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ON THE CORRELATION BETWEEN ENERGY AND DISPLACEMENT

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SUMMARY

The analysis of the seismic response of structures observed during recent earthquakes and the attempts at predicting collapse and damage level has led to the formulation of new methodologies, that take into account the actual damage potential of the ground motion and the structural behaviour. As structural damage during an earthquake ground motion may be due to excessive deformations or to the cumulative cyclic damage, reliable methods for estimating energy and displacement demands on structures are needed. Aim of this paper is the characterization of the seismic demand on multi-story framed structures by means of appropriate parameters formulated in terms of energy and displacement. The need of taking into account the local seismic demands has led to the adoption of a simplified shear-type model, capable of providing concise results of the seismic response of different structural systems subjected to a large number of strong motion records. The proposed methodology allows to take all the vibration modes that implicitly contribute to the seismic response into account, and to describe completely the distribution of displacement and energy dissipation along the height of the structure. Twenty different reinforced concrete, two bay-frames were studied as representative of various typologies of current buildings. A stiffness-degrading hysteretic model was used to represent the cyclic behavior of the frames in each story. The effect of the stiffness distribution patterns along the height of the structures and the hysteresis models describing the cyclic behavior of the systems was evaluated. Results indicate that is possible to extend the characterization of the relationships between energy and displacement from SDOF systems to MDOF systems. Moreover, the correlation between energy and inter-story drift demands appears stronger than the analogous one between energy and top displacement.

INTRODUCTION

One of the most important elements in performance based seismic engineering, for the design of new facilities as well as the seismic evaluation of existing ones, is the assessment of the seismic demand. Various studies suggested that improved performance parameters, such as deformation and energy demands could be considered explicitly during seismic design (Bertero [1], Krawinkler [2], Priestley [3], Teran-Gilmore [4], Fajfar [5], Leelataviwat [6]). Actually, having been considered into recent design guidelines, the displacement-based approach is more familiar (Bommer [7], Miranda [8, 9, 10], Gupta

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[11], Krawinkler [12], Whittaker [13], Borzi [14], Decanini [15]); on the contrary there is a considerably lesser amount of research on the development of an energy-based methodology (Akbas [16], Leelataviwat [17]), that is mainly focused on satisfying the energy balance equation using a monotonically increasing deformation approach. However it has been widely recognized that the use of the energy approach allows to properly select the design earthquake ground motions and consequently to improve the seismic hazard assessment procedures, to optimize the design, and to decide on strategies for the implementation of innovative protective systems such as passive energy dissipation and base isolation devices (Chai [18], Chou [19], Decanini [20, 21], Fajfar [22], Ghosh [23], Hori [24], Manfredi [25], Ordaz [26], Reinoso [27], Riddell [28], Teran-Gilmore [29]).

Several researches assessed the energy and displacement demands in single-degree-of-freedom (SDOF) systems. In particular, only few attention was devoted to energy analyses for multi-story building structures (Chou [30], Decanini [31], Estes [32], Shen [33], Leelataviwat [17]). To broadly extend the evaluation of such demands to multi-degree-of-freedom (MDOF) systems is essentially needed. In this paper, in order to increase the understanding on the elastic and inelastic dynamic response of MDOF systems, energy and displacement demands on such systems were analyzed by resorting to opportune non-dimensional relationships between them. To this purpose, two pairs of parameters were proposed: the former two relate energy quantities (namely, input and hysteretic energy) to the top (roof) displacements; the latter two relate the same energy quantities to the maximum inter-story drift. From the knowledge of the correlation between energy and displacement amount for MDOF systems it could be possible either to define global and local displacement demands on the basis of energy design spectra, or conversely to establish energy demands on the basis of design displacement demands.

In this study simplified MDOF models were used to represent a generality of lateral load resisting systems, in order to identify the dynamic behavior pattern clearly, to quantify the influence of different structural characteristics, and to exemplify local and global seismic responses by the assessment of spectral quantities. The effect of significant mechanical properties of MDOF systems such as the stiffness distribution patterns along the height of the structures and the hysteresis models characterizing the cyclic behavior of the systems was evaluated on the basis of this simplified methodology.

RELATIONSHIPS BETWEEN ENERGY AND DISPLACEMENT DEMAND

The identification of reliable relationships between energy and displacement demands represents a fundamental issue in both the development of more reliable seismic code provisions and the evaluation of seismic vulnerability aimed to the upgrading of existing hazardous facilities.

Even though the seismic performance of a structure is directly related to the global and local deformations of the structure, the energy balance formulation appears much more effective in concept, as it permits a rational assessment of the energy absorption and dissipation mechanisms that can be effectively accomplished to balance the energy imparted to the structure. As the two aspects could become consistently integrated within a performance-based seismic design methodology, understanding how input and dissipated energy are correlated with displacement demands emerges as a decisive prerequisite.

For SDOF systems, Fajfar [34] and Fajfar & Vidic [22] proposed a non-dimensional parameter, γ, defined by the following formula:

$$\gamma = \frac{\sqrt{E_H / m}}{\omega \delta} \tag{1}$$

where E_H is the dissipated hysteretic energy, m is the mass of the system, ω is the natural circular frequency and δ is the maximum displacement of the system. This expression, which represents a normalization of the dissipated hysteretic energy, can be read as the ratio between two equivalent velocity amounts. The above relationship was introduced by Fajfar & Gaspersic [5] in a non-linear methodology for the seismic damage analysis of reinforced concrete buildings (i.e., the so-called *N2 method*) applicable to the planar analysis of building structures vibrating predominantly in the first mode, both in elastic and in inelastic range. As also shown by Decanini [31], there exists a stable approximately parabolic relationship between global displacement (herein named *roof displacement*, δ_{roof}) and hysteretic energy, E_H, demands for equivalent single-degree-of-freedom (ESDOF) systems systems, modeled by assuming an assigned time-independent global deflection shape for the lateral displacements of the structure, thus restricting its dynamic response to the first vibration mode only.

More stable quantities than that obtained with the γ parameter can be yielded by setting a relation between the square root of the input energy and the displacement. As a matter of fact the input energy E_I represents an effective tool in the characterization of the seismic demands; moreover, it constitutes a very stable parameter, scarcely depending on the hysteretic properties of the structure. A new parameter, ζ, was then defined as follows (Teran-Gilmore [4, 29])

$$\zeta = \frac{\sqrt{E_I / m}}{\omega\delta} \tag{2}$$

where E_I is the input energy and again m is the mass of the system, ω is the natural circular frequency and δ is the maximum displacement of the system. In particular, it was found that the quantity above is more stable than that expressed by γ (Decanini [21, 31]).

As a general rule methods based on the analysis of the dynamic response SDOF or ESDOF systems permit to obtain a quite good evaluation of global displacement and energy demands. However, as they neglect significant effects on the seismic response of multistory frames due to higher modes, they cannot be used for the estimation of local energy and displacement demands; besides, it should be considered that the local seismic behavior is also strongly affected by the particular characteristics of the strong ground motions. Therefore, in order to extend the characterization of the relationships between energy and displacement demands for multi-degree-of-freedom (MDOF) systems, in the present work two further pairs of parameters are defined, one that relates input or hysteretic energy with global displacements, the other that correlates energy quantities with interstory drifts.

The first two parameters ζ' and γ', respectively depending on the input energy, E_I and on the dissipated hysteretic energy, E_H, can be directly derived by utilizing modified expressions of formulae derived for the SDOF systems, Equations (2) and (1) in that order, as

$$\zeta' = \frac{\sqrt{E_I / m}}{\omega_1 \delta_{roof}} \tag{3}$$

$$\gamma' = \frac{\sqrt{E_H / m}}{\omega_1 \delta_{roof}} \tag{4}$$

where m is the total mass of the system, ω_1 is the fundamental frequency, and δ_{roof} is the top displacement. The definition of the second two parameters, γ'' and ζ'', required instead further modifications of Equations (2) and (1) respectively. Substitution of the global displacement, δ, with the inter-story drift, Δ_{max}, in Equations (2) and (1) leads to the following expressions:

$$\zeta'' = \frac{\sqrt{E_I / m}}{\omega_1 \cdot N \cdot \Delta_{max}} = \frac{\sqrt{E_I / m}}{\omega_1 \cdot N \cdot h \cdot IDI_{max}} \tag{5}$$

$$\gamma'' = \frac{\sqrt{E_H / m}}{\omega_1 \cdot N \cdot \Delta_{max}} = \frac{\sqrt{E_H / m}}{\omega_1 \cdot N \cdot h \cdot IDI_{max}} \tag{6}$$

where N is the number of storys, h is the story height and $IDI_{max} = \Delta_{max}/h$ is the maximum interstory drift index. The quantities above have proved (Mura [35]) to be capable of yielding the best results in terms of statistical stability with regard to the characteristics of the ground motion records considered.
Introducing the coefficient of distortion, *COD*, defined as the ratio of the maximum interstory drift index, IDI_{max}, to the average interstory drift index, IDI_{avg} (Teran-Gilmore [4]), in Equations (5) and (6) and considering frame structures having the same height in all stories, so that the total height of the frame and the maximum interstory drift index are expressed by

$$H = Nh \tag{7a}$$

$$IDI_{max} = COD \cdot IDI_{avg} = COD \frac{\delta_{roof}}{H} \tag{7b}$$

which implies

$$N \cdot h \cdot IDI_{max} = H \cdot IDI_{max} = COD \cdot \delta_{roof} \tag{8}$$

leads to the following relationships:

$$\zeta'' = \frac{\zeta'}{COD} \tag{9}$$

$$\gamma'' = \frac{\gamma}{COD} \tag{10}$$

STRUCTURAL SYSTEMS AND GROUND MOTIONS

The objective of this research is to carry out the assessment of both energy and displacement demands in multi-degree-of-freedom (MDOF) systems in order to verify the consistency of the relationships introduced above. Therefore, for the need of generality of the results and hence of the conclusions, the MDOF systems selected as representative of structural frame models are not intended to correspond to specific structures. Instead, a simplified model was used in this study for the estimation of the dynamic responses to different ground motions, so that the sensitivity of results to different mechanical properties can be readily evaluated. Dynamic analyses were performed using an equivalent discrete shear-type model (ESTM model), which allowed a relatively simple procedure in the integration of the equation of the motion (Decanini [36, 37]). The effectiveness of the ESTM model was also validated by comparing the results with those derived from more detailed non-linear time histories analyses (Mura [35], Decanini [37]). The implementation of a simplified modeling permitted to achieve a spectral representation of energy and displacement demands at both global and local level and to perform an extensive parametric investigation on different structures.
In this paper, ten multi-story structural systems are modeled by using two-dimensional, two-bay generic frames with constant story height and beam spans (Figure 1). The number N of stories considered in the analysis varies from 2 to 24 in order to simulate a significant range of typologies of reinforced concrete buildings. For the characterization of the inelastic response of multi-story frames subjected to ground motions, a further approximation was introduced in order to describe the hysteretic behaviour of the system by means of simple rules. In this case it was necessary to define approximately a yielding resistance for each story.
The main aspects of the structural response of multi-story frame systems subjected to strong ground motions are connected with the mechanism of development of plastic deformations within the structure. In

a well-designed frame, possibly according to the capacity design rules, the formation of soft-storeys should be avoided taking care that the inelastic deformation demands are uniformly spread throughout the structure. This can be achieved provided that a well defined global mechanism, the so-called beam-sway mechanism, is ensured. The development of such a mechanism implies that plastic hinges are formed in all beams at all storeys, while the strength capacity of columns and joints is preserved.

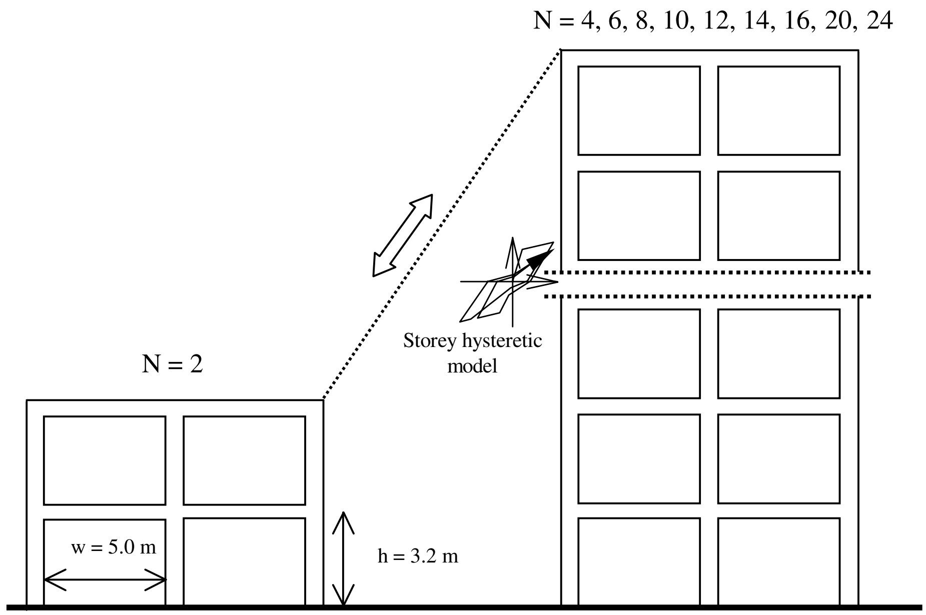


Figure 1. Structural layout of the analyzed frames.

To this purpose, in the adopted simplified modeling it was necessary to manage accurately the local inelastic behavior in the ESTM model that operates at story level.

By means of comparison with other researches (Nassar [38], Seneviratna [39]) and ad hoc analyses, the strain hardening was identified as a simple tool capable to ensure a beam-sway mechanism. Such assertion is based prevalently on the fact that the stiffness reduction caused by the concentration of plastic deformations in the beams of a given story, though significant is less rapid than in occurrence of a story mechanism. For this reason the strain hardening ratio, p, was tuned to a value $p = 10\%$ for properly designed RC frames.

Another important issue is constituted by the choice of a data-set of accelerometric signals adequate to represent the major characteristics of the seismic demand on the analyzed structures. Recorded ground motions covering a broad variety of condition in terms of frequency content, duration and amplitude were appositely selected. In addition, from the recognition of the particular significance of pulse-like time histories in causing large energy and displacement demands to the structures, a considerable number of near-fault signals was included in the data-set of records, taking into account the presence of both forward and backward directivity effects. Thus, a total of 45 records were chosen in order to represent different seismic conditions in terms of magnitude, source-to-site distance, fault mechanism; preliminary analyses were carried out on SDOF systems in order to identify the factors that influence the signal nature greatly. In Table 1 the earthquakes from which the time histories were selected, are listed, while in Figure 2 the distribution of the records according to magnitude, M_w and the closest distance from the surface projection of the fault rupture, D_f, is shown.

Table 1. Earthquakes and strong motions considered.

Earthquake	Year	M_w	Recording Station	*PGA* (cm/s^2)	Earthquake	Year	M_w	Recording Station	*PGA* (cm/s^2)
Imperial Valley	1940	7.0	El Centro Array #9	342	Loma Prieta	1989	6.9	Capitola	463
Tokachi-Oki	1968	7.9	Hachinns	312	Landers	1992	7.3	Lucerne #	713
Tokachi-Oki	1968	7.9	Hachinew	206	Landers	1992	7.3	Joshua Tree #	278
Friuli	1976	6.5	Tolmezzo	348	Erzican	1992	6.7	Erzincan	505
Romania	1977	7.5	Bucharest-BRI	202	Northridge	1994	6.7	Rinaldi Receiving Sta #	822
Tabas, Iran	1978	7.4	Tabas	835	Northridge	1994	6.7	Sylmar - Olive View FF	827
Montenegro	1979	6.9	Bar-Skupstina Opstine	356	Northridge	1994	6.7	Newhall - Fire Sta	579
Montenegro	1979	6.9	Petrovac-Hotel Oliva	446	Northridge	1994	6.7	Santa Monica City Hall	866
Montenegro	1979	6.9	Ulcinj-Hotel Olimpic	236	Kobe	1995	6.9	Kobe University	285
Imperial Valley	1979	6.5	El Centro Array #7	454	Kobe	1995	6.9	KJMA	806
Imperial Valley	1979	6.5	Agrarias	217	Kobe	1995	6.9	Takatori	599
Imperial Valley	1979	6.5	Bonds Corner	760	Kobe	1995	6.9	Port Island (0 m)	309
Imperial Valley	1979	6.5	Calexico Fire Station	270	Dinar	1995	6.4	Dinar	345
Imperial Valley	1979	6.5	EC Meloland Overpass FF	291	Kocaeli	1999	7.4	Sakarya	369
Imperial Valley	1979	6.5	El Centro Array #6	431	Kocaeli	1999	7.4	Yarimca	342
Irpinia	1980	6.8	Calitri	153	Kocaeli	1999	7.4	Duzce-Met.	351
Cile	1985	7.8	Llolleo	698	Duzce	1999	7.1	Duzce-Met.	525
Messico	1985	8.1	Secretaria com. & tran.	168	Duzce	1999	7.1	Bolu	807
Nahanni	1985	6.8	Site 1	1075	ChiChi	1999	7.6	TCU129	991
San Salvador	1986	5.8	Geotech Investig Center	681	ChiChi	1999	7.6	TCU052	341
Superstitn Hills	1987	6.5	Parachute Test site	446	ChiChi	1999	7.6	TCU068	555
Loma Prieta	1989	6.9	Los Gatos Pres. Center	552	ChiChi	1999	7.6	TCU065	799
Loma Prieta	1989	6.9	Corralitos	617					

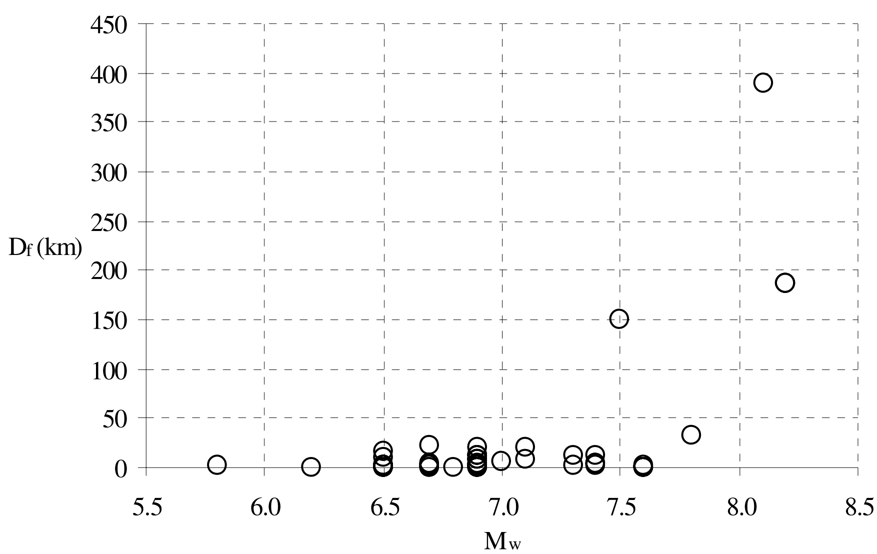


Figure 2. Magnitude versus minimum distance to the causative fault.

RESULTS OF THE ANALYSES

Generally the shapes of the spectra of the inter-story drift index, *IDI*, defined as the inter-story displacement normalized by the story height, are more influenced than the displacement spectra by the energy content of signal. This circumstance emerges from the comparison between energy and drift spectra, which indicate both spectral coincidence of periods where the maximum values are attained and agreement in the general trend. Differently from the case of energy and drift spectra, similar correspondences are not recognizable in the displacement spectral shapes. This should mean that a strong energy demand imposed to a structural systems does not necessarily cause a strong top displacement, while a strong local deformation demand is quite likely to occur.

The trend to assume the same shape of the input energy spectra is confirmed by the frequent coincidence of periods between energy and drift peaks and valleys. In Figure 4 the spectral shapes of the maximum interstory drift, IDI_{max}, estimated in this study, are compared to the spectral shapes, relevant to SDOF systems, of the input energy, E_I and the acceleration, S_a. The spectra were computed for ground motions of very different characteristics. More specifically Erzincan (Figure 3a) represents a typical forward directivity pulse-like time history, while Hachinoe (Figure 3b) stands for a far-field long duration record.

However, the maximum drift is greatly influenced by both the amount of energy input and the way the energy is imparted to the structure. A greater rate of input in the energy demand time history influences strongly the drift demand for pulse-like time histories in comparison with long duration motions, which of course could impart the same amount of energy to the structure, but in a longer time. As a matter of fact, near-fault records could induce in the structure a lower number of cycles than far-field ones, but with a higher energy content. This circumstance can account for a larger concentration of the drift demand.

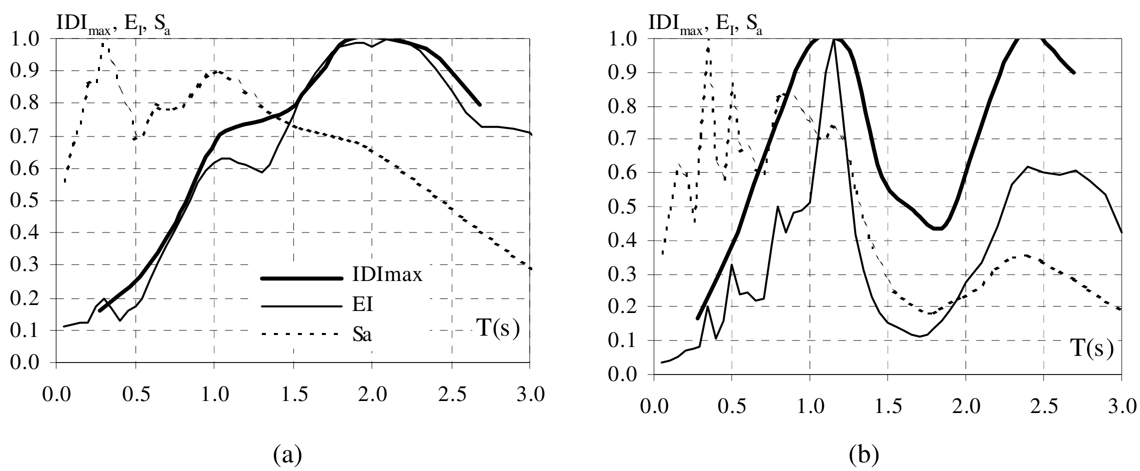


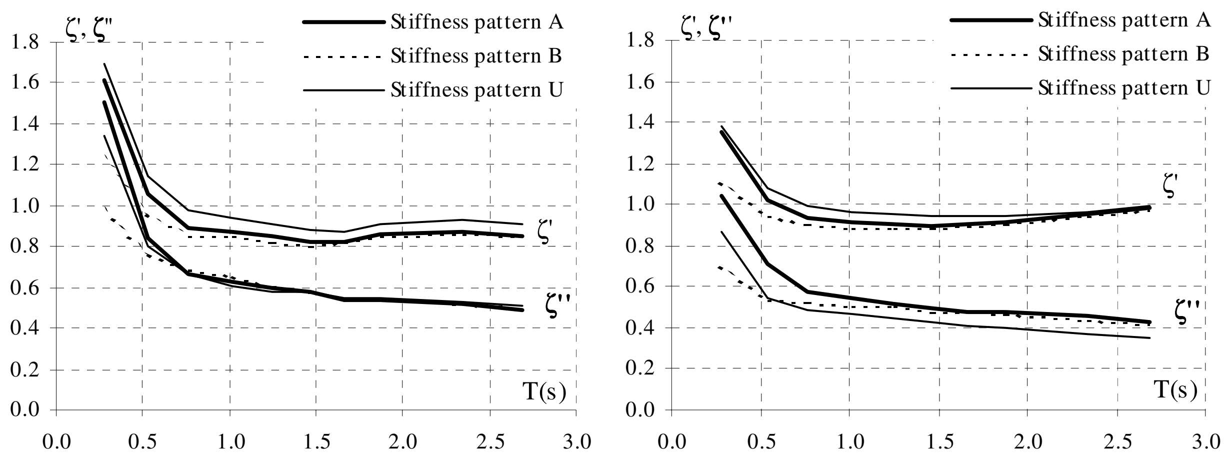
Figure 3. Comparison between normalized elastic spectra of IDI_{max}, E_I and S_a. Erzincan (a), Hachinoe (b).

Influence of the stiffness distribution pattern

One aspect of the dependency of the selected parameters for the quantification of the seismic demands in terms of energy and displacement on structural properties of the considered frames is constituted by the influence of the adopted stiffness distribution patterns through the height of the multi-story frames.

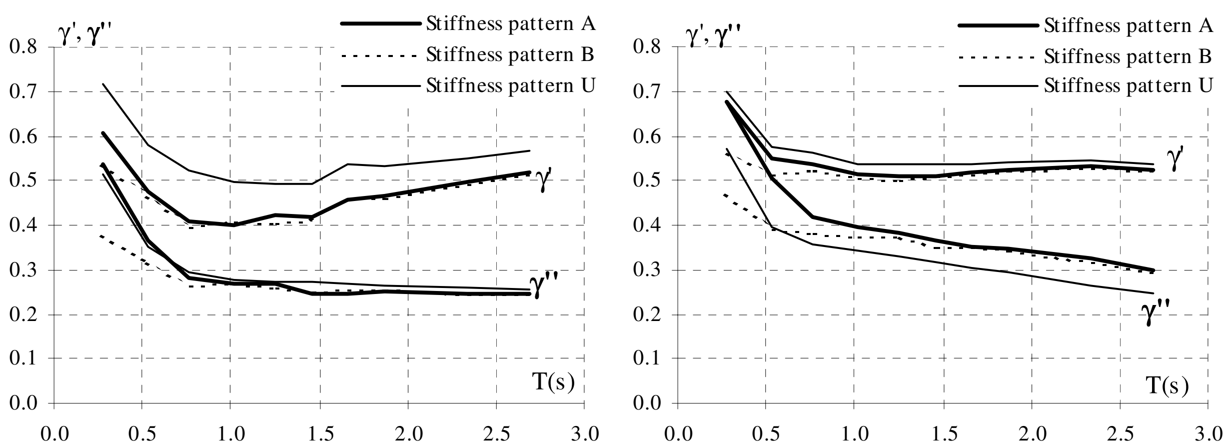
For this reason each selected frame was designed according to three different stiffness pattern, namely (i) a realistic approximately parabolic stiffness distribution with full constraint for the joints at the base of the columns (stiff foundation structures), denoted as *stiffness pattern A*; (ii) the same stiffness distribution as pattern *A* but in presence of a flexible foundation, denoted as *stiffness pattern B*; (iii) a uniform distribution of stiffness along the height, defined by calibrating the stiffness so as to obtain the same

vibration periods as the stiffness distribution *A*, denoted as *stiffness pattern U*.
Generally, the parameters ζ' and ζ'' are not significantly influenced by the stiffness distribution along the height of the frames, either in the elastic and in the inelastic range (Figure 4a and 4b, respectively).
The lowest values of the parameter ζ'' can be easily explained by the fact that it is derived from ζ' by division by the coefficient of distortion *COD*, which is a quantity always greater than unity. The behaviour exhibited by scheme *B* differs from that of scheme *A* only in the low-period range, due to the larger influence of the stiffness reduction at the first story, while assuming the uniform stiffness distribution *U* appear to produce considerably divergences from spectra computed according to the other two patterns. Analogous consideration can be made for the parameters γ' and γ''; however, divergences of spectra relevant to the stiffness distribution pattern *U* from those relevant to *A* and *B* schemes appear more marked than those observed for ζ' and ζ'' (Figure 5a and 5b).



(a) (b)

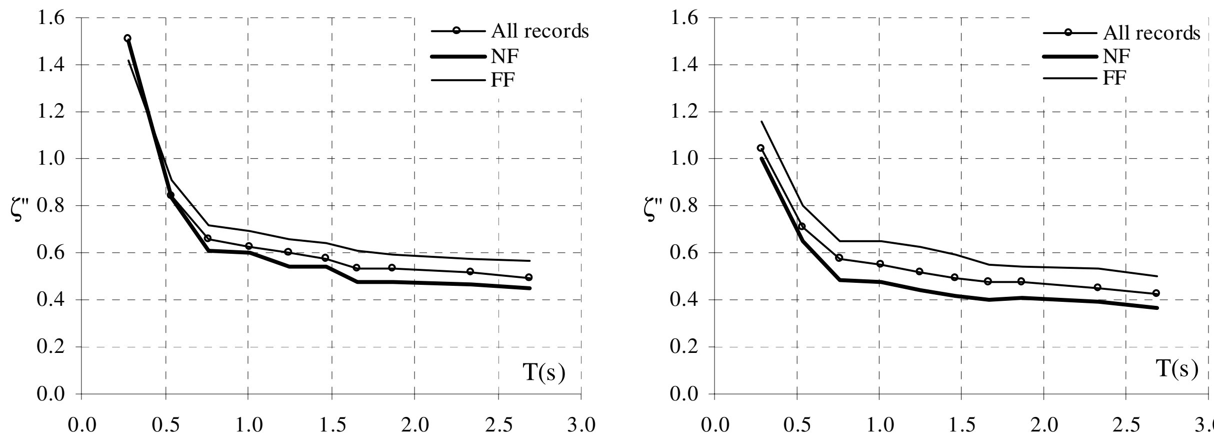
Figure 4. ζ' and ζ'' spectra. Comparison between stiffness distribution patterns. Median all records. (a) Elastic; (b) $\mu = 4$ (hysteretic model DGR3).



(a) (b)

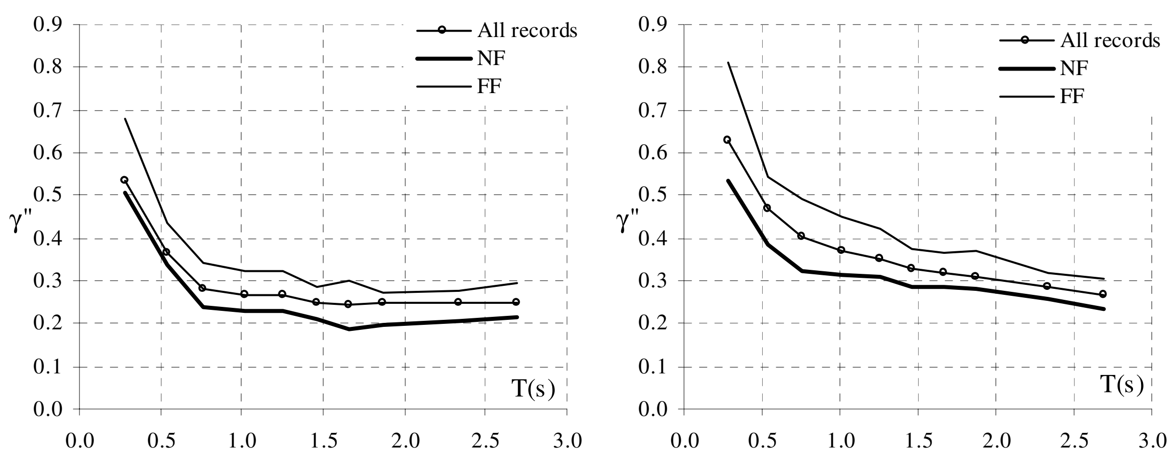
Figure 5. γ' and γ'' spectra. Comparison between stiffness distribution patterns. Median all records. (a) $\mu = 1.5$; (b) $\mu = 4$ (hysteretic model DGR3).

Although the ground motions utilized in this study differ noticeably in terms of frequency content, duration and amplitude, it was possible to make some consideration on statistical grounds. First of all, it was noted that the value of the coefficient of variation, *COV*, ranges between 0.15 and 0.40 for the four parameters ζ', ζ'', γ', γ'' and the whole dataset of record, both in the elastic and inelastic range. It was also observed that ζ'' has lower *COV* values than ζ', particularly, in the medium-long period range, indicating that the energy demand is better correlated to the interstory drift than to the roof displacement demand. A large dispersion was observed in the high frequency region, principally for the two-story frames in the elastic range, consistently with the behaviour already detected for SDOF systems (Decanini [31]. Similar considerations can be made with reference to the inelastic range, with the exception of a significant decrease of the dispersion for the lowest frames.



(a) (b)

Figure 6. ζ'' spectra. Median all, Near-fault (NF), Far field (FF) records. Stiffness distribution patterns A. (a) Elastic; (b) μ = 4 (hysteretic model DGR3).



(a) (b)

Figure 7. γ'' spectra. Median all, Near-fault (NF), Far field (FF) records. Stiffness distribution patterns A. (a) μ = 1.5; (b) μ = 4 (hysteretic model DGR3).

The influence of source-to-site distance, D_f, deserves further consideration. In Figure 6 and 7 the median spectra of the parameters ζ'' and γ'', grouped as near-fault, NF, and far-field, FF, records, together with the median spectra of all records, are shown for the elastic case and ductility ratios μ equal to 1.5 and 4. It is possible to detect that while the spectral shapes are very similar, the NF spectral values are systematically lower than the other ones, indicating a largest deformation demand associated to a very limited number (one or two) loading cycles. This effect is due to the presence of long duration pulses in near-fault time histories causing a sudden energy dissipation in a short time. Displacements of large amplitude takes place consequently, with corresponding relatively lower ratios between the square root of the energy demand and the displacement demand. On the contrary, the energy demand on a structural system subjected to a far-field motion tends to gradually increase during a longest time interval causing an incremental build up of deformations. Similar results also were found for the parameters ζ' and γ'.

Influence of the hysteretic model

A stiffness-degrading hysteretic model was then adopted to simulate the cyclic behaviour of the frames in each story. Many hysteretic models were proposed to predict the non-linear behavior of reinforced concrete structural systems. Such models are typically characterized by control parameters, which govern the shape of the generated loops, that have to be calibrated from observed experimental testing. Moreover, in highly non-linear material like reinforced concrete the system characteristics are continually altered by either degradation of strength and stiffness or apparent pinching of loops resulting from repeated opening and closing of cracks. Consequently, most computational algorithms included in various programs generally utilize simplified piece-wise, linear hysteretic macro-models which relate force and deformation or moment and curvature in the inelastic range. Such macro-models have the advantage of capturing the global behavior in an equivalent sense without resorting to complex finite element discretization.

The force-deformation behavior in concrete structures is influenced by many factors such as the nature of the response and the level of the reinforcement detailing. In such cases, it is necessary to include more than one type of degrading behavior to model the expected response. Two extreme patterns of behavior can be considered: stable flexural response, characteristic of well-detailed, well-confined flexural elements, and severely degraded response, likely to be observed in shear-critical elements such as inadequately reinforced concrete joints and poorly confined short columns or coupling beams.

Thus, on the basis of the aforementioned consideration, six histeretic models were selected, namely the elastic-perfectly plastic model, EPP, introduced as a term of comparison, and five degrading models, DGR1-5 (Table 2).

Table 2. Characteristic of the hysteretic models used in this study.

EPP	
DGR1	Reloading stiffness degradation
DGR2	Reloading stiffness degradation, strain hardening ratio p = 10%
DGR3	Reloading and unloading stiffness degradation, strain hardening ratio p = 10%
DGR4	Reloading and unloading stiffness degradation, pinching effect, strain hardening ratio p = 10%
DGR5	Reloading and unloading stiffness degradation, strength degradation, strain hardening ratio p = 10%

The hysteresis model used in this study, represented in Figure 8, utilizes several control parameters that establish the rules for inelastic loading reversals. Stiffness degradation is modeled as a function of ductility, strength deterioration is modeled as a function of both dissipated energy and ductility and pinching is modeled by two independent parameters to control the degree of pinching.

The constitutive law is controlled by four parameters, namely p, α, β, γ. The parameter p, the strain hardening ratio introduced above, controls the post-yielding stiffness and was set equal to 0.1; α is related to the unloading stiffness; β controls the strength degradation; γ controls the pinching effect due to closing cracks during the reloading phase. If α tends to infinity there is no stiffness degradation during the unloading phase; the value $\alpha = 2$ represents a mean value. For $\beta = 0$ there is no strength degradation due to energy dissipation; the value $\beta = 0.1$ corresponds to a mean value for which this effect is quite reasonable, as for larger values it can lead to unrealistic results or produce numerical instability. For $\gamma = 1$ there is no pinching, while $\gamma = 0$ corresponds to the maximum pinching effect; $\gamma = 0.5$ can be considered a realistic values even though it leads to quite significant effect. It is also possible to note that, unless of secondary effects on more internal cycles, the DGR1 and DGR2 models correspond to the Clough model without and with strain hardening, respectively, while the DGR3 model matches the Takeda model.

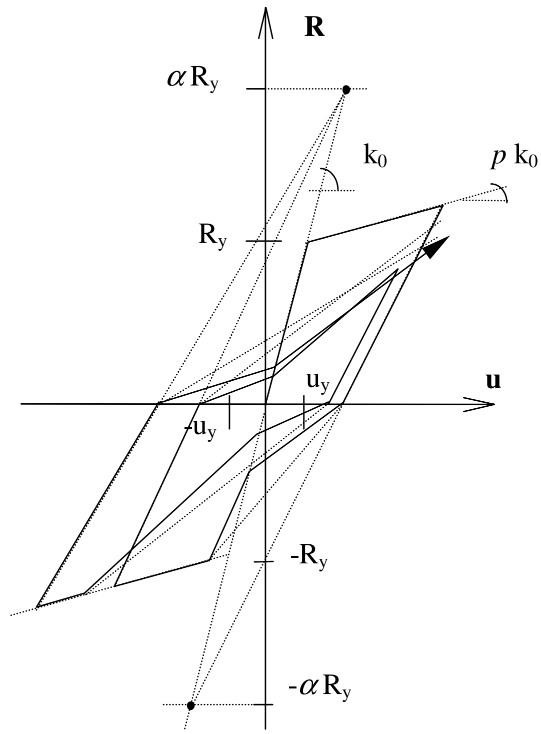
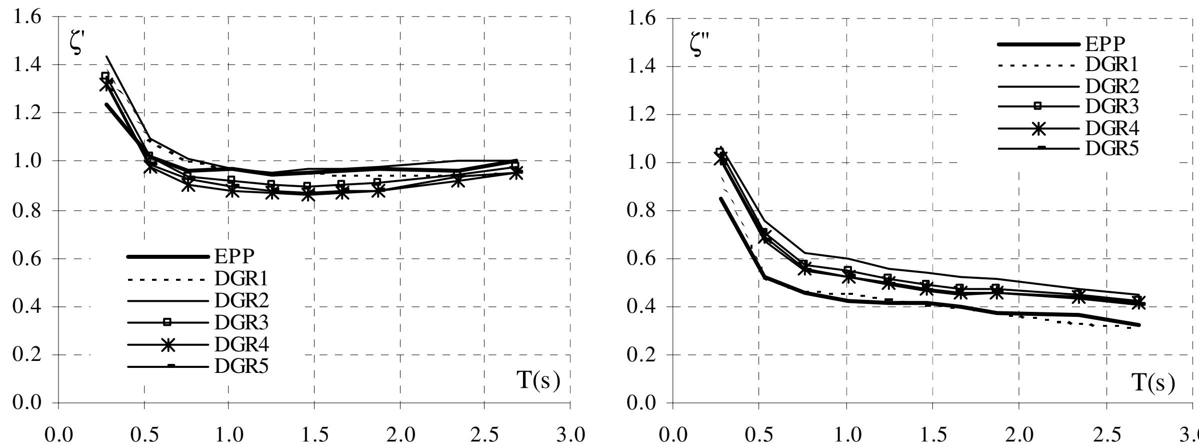


Figure 8. Tipical cyclic behavior of the four parameter hysteretic model.

The influence of the hysteretic behaviour is generally not significant, though with some exceptions. In Figures 9 and 10 the median spectra of the parameters ζ', ζ'' and γ', γ'', respectively, are shown for a ductility ratio $\mu = 4$. The trend of the degrading models is substantially different from that of the EPP model, particularly for the parameters ζ'' and γ''. This can be attributed the fact that in a degrading hysteretic behaviour the maximum displacement is directly related to the amplitude of the instantaneous oscillation rather than to a residual cumulated displacement, as it usually occurs for the EPP model.

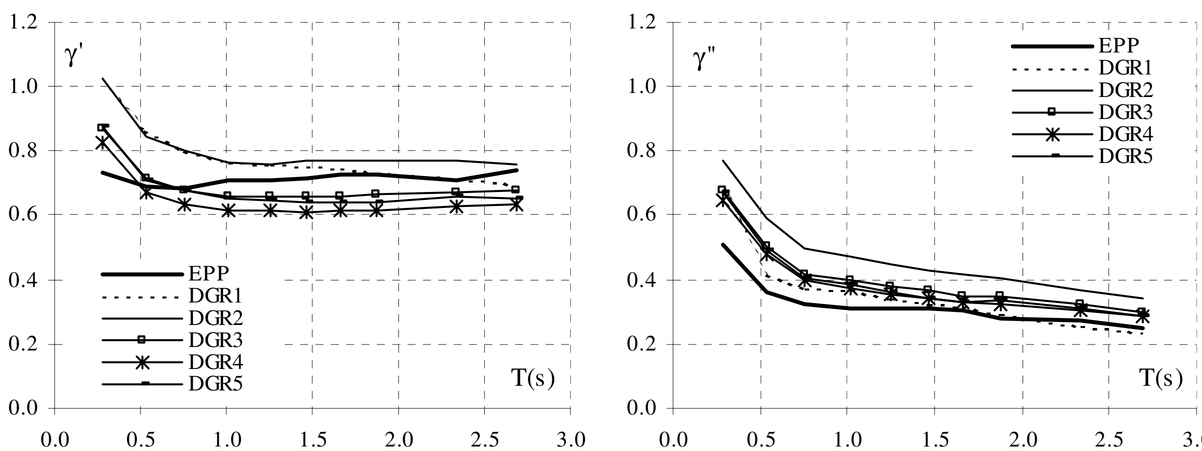
The spectra corresponding to the degrading models DGR3, DGR4 and DGR5 are very close in the whole period range and for the various ductility ratios.

As it was observed for the influence of the stiffness distribution pattern, in the high frequency range the parameters ζ', ζ'' and γ', γ'' exhibit the maximum spectral values, that tend to attenuate as the ductility increases. This effect is prevalent for the parameters ζ' and ζ''. For example, as far as ζ' is concerned, it could be mainly attributable to the way the absolute input energy is defined, and therefore can be explained in the light of behavior of SDOF systems. In fact, for SDOF systems in the elastic case the input energy tends to the value $PGV^2/2$, where PGV is the peak ground velocity, for $T \to 0$. Consequently its square root moves to $PGV/\sqrt{2}$, while the displacement δ tends quickly to 0 so as $\omega\delta = 2\pi\delta/T$ tends to 0. The analogy with the behavior of MDOF systems comes out as soon as one recognizes that the input energy and the displacement δ mentioned above correspond, apart from a participation factor raised to the first and to the second power respectively, to the quantities δ_{roof} and E_I in equation (3). In the inelastic range for the lowest periods there is a slight energy modification while the displacement amplification is significant ($R_\delta \rightarrow \mu$ for $T \rightarrow 0$) and therefore the values of ζ' and ζ'' are lesser.



(a) (b)

Figure 9. ζ' (a) and ζ'' (b) spectra. Comparison between hysteretic models. Median all records. Stiffness distribution pattern A. μ = 4.



(a) (b)

Figure 10. γ' (a) and γ'' (b) spectra. Comparison between hysteretic models. Median all records. Stiffness distribution pattern A. μ = 4.

Finally, it was observed that ζ' and ζ'' spectra are not much influenced by the ductility ratio, while γ' and γ'', related to the dissipated hysteretic energy, are more affected by ductility, especially in the low ductility range.

CONCLUSIONS

In this paper reliable relationships between energy and displacement demands for MDOF systems were analyzed by means of an simplified equivalent shear-type model (ESTM), able to provide a reasonable estimation of the seismic response of MDOF systems at global and local level. To this purpose several parametric analyses were performed on a wide range of frame structures, subjected to recorded ground motions of different characteristics in order to provide a spectral representation of the seismic demands. The extension of the characterization of the relations between energy and displacement demands from SDOF systems to MDOF systems was achieved by introducing two pairs of indices that relate input energy and dissipated hysteretic energy to both roof displacement and inter-story drift. Such expressions could be interpreted as the ratios between equivalent velocities.

On the basis of the above mentioned simplified methodology, it was possible to assess the effects of the stiffness distribution patterns along the height of the structures and the hysteretic models characterizing the cyclic behavior of the simplified MDOF models on the examined parameters. As far as the hysteretic behaviour is concerned, it was found that its influence is generally not important for the degrading models, in the whole period range and for various ductility ratios; on the contrary, the EPP model exhibits a trend significantly divergent from the former ones. The influence of the stiffness distributions through the height of the multi-story frames is not particularly significant. However, it was possible to detect a certain deviation of the uniform stiffness pattern in comparison with to the respect of parabolic stiffness distribution schemes.

However, the fact that the results obtained do not appreciably depend either on the hysteretic model for degrading systems, or on the usually employed stiffness distribution schemes, indicates the possibility to reduce the complexity of the problem when extending the methodology to a broader set of structural systems and strong motions records.

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