ENERGY AND DISPLACEMENT DEMANDS IMPOSED BY NEAR-SOURCE GROUND MOTIONS

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SUMMARY

This paper examines the effects of near-fault ground motions on the structural behavior by means of energy and displacement parameters. In the present research the effect of long period pulses, present in the near-fault records, which may cause severe damage, has been analysed by means of the elastic and inelastic Seismic Input Energy Spectra, Hysteresis Energy Spectra, Hysteretic to Input Energy Ratio Spectra, Displacement Response Spectra. Two hysteretic models, namely elastic-perfectly plastic and degrading pinching model, have been utilized to describe the nonlinear force/deformation behavior of the examined SDOF systems. Moreover, the response of some RC frame systems when subjected to near-fault strong ground motion has been investigated by means of simplified analysis methodologies.

INTRODUCTION

The present research is intended as a first step in the investigation of the effects of the presence of long duration accelerometric pulses in near-fault ground motion on the performance demand for both energy and displacement aspect of the structural response. This objective has directed the study to the identification of some response parameters as the operative means for a complete characterization of seismic demand for a structure subjected to near-fault accelerometric time histories. The presence of long duration accelerometric pulses in the ground motion constitutes an important factor in causing damage, as it involves the transmission of large energy amounts to the structures in a very short time, with high energy dissipation and displacement demands. This twofold aspect can be investigated by searching for the existence of a. Since both phenomena influence the damage that a structure can suffer during a strong ground motion, a relationship between energy and displacement demand has been searched for, which could allow the improvement of design methodologies for the near-fault case. In the present research this investigation has been limited to multistory frame structures, with or without degrading effect, by means of different simplified analysis procedure.

APPROXIMATED METHODS ADOPTED FOR PREDICTION OF MDOF RESPONSE

Equivalent SDOF system

Two different approaches have been used in this study in order to predict the response characteristics of MDOF systems subjected to near-fault ground motions. The first type of approach [Rodriguez, 1994; Fajfar and

Gaspersic, 1996] is based on the assumption of an assigned time-independent global deflection shape of the structure, involving the estimation of the values of story displacements normalized by top displacement, included in a shape vector $\{\Phi\}$. In this way, the lateral displacements vector at a generic time can be expressed as

$$\{u(t)\} = \{\Phi\} x(t) \tag{1}$$

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This assumption corresponds to consider only the first mode of vibration both in elastic and in inelastic range of deflection. This fact implies, for each target ductility level of response to be investigated, the choice of a correct type of distribution of plastic behavior on the height of the structure. Based on this approach, the response of the structure can be conceptually reduced to the response of an equivalent SDOF (ESDOF) system, characterized by a period of vibration equal to the fundamental period of the structure. If the equations of motion of the MDOF system subjected to the ground motion $u_g(t)$ are in the form

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+\{R(u(t))\}=-[M]\{1\}\ddot{u}_g(t) \tag{2}$$

were $R(\cdot)$ is the elasto-plastic restoring force, the equation of motion of the ESDOF system can be written as

$$M_{eq}\ddot{x}(t)+C_{eq}\dot{x}(t)+R_{eq}(x(t))=-L_{eq}\ddot{u}_g(t) \tag{3}$$

where $M_{eq}=\{\Phi\}^{\mathrm{T}}[M]\{\Phi\}$; $C_{eq}=\{\Phi\}^{\mathrm{T}}[C]\{\Phi\}$; $R_{eq}(t)=\{\Phi\}^{\mathrm{T}}\{R(t)\}$; $L_{eq}=\{\Phi\}^{\mathrm{T}}[M]\{1\}$. Denoting the quantity $PF=L_{eq}/M_{eq}$ as the participation factor of the mode shape $\{\Phi\}$, the solution $x(t)$ of equation (3) can be derived from the solution $x_S(t)$ obtained for a SDOF system subjected to a base acceleration $\ddot{u}_g(t)$ and characterized by the same period of vibration, mass $m=M_{eq}$, damping coefficient $c=C_{eq}$, restoring force $r(t)=R_{eq}(t)/PF$, by means of the relationship

$$x(t)=PF\cdot x_S(t)\,. \tag{4}$$

Once found the solution $x(t)$ for the ESDOF system, the MDOF displacements are given by the expression (1). This procedure is also useful to determine a constant ductility response, when the global displacement ductility value μ is assigned. The maximum base shear is calculated as

$$V_{\max}=\frac{L_{eq}^{\;2}}{M_{eq}}C_y g=M_{eff}C_y g \tag{5}$$

where M_{eff} is the effective mass associated to the assigned modal shape, and the product $C_y g$ represents the yield resistance for unit mass of the associated SDOF system, i.e. the spectral pseudo-acceleration for elastic response or the same quantity divided by the reduction ductility factor for inelastic response. The energy balance equation for the MDOF system can be written in the usual form

$$E_I(t)=E_k(t)+E_s(t)+E_H(t)+E_D(t) \tag{6}$$

where the energy quantities are respectively absolute input energy, absolute kinetic energy, elastic strain energy, hysteretic energy and damping energy. The absolute input energy for a MDOF system can be written as:

$$E_I(t)=\int\sum_{i=1}^{N}m_i\ddot{u}_{ti}(t)du_g \tag{7}$$

where $\ddot{u}_{ti}(t)$ is the total (absolute) acceleration of the mass m_i. The integration is extended to the total duration of the ground motion. All energy terms in equation (6) can be easily calculated by means of the above described methodology. It can be shown that the energy amounts are numerically very near to the corresponding quantities calculated for the SDOF system and multiplied by the factor $(PF)^2$. In this research two different hysteretic models have been used for inelastic response of the ESDOF system, namely the elastic-perfectly plastic (EPP) model, representing frame structures characterized by non-degrading behavior, and a model characterized by hardening ratio equal to 0.10, by degrading effects in stiffness and strength and by pinching effect; this latter model will be indicated as DGR. Several critical observations can be made to the ESDOF method for estimating MDOF response; the most important ones can be summarized as follows:

- Assuming a constant shape of vibration corresponds to the hypothesis that the displacement distribution of the structural response can be described by means of an effective mode shape of the structure.
- The estimation of global resistance demand for any target ductility level by means of an ESDOF system necessarily leads to a demand value that is smaller than the corresponding elastic one; in this way every local effect of amplification in interstory drift demand due to inelastic behavior is neglected.
- In terms of energy dissipation demand, the assumption of the plastic mechanism corresponding to the assigned global deflection shape leads usually to consider a priori a very good inelastic behavior, with an approximately uniform distribution of plastic deformations along the height of the structure. This can be in contrast with local high dissipation demand due to concentration of ductility response in one story or in a limited number of stories of the building.

The previous observations tend to put a stress on the risk of underestimating some aspects of structural response, especially in the event of a structure subjected to a near-fault ground motion. In general, the seismic behavior of a structure in the far-field can be reasonably described by a selective resonance amplification of the frequency content of the ground motion, that is consistent with modeling the response characteristics of the structure as an ESDOF model. On the other hand, a structure placed in the near-field can be subjected to ground motion characterized by long duration acceleration pulses, fact that makes the structural behavior more similar to a wave propagation in an elastic-plastic continuous medium. In fact, the pulse-like character of the ground motion can cause a response peak in the structure before the development of a resonant behavior is possible.

Equivalent Shear Beam

An alternative simplified method of analysis for the estimation of the seismic response of MDOF systems is represented by the study of wave propagation in a continuous system such as a shear beam, whose stiffness and inertial characteristics approximate those of the MDOF system. As it is well known, the equation governing the shear wave propagation due to base motion in an elastic undamped beam is

$$-k_s \frac{\partial^2 u}{\partial y^2} + m \frac{\partial^2 u}{\partial t^2} = -m\ddot{u}_g(t) \qquad (8)$$

where k_s is the shear stiffness and m is the distributed mass for unit length. The wave propagation velocity is $c_w=\sqrt{(k_s/m)}$; it can vary along the beam length if stiffness and mass properties are not constant along the structure height. Since the global shear force acting on a beam section can be written as

$$V(y,T) = k_s \frac{\partial u}{\partial y} \qquad (9)$$

The first term in (8) represents the elastic internal restoring action on the element of mass. If a proportional viscous internal damping associated to shear strain rate is considered, the equation of dynamic equilibrium becomes

$$-k_s \frac{\partial^2 u}{\partial y^2} - c_s \frac{\partial^3 u}{\partial t \partial y^2} + m \frac{\partial^2 u}{\partial t^2} = -m\ddot{u}_g(t) \qquad (10)$$

where $c_s = 2\xi k_s/\omega$ is the damping coefficient. Rigorously speaking, the approximation of a frame structure to a shear beam model would require the structure to be a shear type frame, with infinitely stiff transverses. However, this kind of analysis can be easily extended to a generic frame if the stiffness k_s adequately takes into account the effects of joint rotations [Bertero and Bertero, 1992]. This can be obtained by means of a previous static condensation of the stiffness matrix of MDOF system; the equivalent shear stiffness can be calculated on the basis of the story displacements caused by lateral static forces. The analysis can also be extended to inelastic behavior by means of numerical solution algorithms. High inelastic local deformations in a transversal section of shear beam, corresponding to a single story level of the building, are the effects of the reduction in wave propagation velocity in regions subjected to high ductility demand. These local effects, that cannot be analyzed by means of ESDOF method, can be highlighted if an equivalent shear beam is chosen to simulate the MDOF system response. In these research the EPP hysteretic model has been used for inelastic behavior of the shear beam. In the energy balance formulation, expressed by means of the same equation (6), the absolute input energy for a continuous system of total height H will be modified as follows:

$$E_I(t) = \int \int_H m\ddot{u}_t(t)\,dy\,du_g \,. \qquad (11)$$

SELECTION OF THE ACCELEROMETRIC RECORDS

The quite large number of near-fault records from recent earthquakes indicate that, for a given soil condition, the characteristics of strong ground motion and consequently of the damage potential can vary significantly as a function of the location of the site with respect to the propagation of the rupture. This is due to the rupture directivity effect, i.e. a special effect occurring close to the source, that causes most of the energy to arrive in a single large pulse of motion. This fact may give rise to an amplification of the ground motion at sites toward which fracture propagation progresses, or produce long duration motions having low amplitudes at long periods as the rupture propagates away from the site. The former effect is known as *forward rupture directivity*, while the latter as *backward rupture directivity*. The long-period parts of the signals in forward directivity locations are energetic due to the development of a single, unidirectional, long-period pulse. Energy-based parameters constitute an adequate approach to highlight the damage potential of these kind of signals [Decanini and Mollaioli, 1998], as the transmitted energy depends upon the duration of the acceleration pulse. In this research 44 accelerometric records have been considered (Table 1), obtained during the earthquakes of Imperial Valley

(1979), Landers (1992), Northridge (1994) and Kobe (1995). All of them are near-fault signals, distinguished according to soil type (at the present stage of the research, a distinction has been made only between soil and rock), position with respect to the rupture propagation, backward (B), forward (F), and neutral (N) directivity [Somerville, 1997].

Table 1: Near-fault strong motion records .

Imperial Valley 1979	**Soil Type**	**Directivity**	**Northridge 1994**	**Soil Type**	**Directivity**
Aeropuerto Mexicali	soil	B	Jensen Filter Plant	soil	F
Agrarias	soil	B	Sepulveda VA	soil	F
Bonds Corner	soil	B	Rinaldi Station	soil	F
El Centro, #7 Imp. Val. Co.	soil	F	SCS Station	soil	F
El Centro, #8 Cruick. Rd.	soil	F	SCSE Station	soil	F
El Centro, #5 James Rd.	soil	F	Arleta Fire Station	soil	N
El Centro, #4 Anderson Rd.	soil	F	Newhall -Fire Station	soil	F
El Centro, #6 Houston Rd.	soil	F	Sylmar Park. Lot	soil	F
Landers 1992	**Soil Type**	**Directivity**	**Kobe 1995**	**Soil Type**	**Directivity**
Lucerne Valley N80W	rock	F	Kobe JMA	soil	F
Joshua Tree 0	soil	B	Kobe University	rock	F
			Kobe Port Island	soil	F
			Takatori	soil	F

OBJECTIVES OF THE ANALYSES AND DESCRIPTION OF THE RESULTS

Analysis criteria

Three different R/C plane frame structures have been analyzed, respectively belonging to 4-story, 8-story and 12-story buildings. The schemes of the structures with the fundamental vibration periods are illustrated in Figure 2; the cross-sections data are in centimeters near beams and columns (the first number indicates the out-of-plane member width), while the inter-story height and the beams span are respectively equal to 3.30 m and 5 m for all of the three frames. The vertical load for unit length of beams is equal to 35 kN/m for every story of the frames.

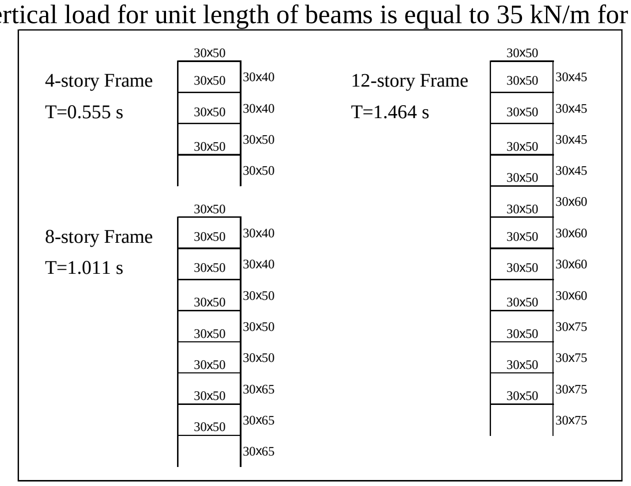

Figure 1: Schemes of the frame structures.

The analysis procedure has been constructed according to the following criterion. Constant target ductility analyses have been performed by means of the ESDOF method; the global ductility levels that have been investigated are: μ=1 (elastic), μ=2, μ=4. As far as lateral displacements are considered, the first mode shape has been considered for the elastic deformation, while a linear distribution has been assumed for the inelastic deformation. In this way the input energy imparted to the structures, the energy dissipation demand, the maximum top displacements and the strength demand corresponding to the assigned ductility values have been evaluated. The yield story strengths required by triangular force pattern have been obtained from the base shear resulting from this first step; the same force distribution has been used in order to evaluate the elastic shear story stiffness values. The inelastic response histories of the equivalent shear beam have been performed neglecting brittle collapse and assuming a unlimited ductility capacity for every story. Consequently, in some cases very high story ductility demand and strong energy dissipation have been found, especially at the first story level.

Response parameters for energy and displacement demand

According to experience, structural damage depends on both maximum deformation and energy dissipation. Since near-fault ground motions can generate very large deformation demand, together with high energy input, it seems to be very interesting to investigate the correlation between displacement and energy amounts in order to include opportunely displacement parameters in design procedures based on energy concepts. Such a parameter can be represented by the ratio [Fajfar and Gaspersic, 1996]

$$\gamma = \frac{\sqrt{E_H / m}}{\omega\delta} \tag{12}$$

were ω is the natural circular frequency and δ is the maximum displacement. This expression can be read as the ratio between two equivalent velocity amounts. In the original formulation it is written for SDOF systems; however, considering the relationship between the ESDOF energy and displacement parameters and the corresponding SDOF ones, it is possible to conclude that the same value of γ characterizes, within the limits of the ESDOF method validity, both the response to a given ground motion of a MDOF system and of the SDOF system having the same period of vibration. The γ parameter is usually very stable in the near-fault; its stability decreases when distance from the fault increases, with a trend that depends on the soil nature: more dispersion is obtained for soft soil. The good stability of γ parameter for the records analyzed in this paper (coefficient of variation smaller than 0.3 in the periods greater than 0.5 s) is confirmed by the approximately parabolic relationship between top displacement (δ_{top}) and hysteretic energy (E_H), as illustrated in Figure 2 for ductility 2 and 4 and for the 12-story frame. In general, in the case of near-fault ground motions it is reasonable to expect lower values for γ parameter than in the case of large distance from the seismic source; in fact a violent acceleration pulse can cause a strong displacement demand with only one large plastic excursion. However, this trend appears significantly influenced by other factors, as soil stiffness, and it would require wide investigations.
An alternative approach can be based on the correlation between maximum displacement and input energy. As suggested by Teran-Gilmore (1996), to establish a relationship between the square root of the input energy and the displacement leads to stable quantities. This choice can be convenient because some design procedures based on energy concepts have been developed with the use of input energy [Decanini and Mollaioli, 1998]. This leads to the definition of the parameter

$$\zeta = \frac{\sqrt{E_I / m}}{\omega\delta} \tag{13}$$

In particular, it was found by the authors of the present paper that the above quantity is more stable than the parameter γ.The observations on the substantial coincidence of MDOF and SDOF values of γ parameter can be extended to ζ. The stability of ζ is yet greater then the one of γ. As a consequence, also the relationship E_I-δ_{top} results in an approximately parabolic trend, as Figure 3 shows for μ=2 and μ=4, 12-story frame.
The displacement demand in MDOF systems must be defined by a formulation that takes into account local concentrations of inelastic deformation. This fact is particularly important for near-fault signals, that can cause strong ductility demand in limited regions on the height of a structure. The parameter usually adopted to describe the maximum deformation demand for a multi-story building is the interstory drift index, $IDI_{\max}$, defined as the maximum interstory drift normalized by story height,

$$IDI_{max} = \frac{\Delta_{max}}{h} \tag{14}$$

If the maximum top displacement is given, the mean interstory drift index can be calculated as:

$$IDI_{mean} = \frac{\delta_{top}}{H} \tag{15}$$

where H is the total height of the structure. The concentration of drift demand on some parts of the structure height can be expressed synthetically by means of the coefficient of distortion *COD*, defined as [Teran-Gilmore, 1998]

$$COD = \frac{IDI_{\max}}{IDI_{mean}} \tag{16}$$

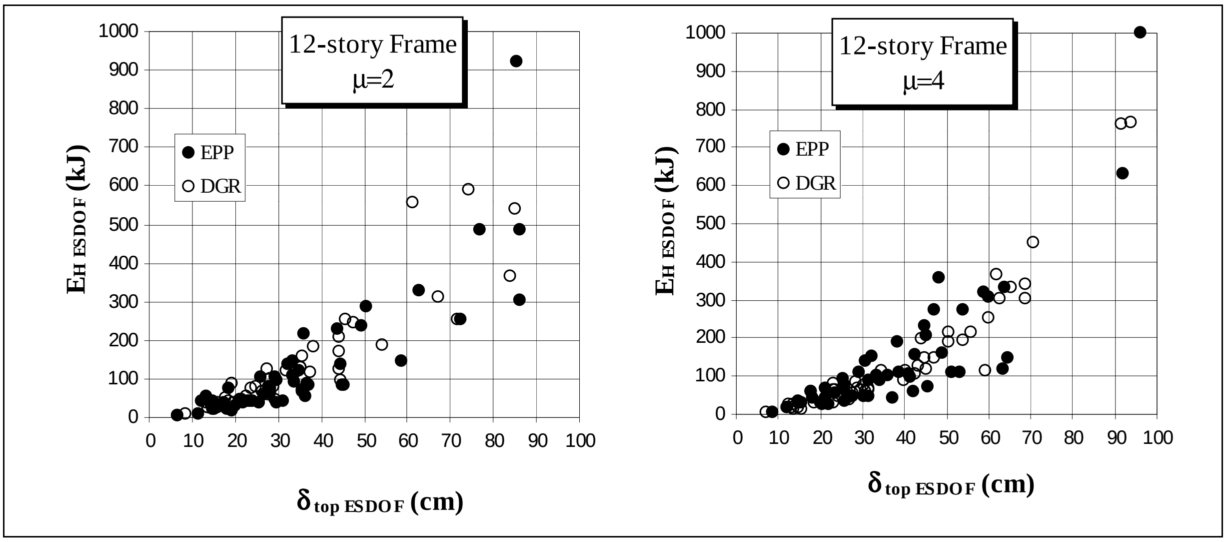

Figure 2: Correlation between hysteretic energy and top displacement. ESDOF method

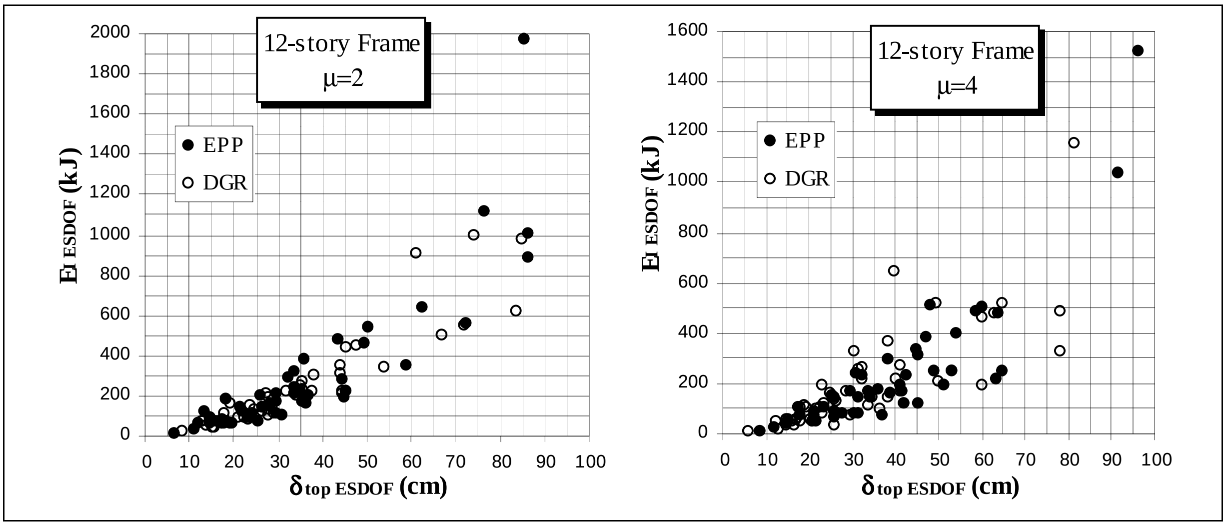

Figure 3: Correlation between input energy and top displacement. ESDOF method

As a general rule, *COD* tends to increase as the inelastic behavior increases. An analysis carried out by means of an ESDOF method, in which the structural response is defined in a synthetic way, and deformation shape is a work hypothesis formulated to obtain global response results, cannot provide any information on the real distribution of drift demand, especially if strong local demand is expected. For this reason, in the present research this aspect of seismic demand has been investigated by means of the continuous approximate shear beam model. A good coincidence of results has been found between the two methods, that have been linked as described in paragraph 4.1, both for global displacements and energy demand. In particular, for top displacement the best coincidence has been obtained in elastic range, while the scatter increases when the ductility increases; for energy, instead, the differences seem to decrease when the ductility increases. An interesting observation can be made if the correlation between top displacements and maximum drift demands is considered: for the elastic case an exactly linear relationship is found, fact that demonstrates the low difference among the signal considered in the way they excitate different modes of vibration. However, in inelastic range and with an increasing trend when ductility increases, strong variations are observed in the drift demand from the values estimated on the basis of the maximum top displacement. Figure 4 shows this trend for the 12-story frame. This means that local and global displacement demand do not vary in the same way in inelastic range; on the contrary, the comparison between elastic and inelastic displacement responses shows that for some signals top displacement can decrease when local drift increases. This fact can be explained with a reduction in energy transmission towards highest stories when a strong energy input finds the low levels of the structure in a plastic phase of cyclic response. However, a particular investigation would be made on each signal in order to obtain some general rules of behavior.

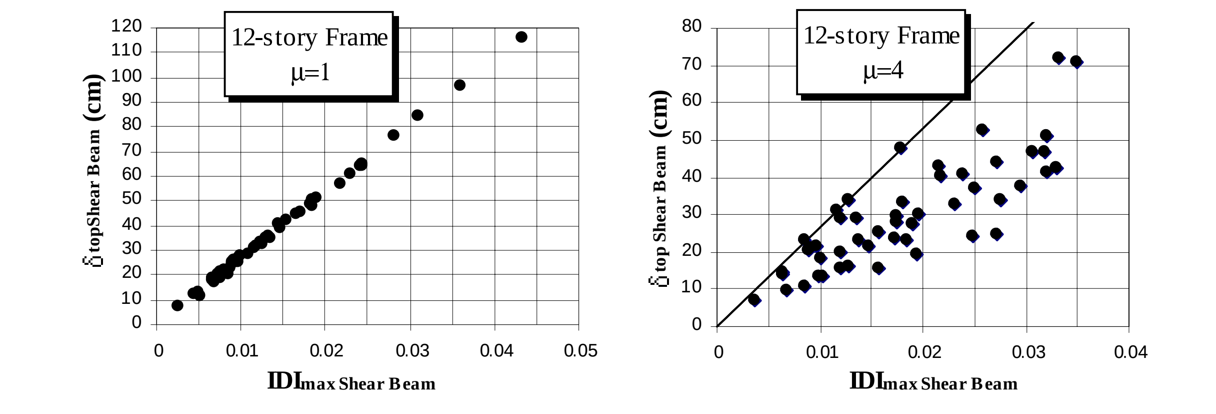

Figure 4: Correlation between top displacement and maximum interstory drift index. Shear Beam model.

In Table 2 some notable results for IDI_{max} are reported. In general, the inelastic amplification in drift demand is significant. It can be noted that for some records the drift demand seems to decrease in the passage from elastic response to inelastic response at ductility level μ=2.

Table 2: Maximum interstory drift ratio for different signals.

Imperial Valley	4-story Frame			8-story Frame			12-story Frame		
Record	μ=1	μ=2	μ=4	μ=1	μ=2	μ=4	μ=1	μ=2	μ=4
El Centro #6 - 230	0.0060	0.0061	0.0085	0.0079	0.0136	0.0203	0.0090	0.0173	0.0296
El Centro #7 - 230	0.0085	0.0092	0.0152	0.0160	0.0139	0.0226	0.0123	0.0114	0.0272
El Centro #5 - 230	0.0090	0.0076	0.0126	0.0114	0.0155	0.0220	0.0075	0.0140	0.0276
Landers	4-story Frame			8-story Frame			12-story Frame		
Record	μ=1	μ=2	μ=4	μ=1	μ=2	μ=4	μ=1	μ=2	μ=4
Lucerne Valley - N80W	0.0058	0.0151	0.0195	0.0067	0.0080	0.0160	0.0131	0.0199	0.0320
Joshua Tree - 0	0.0062	0.0070	0.0057	0.0107	0.0083	0.0088	0.0075	0.0096	0.0121
Northridge	4-story Frame			8-story Frame			12-story Frame		
Record	μ=1	μ=2	μ=4	μ=1	μ=2	μ=4	μ=1	μ=2	μ=4
Jensen F.P. N292	0.0119	0.0160	0.0195	0.0298	0.0277	0.0313	0.0244	0.0264	0.0318
SCS - S38E	0.0087	0.0075	0.0163	0.0254	0.0285	0.0308	0.0311	0.0249	0.0217
SCS - N52E	0.0083	0.0083	0.0140	0.0261	0.0313	0.0307	0.0184	0.0261	0.0331
SCSE - N18E	0.0095	0.0099	0.0166	0.0155	0.0223	0.0313	0.0126	0.0164	0.0307
Rinaldi - S48W	0.0143	0.0215	0.0361	0.0338	0.0317	0.0371	0.0282	0.0314	0.0320
Newhall - 360	0.0125	0.0126	0.0253	0.0188	0.0180	0.0259	0.0229	0.0145	0.0239
Sylmar Park.Lot - 360	0.0180	0.0224	0.0299	0.0150	0.0173	0.0250	0.0219	0.0281	0.0251
Kobe	4-story Frame			8-story Frame			12-story Frame		
Record	μ=1	μ=2	μ=4	μ=1	μ=2	μ=4	μ=1	μ=2	μ=4
Takatori - 000	0.0120	0.0127	0.0134	0.0194	0.0187	0.0432	0.0433	0.0275	0.0332
Kobe JMA - NS	0.0191	0.0428	0.0559	0.0302	0.0230	0.0133	0.0244	0.0224	0.0172
Kobe University - NS	0.0037	0.0060	0.0110	0.0116	0.0088	0.0184	0.0190	0.0112	0.0175
Port Island – NS – 0m	0.0043	0.0055	0.0184	0.0145	0.0167	0.0283	0.0242	0.0190	0.0259

It is useful to advert that this apparent anomaly is due in some cases to the fact that in elastic range the equivalent shear stiffness at the first story is greater than those of higher stories because of rigid foundations effects; for this reason a lower drift demand is associated to the first story, and the maximum drift observed is localized at an higher story. When the structure yields, instead, a very high ductility demand occurs at the first story, and maximum drift demand moves toward the base level; the yielding of the first story can concentrate at this level the energy dissipation and avoid or limit the yielding of the higher stories. These circumstances can result in a higher drift peak in elastic than in inelastic range of behavior. However, a general trend must be searched taking into account several other factors characterizing every single signal. Some particular behavior of the different records can be noted. For example, Kobe JMA (NS) record shows very high level of drift demand for the 4-story frame; for the higher frames there is a clear tendency to reduce maximum drift in inelastic range. For Rinaldi station record the drift amounts for the three frames are comparable. Some of these behaviors can be explained by considering energy spectral distribution. A correlation similar to those observed between energy and global displacements is detected between energy and drift demand, but with a greater dispersion in results, that demonstrates the complex nature of relationship between global parameters, like input energy is, and concentration of ductility demand.

CONCLUSIONS

The combined procedures used in this research, although limited by the approximations implicitly present in their formulation, have allowed a partial investigation on the response behavior of a multistory frame structure subjected to near-fault ground motion, in terms of correlation between energy and displacement demand. The results seem to indicate the possibility of individuating general criteria, based on the use of global response parameters, that could usefully be included in design procedures for structures built near a seismic source. Based on the results of this research, the construction of a reliable relationship between energy dissipation demand and global displacement seems to be possible. This can be made through the evaluation of the response parameter γ, for a direct correlation between maximum displacement and hysteretic energy, or by means of the response parameter ζ, for a procedure that uses the available design spectra of input energy and hysteretic to input energy ratio. The other fundamental aspect of the problem, the local drift demand, that can be quantified by means of the coefficient of distortion *COD* together with the global displacement demand, shows a less stable correlation with the energy parameters, perhaps due to the reduced number of near fault signals which have not permitted to perform more detailed analyses on the influence of the soil and the rupture mechanism effect.

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