismic time-history would also allow to decide whether it is worth modeling this mechanism or not.

For these reasons, expressed in the context of RC frame structures in seismic loading, and without considering any interaction between the structure and its surrounding environment, modeling energy dissipation is a paradigm [15] for performance-based engineering.

REFERENCES

[1] M.J.N. Priestley, G.M. Calvi, M.J. Kowalsky, *Displacement-based seismic design of structures*. IUSS Press, Pavia, Italy, 2007.

[2] FEMA P695, *Quantification of Building Seismic Performance Factors*. FEMA, Washington DC, June 2009.

[3] A. Filiatrault, E. Lachapelle, P. Lamontagne, Seismic performance of ductile and normally ductile concrete moment resisting frames - Part I: Experimental study. *Canadian Journal of Civil Engineering*, **25**, 331–352, 1998.

[4] PEER-2010/111 or PEER/ATC-72-1, *Modeling and Acceptance Criteria for Seismic Design and Analysis of Tall Buildings*. PEER, Richmond (CA), October 2010.

[5] A. Zona, M. Barbato, J.P. Conte, Nonlinear Seismic Response Analysis of Steel–Concrete Composite Frames. *ASCE Journal of Structural Engineering*, **134**(6), 986–997, 2008.

[6] S. Saatci, *Behavior and modeling of reinforced concrete structures subjected to impact loads*. PhD Thesis, University of Toronto, Department of Civil Engineering, Canada, 2007. `http : //www.civ.utoronto.ca/vector/`

[7] J. Wang, Intrinsic damping: Modeling techniques for engineering systems. *ASCE Journal of Structural Engineering*, **135**(3), 282–291, 2009.

[8] F.A. Charney, Unintended consequences of modeling damping in structures. *ASCE Journal of Structural Engineering*, **134**(4), 581–592, 2008.

[9] J.F. Hall, Problems encountered from the use (or misuse) of Rayleigh damping. *Earthquake Engineering and Structural Dynamics*, **35**, 525–545, 2006.

[10] P. Léger, S. Dussault, Seismic-Energy Dissipation in MDOF Structures. *ASCE Journal of Structural Engineering*, **118**(6), 1251–1267, 1992.

[11] H. Krawinkler, Importance of good nonlinear analysis. *The Structural Design of Tall and Special Buildings*, **15**, 515–531, 2006.

[12] A.J. Carr, *Ruaumoko manual, theory and user's guide to associated programs*, University of Cantabury, Christhurch, New Zealand, 2004.

[13] CSI, *Perform3D user's manual*, California, 2007.

[14] P. Jehel P, A. Ibrahimbegovic, P. Léger, L. Davenne, Towards robust viscoelastic-plastic-damage material model with different hardenings / softenings capable of representing salient phenomena in seismic loading applications. *Computers and Concrete*, **7**(4), 365–386, 2010.

[15] T.S. Kuhn, *The Structure of Scientific Revolutions, 2nd edition*. In *International Encyclopedia of Unified Science*. The University of Chicago Press, Chicago, 1970.