



# Equivalent SDOF systems for the estimation of seismic response of multistory frame structures

L. Decanini, F. Mollaioli, A. Mura  
*University of Rome "La Sapienza", Italy*

## Abstract

In this research an approximate investigation has been carried out on the seismic response of multistory frame structures. The simplifying hypothesis on which the adopted methodology is based is the assumption of an assigned time-independent global deflection shape for the lateral displacements of the frame. This hypothesis corresponds to consider the dynamic response of the frame limited to the first vibration mode only, both in elastic and in inelastic behavior. The above mentioned simplification firstly allows the reduction of the response of MDOF systems to the response of an equivalent simple system (ESDOF), defined by means of appropriate values for mass, stiffness and viscous damping; on the other hand, it allows an approximate extension of the calculation of parameters characterizing the seismic response, easily obtainable for SDOF systems, to multistory frame systems. The analyses have been concerned different aspects of seismic response: strength, displacement, input energy and dissipated energy demands have been evaluated. The study has been extended to some damage indexes, although these parameters still do not have an exact and complete definition. The simplifying choice of using an assigned modal shape also for the inelastic response, although affected by the approximations implicitly present in this formulation, offers the possibility to investigate the influence of the adopted global deflection shape on response parameters; the importance of this aspect is in the fact that the shapes can correspond to different stiffness and strength distribution along the height of the building.

## 1 Introduction

The purpose of the present research is to test the suitability of a simplified nonlinear method for the evaluation of seismic response of multistory frame structures for strength and displacement demand, and for energy dissipation demand. The method is based on the definition of an equivalent single-degree-of-freedom system (ESDOF), characterized by appropriate values for mass, stiffness, viscous damping and yielding strength. The response parameters of the

seismic response of the multistory frame structure are in this way related to the elastic or inelastic response spectra calculated for SDOF systems.

The theoretical starting point for this procedure is very similar to the modal analysis of frame structures. In fact a time-independent global deflection shape is assumed for the lateral displacements of the building stories. In this way, the displacement vector of the frame at a generic time is expressed as

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

where  $\{\Phi\}$  is the vector that defines the deflection shape and  $x(t)$  expresses the time-dependent amplitude of motion. This assumption allows to reduce the MDOF equations of motion

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

to the ESDOF equation

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

where

$$M_{eq} = \{\Phi\}^T [M] \{\Phi\}; C_{eq} = \{\Phi\}^T [C] \{\Phi\}; R_{eq} = \{\Phi\}^T \{R(t)\}; L_{eq} = \{\Phi\}^T [M] \{1\}. \quad (4)$$

The quantity

$$\Gamma = L_{eq} / M_{eq} \quad (5)$$

can be interpreted as a modal participation factor, if the assumed displacement shape  $\{\Phi\}$  is seen as a modal shape. The solution  $x(t)$  of equation (3) can be derived from the solution  $x_S(t)$  obtained for a SDOF system subjected to the same base acceleration history and characterized by the same period of vibration, mass  $m = M_{eq}$ , damping coefficient  $c = C_{eq}$ , restoring force  $r(t) = R_{eq}(t)/\Gamma$ , by means of the relationship

$$x(t) = \Gamma \cdot x_S(t) \quad (6)$$

The evaluation of the MDOF displacements is then given by the expression (1). This procedure is also useful to determine a target ductility response, when the global displacement ductility value  $\mu$  is assigned. Once the value of the seismic strength coefficient  $C_y$  for the SDOF system, defined as the strength demand normalized by the system weight, is found, the yielding base shear for the frame structure is determined by means of the expression

$$V_{by} = \frac{L_{eq}^2}{M_{eq}} C_y g = M_{eff} C_y g \quad (7)$$

where  $M_{eff}$  is the effective mass associated with the assigned modal shape.

The energy balance equation for the MDOF system can be written in the usual form

$$E_I(t) = E_k(t) + E_s(t) + E_H(t) + E_D(t) \quad (8)$$

where the energy quantities are respectively absolute input energy, absolute kinetic energy, elastic strain energy, hysteretic energy and damping energy. By means of the ESDOF procedure, the energy quantities for the MDOF systems can be evaluated multiplying the corresponding SDOF quantities by a factor equal to  $\Gamma^2$ , as can be easily shown introducing the relations (1) and (6) into the MDOF energy expressions, e.g. for the input energy, hysteretic plus elastic strain energy and damping energy:

$$E_I(t) = \sum_{i=1}^N m_i \ddot{u}_i(t) du_g ; E_H(t) + E_s(t) = \int \{R(t)\}^T \{du\} ; E_D(t) = \int \{\dot{u}\}^T [C] \{du\} \quad (9)$$

where  $\ddot{u}_i(t)$  is the total (absolute) acceleration of the mass  $m_i$ , and the time integration is extended to the duration of ground motion.

Several Authors have chosen, with some differences in procedures and aims, an ESDOF approach for the evaluation of the multistory structures seismic response. Fajfar [1] has adopted an equivalent SDOF method as a step of seismic design procedure. The definition of force-displacement curve for inelastic behavior has been obtained by a preliminary pushover analysis of the frame model. After that, the elastic or inelastic response of the ESDOF system has been deduced from the capacity spectra previously constructed. The nonlinear response of the ESDOF system in terms of top displacement has been successively used in order to calibrate an equivalent static analysis that provides local quantities of seismic displacement demand, as story drifts and rotations. The lateral forces pattern adopted for the pushover analysis is consistent with the assumed displacement shape.

Iwan, Huang and Guyader [2] have related the response of the SDOF system corresponding to the frame structure to capacity spectra affected by equivalent viscous damping; the Authors highlight that this technique is not conservative, especially when the maximum response is not caused by structural resonance, but induced by long duration acceleration pulses, as in near-fault ground motions. In order to assess the local deformation parameters values, a pushover analysis with load pattern resembling the first mode shape of the structure has been done, and the results have been compared with those obtained by means of nonlinear analysis of shear-building models characterized by a bilinear story hysteretic model. The Authors have found that local response in terms of story drifts can be much larger than the displacement response obtained by an equivalent static pushover analysis.

Also Kuramoto and Teshigawara [3] have proposed the conversion of the frame systems into an equivalent SDOF system, for which a bilinear hysteretic model, previously defined by means of pushover analysis, has been adopted. For all the frames analyzed (reinforced concrete and steel frames) it has been found the response to one artificial earthquake wave. The results have shown large differences in local displacement values from a complete inelastic MDOF analysis for frames composed of more than ten stories. For ten story-high frames or lower frames, however, such differences have proved to be very small.

Rodriguez [4] has adopted the ESDOF procedure to evaluate the hysteretic energy dissipated by multistory frame and shear wall buildings. This parameter has been used in the calculation of a damage index for structures subjected to strong ground motions.

Tso, Zhu and Heidebrecht have analyzed reinforced concrete frames, comparing input energy and hysteretic energy for unit mass obtained by ESDOF analysis with the corresponding values of MDOF analysis. For the hysteretic energy it has been found a better correlation than that for input energy; for both energy quantities the correlations have shown a loss of precision when the number of stories increases.

Decanini, Mollaioli and Saragoni [6] have used the ESDOF procedure in order to evaluate the global displacement and energy demands for frame structures subjected to near-fault ground motions and to determine the strength demand for prefixed ductility levels. These response parameters have been compared with the results of analysis of an equivalent shear beam model characterized by



elastic-perfectly plastic hysteretic behavior. A good correlation has been observed between the two methods results; the best coincidence has been found for top displacement in elastic range, for input energy and hysteretic energy in case of intermediate or high ductility levels.

In the present research the seismic response of three reinforced concrete one-span plane frames to 16 natural signals has been examined by means of the ESDOF method. The characteristics of the frames are resumed in Table 1.

Table 1. Geometric and inertial characteristics of the analyzed frames

Span length $L=5.00$ m		4-story Frame - $T_1 = 0.56$ s	
Vertical span load $w=35$ kN/m		Level	Columns sections
Interstory height $h=3.30$ m		1-2	30x50 cm
Beams section 30x50 cm		3-4	30x40 cm
8-story Frame - $T_1=1.01$ s		12-story Frame - $T_1=1.46$ s	
Level	Columns sections	Level	Columns sections
1-3	30x65 cm	1-4	30x75 cm
4-6	30x50 cm	5-8	30x60 cm
4-6	30x40 cm	9-12	30x45 cm

The Table 2 includes the signals used for the analyses. The records relative to the events of Imperial Valley 1979, Landers 1992, Kobe 1995 and Northridge 1995 that have been considered belong to the class of near-fault signals.

Table 2. Accelerometric records used for the analyses

<b>Imperial Valley 1979</b>	<b>Kobe 1995</b>
Bonds Corner - 230	Kobe JMA - NS
El Centro #7 - 230	Kobe University - NS
<b>Northridge 1994</b>	Port Island - NS
Rinaldi - S48W	Takatori - 000
Newhall - 360	<b>El Centro 1940 - El Centro - 180</b>
Sylmar Park.Lot - 360	<b>Irpinia Italy 1980 - Calitri - EW</b>
<b>Landers 1992</b>	<b>Friuli Italy 1976 - Tolmezzo - WE</b>
Lucerne Valley - N80W	<b>Cile 1985 - Llolleo - N10</b>
Joshua Tree - 0	<b>Mexico 1985 - SCT - 270</b>

The analyses have been done for all the frames with the assumption of a linear shape of deflection both for elastic and inelastic deformation. This choice should imply the consideration of the fundamental mode response effects for regular buildings. The results, obtained for elastic behavior and for target global ductility ratio equal to 2, 4 and 6, have been compared with the results of MDOF analysis of equivalent shear-building models having the same base shear strength calculated for ESDOF models. A mass-proportional damping equal to 5% of critical value has been assumed. The same damping ratio has been considered for the first two modes of MDOF system. For the cyclic behavior of the ESDOF system a stiffness degrading hysteretic model for flexural reinforced concrete structures has been adopted, with bilinear envelop and post-yielding hardening ratio equal to 0.1; the same hysteretic rules has been considered for the story cyclic behavior. The comparison has concerned firstly the global seismic demand

parameters, as top displacement and input and hysteretic energy. Then the suitability of prediction for local seismic demand, in terms of story ductility and hysteretic energy demand, has been checked with comparison between pushover analysis results and “exact” MDOF results.

## 2 Global seismic displacement and energy demand

The values of top displacement are in most cases slightly overestimated by the ESDOF predictions, and the ductility level does not influence significantly this trend. On average the differences between the two methods increase with the number of stories. The mean ratios between MDOF and ESDOF, calculated on all the record analyzed, assume respectively the values of 0.95, 0.92 and 0.90 for 4, 8 and 12-story frames. With the exception of few cases, the evaluation of top displacement by means of the ESDOF procedure can be considered satisfactory. The cases of 4 and 12 stories are shown in Figure 1. From the global displacement point of view, the approximated linear shape adopted seems to give reasonable results. For the 12-story frame, a general trend of decrease in the MDOF top displacement in relation to the ESDOF prediction is found when ductility increases: the ratios of displacements on average decrease from 0.93 for elastic case to 0.87 for  $\mu=6$ . This results are consistent with the slight trend highlighted by Gupta and Krawinkler (2000), and show the presence of larger concentrations of local drifts in inelastic range in comparison to the elastic behavior.

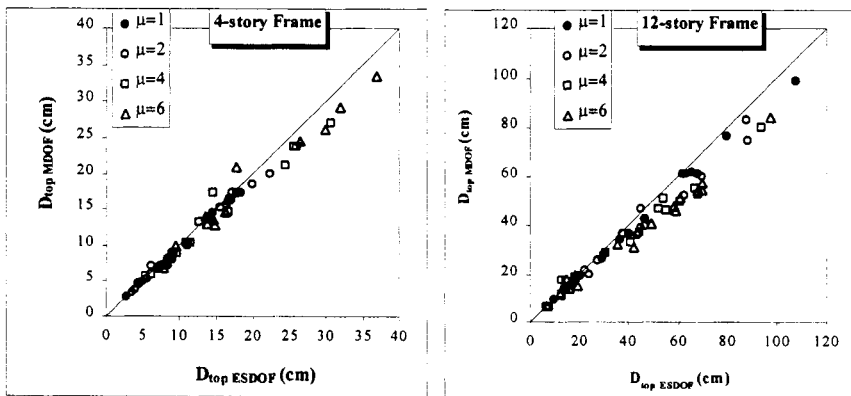


Figure 1: Comparison of top displacement values between ESDOF and MDOF analyses results

The global input energy, in the present paper considered in the absolute formulation, shows that the ESDOF procedure gives underestimated values; the ESDOF input energy values increasingly diverge from the MDOF values as the number of stories grows, which means that the error in evaluation is caused by the fact that the ESDOF approximation neglects the influence of higher modes. These differences increase also when ductility increases, demonstrating a growing importance of the contributes of the higher modes to the total energy imparted to the structures in the inelastic range. The average values of the ratio between MDOF and ESDOF analyses are resumed in Table 3 and represented in Figure 2 for the 4 and 12-story frames.



Table 3. Mean values of MDOF to ESDOF input energy ratios

4-story Frame				8-story Frame				12-story Frame			
$\mu=1$	$\mu=2$	$\mu=4$	$\mu=6$	$\mu=1$	$\mu=2$	$\mu=4$	$\mu=6$	$\mu=1$	$\mu=2$	$\mu=4$	$\mu=6$
1.00	1.03	1.06	1.08	1.06	1.18	1.21	1.25	1.26	1.31	1.39	1.46

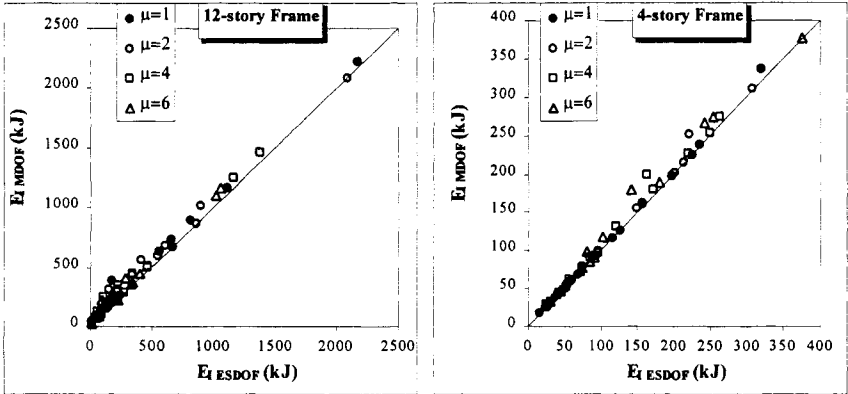


Figure 2: Comparison of input energy values between ESDOF and MDOF analyses results

The global hysteretic energy shows a similar trend, although the mean values of the energy ratios MDOF energy / ESDOF energy show a less clear influence of ductility for 4 and 8-story frames. However, for 12-story frames the influence is stronger than in the case of input energy. These mean values are resumed in Table 4.

Table 4. Mean values of MDOF to ESDOF hysteretic energy ratios

4-story Frame			8-story Frame			12-story Frame		
$\mu=2$	$\mu=4$	$\mu=6$	$\mu=2$	$\mu=4$	$\mu=6$	$\mu=2$	$\mu=4$	$\mu=6$
1.12	1.11	1.12	1.24	1.23	1.27	1.37	1.42	1.47

In order to point out the effective influence of higher modes on the hysteretic behavior, especially for local dissipation, as will be presented in the next paragraph, an alternative analysis has been done by means of the MDOF shear system. In this analysis the contribution of the higher modes to seismic response has been cut off by means of high values of viscous damping ( $\geq 50\%$ ) artificially imposed to the second mode and to the higher ones. In Table 5 the hysteretic energy ratios between MDOF and ESDOF analyses results are presented for all the records considered. In the second half of the table the energy values obtained by MDOF analysis with the contribution of the first mode only have been used. All the values are very close to unity. The influence of the nature of the signal is evident in exalting the contribution of the fundamental mode or of the higher modes. This comparison confirms that in some cases the prediction of hysteretic energy demand obtained by ESDOF procedure gives a good approximation, while in other cases this prediction is not satisfactory. A further investigation should explain which characteristics of the signal can influence this result, and, if

possible, the way the ESDOF procedure should be corrected in order to improve its suitability. The results resumed in Table 5 should be used with further information on effective hysteretic performance, because many cycles having small amplitude may cause low damage level in the structure.

Table 5. Hysteretic energy ratios considering all modes or only the first mode

12 story frame Records	All modes			Only 1 <sup>st</sup> mode		
	$\mu=2$	$\mu=4$	$\mu=6$	$\mu=2$	$\mu=4$	$\mu=6$
Bonds Corner - 230	2.07	1.90	2.03	1.04	1.10	1.10
El Centro #7 - 230	1.08	1.12	1.08	0.99	0.99	0.99
Rinaldi - S48W	1.11	1.28	1.40	0.99	1.04	1.05
Newhall - 360	1.30	1.31	1.44	1.01	1.05	1.05
Sylmar Park.Lot - 360	1.06	1.07	1.07	1.00	1.00	1.01
Kobe JMA - NS	1.36	1.51	1.59	1.01	1.05	1.08
Kobe University - NS	1.08	1.20	1.30	1.01	1.03	1.04
Port Island - NS	1.03	1.04	1.08	0.97	1.02	1.03
Takatori - 000	0.99	1.08	1.13	0.99	1.02	1.03
Lucerne Valley - N80W	1.08	1.07	1.04	0.99	0.99	0.99
Joshua Tree - 0	1.44	1.65	1.80	1.02	1.06	1.08
El Centro 1940 - 180	1.60	1.51	1.45	1.04	1.03	1.04
Calitri - EW	1.01	1.25	1.32	0.96	1.02	1.02
Tolmezzo - WE	2.76	2.46	2.64	1.14	1.16	1.20
Llolleo - N10	1.85	2.15	2.12	1.05	1.11	1.10
Mexico SCT - 270	1.15	1.07	1.09	0.83	1.00	1.01

### 3 Local seismic displacement and energy demand

Once the global response parameters in terms of displacement and total hysteretic energy demand have been obtained, no prediction can be made yet about the local seismic demand in terms of deformation parameters or energy dissipation quantities. A solution suggested by some Authors is the calibration of an equivalent static pushover analysis based on the global displacement response of the ESDOF procedure. In this research the pushover analysis has been done very directly, because the frames to be investigated are not existing buildings, but ideal structures. However, the procedure should be conceptually the same for an existing or designed structure.

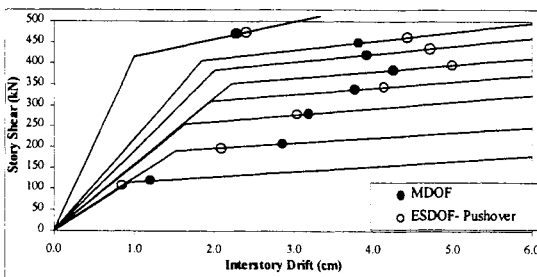


Figure 3: Comparison of the results of pushover analysis and MDOF nonlinear analysis - 8-story Frame -  $\mu=2$  - Frame El Centro #7-230



Hence, the local deformation parameters have been directly derived from the stiffness and strength information after choosing a distribution of lateral equivalent static forces. An inverted triangular pattern has been adopted, consistently with the linear shape adopted in ESDOF analysis. The calculation has been limited to story deformation, represented by interstory drift ratio IDI, that is the interstory drift normalized by the height of the story. The results of this analysis have been compared with those obtained by the "exact" results of the MDOF equivalent shear-building system.

The Figure 3 shows an example of comparison for global target ductility  $\mu=2$ . For both kinds of models the strength distributions on the heights of the frames have been "designed" according to the UBC design patterns.

As for deformation, also for energy dissipation the story demand has been chosen as a local parameter. For an evaluation of story hysteretic energy demand, a very simple scheme of prediction has been tested. Once the global hysteretic energy has been determined, its distribution on the height of the frame has been estimated considering the fraction of energy that a story must dissipate in proportion to its potential cyclic amplitude and to the story cinematic ductility demand. Hence, if  $E_H$  is the global energy dissipation demand for the structure, defining the story coefficients

$$\alpha_i = V_{yi} \Delta_{yi} (\mu - 1) \quad (10)$$

where  $V_{yi}$  is the yielding story shear,  $\Delta_{yi}$  the yielding story drift and  $\mu$  the story ductility demand, the estimate of the hysteretic energy demand for the story will be

$$E_{H,i}^* = \left( \frac{\alpha_i}{\sum_i \alpha_i} \right) E_H \quad (11)$$

The approximate character of this investigation justifies such simplification. The obvious limit of this estimation is given by the fact that cinematic ductility offers very incomplete information on the cyclic seismic demand.

Table 6. Drift and hysteretic energy demand estimates - Takatory

Kobe 1995 - Takatori-000 - 12-story Frame - $\mu=4$									
<i>i</i>	$IDI_{ESDOF}$	$\mu_{ESDOF}$	$IDI_{MDOF}$	$\mu_{MDOF}$	$IDI_1$	$\mu_1$	$E_{H,i}^*$	$E_{H,i}$	$E_{H,i1}$
1	0.0109	3.55	0.0149	4.85	0.0135	4.42	51.15	40.84	53.21
2	0.0204	3.31	0.0298	4.83	0.0266	4.32	101.40	68.68	104.16
3	0.0239	3.35	0.0342	4.79	0.0302	4.24	113.30	82.22	116.49
4	0.0264	3.62	0.0345	4.73	0.0303	4.16	109.98	92.80	113.28
5	0.0305	3.96	0.0357	4.64	0.0312	4.07	107.61	110.29	110.90
6	0.0304	4.21	0.0326	4.52	0.0284	3.93	91.23	109.87	93.28
7	0.0284	4.28	0.0288	4.35	0.0248	3.75	73.06	99.64	73.77
8	0.0253	4.22	0.0246	4.10	0.0210	3.50	54.64	85.34	54.20
9	0.0254	4.02	0.0236	3.73	0.0201	3.18	43.90	82.73	42.73
10	0.0178	3.45	0.0162	3.15	0.0139	2.71	23.17	51.29	22.10
11	0.0094	2.41	0.0083	2.12	0.0079	2.02	7.01	16.82	7.25
12	0.0027	1.01	0.0024	1.00	0.0028	1.06	0.00	0.04	0.11
						Global	776.45	840.57	791.47

Table 6, 7, 8 and 9 show some examples of comparison between the local parameters, in terms of interstory drift index, story ductility and story hysteretic



energy, estimated by means of ESDOF and pushover procedure, and the corresponding MDOF values. In addition, the results of the MDOF analysis limited to the first mode are included.

For the 4-story frame the pushover analysis points out story ductility values identically equal to the target ductility because the UBC design distribution of strength does not consider any top force in addition to the triangular pattern for short period structures, so that the force patterns used for strength distribution and for the pushover analysis are identical.

Table 7. Drift and hysteretic energy demand estimates - Sylmar

Northridge 1994 - Sylmar-360 - 4-story Frame - $\mu=2$									
$i$	$IDI_{MDOF}$	$\mu_{MDOF}$	$IDI_{ESDOF}$	$\mu_{ESDOF}$	$IDI_1$	$\mu_1$	$E_{H,i}^*$	$E_{H,i}$	$E_{H,i,1}$
1	0.0109	2.31	0.0095	2.00	0.0105	2.22	10.10	12.27	11.55
2	0.0135	1.90	0.0142	2.00	0.0143	2.02	13.59	12.22	13.92
3	0.0144	1.95	0.0148	2.00	0.0138	1.87	11.01	11.95	10.32
4	0.0081	1.87	0.0086	2.00	0.0070	1.62	3.68	4.36	2.49
						Global	38.38	40.80	38.27

Table 8. Drift and hysteretic energy demand estimates - El Centro #7

Imperial Valley 1979 - El Centro #7-230 - 8-story Frame - $\mu=2$									
$i$	$IDI_{ESDOF}$	$\mu_{ESDOF}$	$IDI_{MDOF}$	$\mu_{MDOF}$	$IDI_1$	$\mu_1$	$E_{H,i}^*$	$E_{H,i}$	$E_{H,i,1}$
1	0.0069	2.28	0.0073	2.42	0.0070	2.31	7.56	8.15	8.50
2	0.0116	2.06	0.0134	2.39	0.0121	2.16	13.45	12.25	13.80
3	0.0119	1.95	0.0143	2.34	0.0124	2.04	13.31	11.44	12.89
4	0.0129	1.92	0.0152	2.26	0.0130	1.93	12.59	11.42	11.74
5	0.0114	1.92	0.0125	2.11	0.0107	1.80	8.65	9.05	7.69
6	0.0097	1.96	0.0092	1.87	0.0080	1.62	4.64	6.51	4.01
7	0.0087	1.89	0.0064	1.39	0.0063	1.38	1.43	4.14	1.62
8	0.0037	1.29	0.0026	1.00	0.0029	1.02	0.00	0.45	0.02
						Global	61.65	63.41	60.26
Imperial Valley 1979 - El Centro #7-230 - 12-story Frame - $\mu=2$									
$i$	$IDI_{ESDOF}$	$\mu_{ESDOF}$	$IDI_{MDOF}$	$\mu_{MDOF}$	$IDI_1$	$\mu_1$	$E_{H,i}^*$	$E_{H,i}$	$E_{H,i,1}$
1	0.0054	2.20	0.0064	2.58	0.0059	2.37	8.14	6.93	8.80
2	0.0091	1.83	0.0127	2.56	0.0113	2.27	16.05	10.02	16.31
3	0.0093	1.61	0.0145	2.53	0.0125	2.18	17.74	9.40	17.32
4	0.0096	1.63	0.0146	2.48	0.0123	2.08	16.92	9.59	16.08
5	0.0110	1.78	0.0149	2.41	0.0123	1.99	16.12	11.81	15.06
6	0.0116	1.99	0.0134	2.30	0.0110	1.88	13.10	13.55	12.11
7	0.0120	2.23	0.0115	2.16	0.0094	1.76	9.81	14.65	9.08
8	0.0124	2.56	0.0094	1.95	0.0081	1.66	6.50	14.41	6.23
9	0.0144	2.83	0.0084	1.64	0.0079	1.54	4.02	14.90	4.46
10	0.0112	2.69	0.0048	1.16	0.0057	1.37	0.67	9.23	1.90
11	0.0061	1.93	0.0029	1.00	0.0035	1.11	0.00	3.01	0.30
12	0.0024	1.11	0.0016	1.00	0.0018	1.00	0.00	0.09	0.00
						Global	109.07	117.57	107.65

The comparison has been made for all the records analyzed, for the three frame schemes and for ductility level equal to 2, 4 and 6.



However, the estimates are not always precise. The interstory drift and the story hysteretic energy values are often strongly underestimated in the higher part of the 8 and 12-story frames. The ESDOF estimate is in many cases very similar to the MDOF analysis limited to one-mode response.

Table 9. Drift and hysteretic energy demand estimates - Joshua Tree

Landers 1992 - Joshua Tree-0 - 8-story Frame - $\mu=2$									
$i$	$IDI_{ESDOF}$	$\mu_{ESDOF}$	$IDI_{MDOF}$	$\mu_{MDOF}$	$IDI_1$	$\mu_1$	$E_{H,i}^*$	$E_{H,i}$	$E_{H,i1}$
1	0.0041	2.43	0.0041	2.43	0.0040	2.36	10.15	8.65	9.97
2	0.0069	2.19	0.0076	2.41	0.0070	2.21	18.06	14.42	17.74
3	0.0064	1.88	0.0081	2.36	0.0071	2.08	17.88	14.82	17.95
4	0.0067	1.78	0.0086	2.27	0.0073	1.94	16.92	17.34	17.24
5	0.0065	1.94	0.0071	2.13	0.0058	1.75	11.64	14.48	11.46
6	0.0063	2.26	0.0052	1.88	0.0044	1.57	6.26	9.56	5.72
7	0.0061	2.35	0.0036	1.40	0.0033	1.29	1.97	5.03	1.86
8	0.0019	1.18	0.0015	1.00	0.0015	1.00	0.00	0.20	0.00
						Global	82.88	84.50	81.93

## Conclusions

The ESDOF method, although in some cases it neglects important effects of seismic response due to higher modes of multistory frames, seems to be a good means for an approximate evaluation of global displacement and energy demand for these kinds of structures in the period range examined in this research. On the contrary, the estimate of parameters of the local response seems to be in many cases difficult and strongly affected by the particular characteristics of the strong motion. For this evaluation the use of nonlinear MDOF model is to be preferred.

## References

- [1] Fajfar, P. «A Nonlinear Analysis Method for Performance-Based Seismic Design», *Earthquake Spectra*, 16, No. 3, pp573-593, August 2000.
- [2] Iwan, W. D., Huang, C.-T. and Guyader, A. C. «Important Features of the Response of Inelastic Structures to Near-Field Ground Motion», 12th World Conference on Earthquake Engineering, Auckland, New Zealand, 2000.
- [3] Kuramoto, H. and Teshigawara, M. «Prediction of Earthquake Response of Buildings Using Equivalent Single-Degree-of-Freedom System», U.S.-Japan Workshop on Performance-Based Earthquake Engineering Methodology for Reinforced Concrete Building Structures, Maui, Hawaii, 1999.
- [4] Rodriguez, M., «A Measure of the Capacity of Earthquake Ground Motions to Damage Structures», *Earthquake Engineering and Structural Dynamics*, 23, pp627-643, 1994.
- [5] Tso, W. K., Zhu, T. J. And Heidebrecht, A. «Seismic Energy Demands on Reinforced Concrete Moment-Resisting Frames», *Earthquake Engineering and Structural Dynamics*, 22, pp533-545, 1993.
- [6] Decanini, L., Mollaioli, F. and Saragoni, R. «Energy and Displacement Demands Imposed by Near-Source Ground Motions», 12th World Conference on Earthquake Engineering, Auckland, New Zealand, 2000.
- [7] Gupta, A. and Krawinkler, H. «Estimation of seismic drift demands for frame structures», *Earthquake Engineering and Structural Dynamics*, 29, pp1287-1305, 2000.