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NEW APPROACH FOR THE OPTIMAL YIELD-FORCE COEFFICIENT DISTRIBUTION IN THE SEISMIC DESIGN OF BUILDINGS

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ABSTRACT

One of the main objectives in seismic design of buildings is to prevent the damage concentration in certain stories. As shown by past earthquakes the damage concentration leads to severe damage and even collapse of the structure, especially for near field ground motions. Energy-based design methods address explicitly the tendency of a given story to concentrate damage, and evaluate it through a parameter that measures the deviation of the actual lateral strength of the story with respect to an optimum (yet ideal) value that would make the plastic strain energy, normalized by the yield strength and yield displacement of the story, approximately equal in all stories. The objective of this methodology is to obtain the optimum lateral strength distribution expressed in terms of yield-shear force coefficient. The yield-shear force coefficient is defined as the ratio between the *i*-th story yield-shear force and the total upward weight born by the story. The optimal yield-force coefficient distribution is defined as one that makes the normalized plastic strain energy equal in all stories, thus preventing damage concentration in a given story. This paper proposes a new procedure to estimate for a given building and exciting ground motion the optimal yield-force coefficient distribution. The optimal distribution is estimated by means of the Pattern Search Method by iteratively changing the shear strength distribution until a uniform normalized distribution of damage is obtained. A comparison is carried out between the seismic behaviour of two case study structures designed using the proposed procedure and alternative proposals taken from the literature. The response is estimated in terms of distribution of damage and inelastic deformation.

Keywords: damage concentration; energy-based methods; optimal shear distribution; pattern search method

1. INTRODUCTION

The effect of damage concentration in buildings subjected to seismic actions has been widely reported (Rodriguez and Diaz, 1989)(Meli and Avila, 1989)(Benavent-Climent *et al.*, 2014). In fact, the consequences of this phenomenon in buildings are usually catastrophic triggering the collapse in the majority of the cases. Seismic codes try to guarantee this objective in a simple way e.g. by requiring in frame structures a minimum value for the column-to-beam strength ratio. Furthermore, design requirements are prescribed to avoid sharp in-elevation changes in both the lateral stiffness and mass distributions. Very few codes, however, explicitly evaluate whether or not the structure is prone to damage concentration. As far as the authors know, only the Japanese code includes a quantitative estimation of the damage distribution (Building Research Institute, 2009).
The energy-based methodology makes use of parameters to design the structure that derive from the energy balance equation $E_I=W_e+W_\xi+W_p$, where E_I is the input energy at the base of the building, W_e the elastic vibrational energy, W_ξ is the damping energy and W_p the energy dissipated through hysteretic plastic deformation (Housner, 1956)(Akiyama, 1980). Based on the Housner-Akiyama energy balance

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equation, the damage at the generic ***i***-th story of the structure can be assessed as being the energy dissipated at that story through plastic deformations, W_{pi}. Damage concentration is assumed to be prevented if W_{pi} normalized by the product of the yield strength and yield displacement of the story, $Q_{yi}\delta_{yi}$, is equal at all stories. This normalized energy will be denoted hereafter by the coefficient η_i ($=W_{pi}/Q_{yi}\delta_{yi}$). The distribution of W_{pi} among stories is governed by the distribution of the yield-shear strength coefficient α_i that is defined as the ratio between Q_{yi} and the total upward weight born by the story. The yield-shear force coefficient distribution, α_i/α_1, which leads to an even distribution of η_i along the height of the building is defined as the optimum distribution and is referred to hereafter as $\overline{\alpha}_i = \alpha_{i,opt}/\alpha_1$. Akiyama (1980) proposed an expression for $\overline{\alpha}_i$ which was derived from non-linear time history analyses of numerical models subjected to a single ground motion record (El Centro, 1940). Other expressions for $\overline{\alpha}_i$ have been also proposed by seismic codes (Building Research Institute, 2009) and in the literature (Benavent-Climent, 2011). Such expressions for $\overline{\alpha}_i$, however, provide only a rough approximation of the "exact" optimum distribution since the latter depends actually on the specific characteristic of the exciting ground motion.

This study puts forward a new approach to obtain the "exact" optimal shear-force coefficient distribution for a given earthquake, which is based on a number of non-linear time history analyses carried out on the structure by varying its lateral strength distribution. For this purpose, the direct search optimization methodology is used to find the shear-force distribution which leads to an even distribution of η_i for a given ground motion. The method is applied to a 3- and a 6-story prototype building. The "exact" optimum distribution obtained using the proposed approach is compared with the approximate optimum distributions proposed in the literature. Both near and far field ground motions recorded during real earthquakes are used.

2. ENERGY BASED DESIGN METHODOLOGY

As noted above, the energy-balance approach to seismic design is based on the following equation:

$$W_e + W_\xi + W_p = E_I \tag{1}$$

Akiyama, (1980) showed that E_I is a very stable quantity which depends mainly on the mass, M, and the fundamental period of the structure, T. This equation, can be rewritten for practical use as follows:

$$W_e + W_p = E_I - W_\xi = E_D = \frac{MV_D^2}{2} \tag{2}$$

where E_D is the energy that contributes to damage and $V_D = \sqrt{2E_D / M}$ is the corresponding equivalent velocity.

There are many expressions proposed in the literature to relate E_D with E_I. In this study, the one proposed by Akiyama, (1980) is used:

$$\frac{V_D}{V_E} = \frac{1}{1 + 3\xi + 1.2\sqrt{\xi}} \tag{3}$$

where ξ is the inherent damping ratio of the structure and V_E is calculated from E_I by $V_E = \sqrt{2E_I / M}$.

2.1 Elastic vibrational energy

By adopting an equivalent continuum shear strut model for representing the structure, the elastic vibrational energy, W_e, can be expressed as follows (Akiyama, 1980):

$$W_e = \frac{Mg^2T^2}{4\pi^2}\frac{\alpha_1^2}{2} \tag{4}$$

where g is the acceleration of gravity and α_1 is the yield shear-force coefficient for the ground floor, being the general expression for the yield-force coefficient the following one:

$$\alpha_i = \frac{Q_{yi}}{\sum_{j=i}^{N} m_j g} \tag{5}$$

where N is the number of stories and m_i is the mass of the i-th story.

2.2 Energy dissipated by plastic deformations

The energy dissipated through plastic deformations by the overall building, W_p, is simply the sum of the energy dissipated by plastic deformation by each story, W_{pi}, and it can be expressed in terms of η_i as follows:

$$W_p = \sum_{i=1}^{N} W_{pi} = \sum_{i=1}^{N} \eta_i Q_{yi} \delta_{yi} \tag{6}$$

W_{pi} can be also expressed (Akiyama, 1980) in terms of α_1 as follows:

$$W_{pi} = \frac{Mg^2T^2}{4\pi^2} c_i \alpha_i^2 \eta_i \tag{7}$$

where $c_i = \left(\sum_{j=i}^{N} m_j / M \right)^2 / \chi_i$. The value of χ_i for the ith-story is defined as the ratio k_i / k_{eq}, where k_i is the ith-story lateral stiffness and k_{eq} is the lateral stiffness of an equivalent SDOF (Single Degree of Freedom) system with a mass of M and a period of T, that is, $k_{eq} = 4\pi^2 M / T^2$.

2.3 The standard damage distribution and the optimal yield-shear force coefficient distribution

By definition, when the distribution of the lateral strength along the building height follows the optimum distribution $\overline{\alpha_i}$, the coefficient η_i which characterizes the damage is constant and equal to η at all stories. In this case, for structures with elastic-perfectly plastic restoring force characteristics, the distribution of the plastic strain energy among the stories, W_{pi}/W_p, can be expressed as follows:

$$\frac{W_{pi}}{W_p} = \frac{s_i}{\sum_{j=1}^{N} s_j} = \frac{1}{\gamma_i} \tag{8}$$

where $s_i = c_i \chi_1 \overline{\alpha_i}^2 = \left(\sum_{j=i}^{N} m_j / M \right)^2 \overline{\alpha_i}^2 k_1 / k_i$. The coefficient γ_i is called dispersion damage index for the i-th story. The damage distribution given by Equation (8) is hereafter referred as the standard damage distribution.

Akiyama (1980) proposed the following expression for $\overline{\alpha_i}$ to be used for MDOF (multi degree of freedom) systems with even mass and variable stiffness distributions:

For $x' > 0.2$

$$\bar{\alpha} = 1 + 1.5927x' - 11.8519x'^2 + 42.5833x'^3 - 59.4827x'^4 + 30.1586x'^5 \tag{9}$$

For $x' \leq 0.2$

$$\bar{\alpha} = 1 + 0.5x'$$

where $x' = x / H = (i-1)/N$, with x being the height of the i-th story with respect to the base and H the total height of the building . This equation can be applied also when the maximum value of the mass ratio m_i/m_1 is lower than 2, by calculating x' of the i-th story with $x' = 1 - \sum_{j=i}^{n} m_j / M$.

2.4. Design method

The design of structures according to the energy-balance approach is based on the Equation (2). Using Equations (4, (7 and (8), for a structure whose lateral strength follows the optimum distribution of the yield shear force coefficient $\bar{\alpha}_i = \alpha_{i,opt} / \alpha_1$, the left side of Equation (2), can be expressed as follows:

$$W_e + W_p = \frac{Mg^2T^2}{4\pi^2}\frac{\alpha_1^2}{2} + \frac{Mg^2T^2}{4\pi^2} c_i \bar{\alpha}_i^2 \alpha_1^2 \eta_i \gamma_i = \frac{MV_D^2}{2} \tag{10}$$

By solving Equation (10, the value ${}_i\alpha_1$ of the yield shear force coefficient at the ground story that leads to a given amount of (normalized) plastic deformation η in each story is given by:

$${}_i\alpha_1 = \frac{1}{\sqrt{1 + 2c_i \bar{\alpha}_i^2 \eta_i \gamma_i}} \frac{2\pi V_D}{Tg} \tag{11}$$

Based on the results of a large number of non-linear time history analyses, for reinforced concrete SDOF systems, Akiyama (1980) put forward the following expression:

$$W_e + W_p = \frac{1}{2} Q_y \delta_y + Q_y \delta_y \eta = Q_y \delta_y \left(\frac{1}{2} + 2\bar{\mu}\left(1 + \frac{3}{4}\right)\right) \tag{12}$$

where Q_y and δ_y are the yield strength and yield displacement of the SDOF system. $\bar{\mu} = \left(\left|\mu^+\right| + \left|\mu^-\right|\right)/2$ is the average inelastic deformation ratio, and μ^+ and μ^- are defined for each domain of loading by $\mu = (\delta_{max} - \delta_y)/\delta_y$, where δ_{max} is the maximum interstory drift. Moreover, μ is related to ductility ($\mu_d = \delta_{max}/\delta_y$) throughout the expression $\mu_d = \mu + 1$.

From Equation (12 the value of η is derived as $\eta = 3.5\bar{\mu}$. In a structure whose lateral strength follows the optimum yield shear force coefficient distribution it can be assumed that the relationship between η and $\bar{\mu}$ is equal in all stories. By using the relationship $\eta = 3.5\bar{\mu}$ proposed by Akiyama and substituting in Equation (11 gives the following expression is obtained for i=1:

$$\alpha_1 = \frac{1}{\sqrt{1 + \frac{7\bar{\mu}\gamma_1}{\chi_1}}} \frac{2\pi V_D}{Tg} \tag{13}$$

Equation (13 provides the base shear force coefficient required in a RC structure whose lateral strength follows the optimum distribution so that it can endure a ground motion characterized by V_D, by

experiencing a constant displacement ductility $\bar{\mu}$ and a cumulative plastic deformation $\eta = 3.5\bar{\mu}$ at each story. The term $2\pi V_D/Tg$ ($=\alpha_e$) in the right side of Equation (13 represents the required base shear force coefficient for the structure remaining elastic under a ground motion characterized by V_D, that is, the required value of α_1 so that $\bar{\mu} = 0$ and $\eta = 0$.
Eventually, recalling Equation (5 and noting that $\bar{\alpha}_i = \alpha_{i,opt} / \alpha_1$, the lateral strength Q_{yi} required at the *i*-th story that leads to the optimum yield-shear force coefficient distribution for a ground motion characterized by V_D is given by:

$$Q_{yi} = \alpha_i \sum_{j=i}^{N} m_j g = \bar{\alpha}_i \alpha_1 \sum_{j=i}^{N} m_j g \tag{14}$$

Finally, δ_{yi} is readily obtained as the quotient Q_{yi}/k_i.

3. NEW APPROACH TO OBTAIN THE OPTIMAL YIELD-SHEAR DISTRIBUTION

In order to obtain the "exact" optimal yield-shear force distribution of a MDOF lumped-mass system subjected to a given ground motion a new procedure is proposed. The procedure involves iterative non-linear time history analyses of a numerical model whose lateral strength distribution is modified at each iteration so that to approach the one that makes η_i equal at all stories. For this purpose, the Pattern Search Method (PSM) which belongs to the direct search methodology for optimization of n-dimensional functions (Michael, Torczon and Trosset, 2000) is used. The core of the method is based on the sequential examination of trial solutions involving comparison of each of them with the best obtained up to the time. Moreover, a plan must be layout to find the next best solution from the trials. These methods are often described as derivative-free or zero-order methods because they do not use derivatives.
The PSM is characterized by the evaluation of the objective function at a pattern of points of a rational lattice around the current state, according to a systematic strategy for visiting these points. If the trial is successful in one point of the lattice (a lower value for the objective function is obtained), this will be the new reference point from which a new lattice is built with a greater step size. Otherwise, the point is held but the step size is reduced to build a new lattice. This procedure is particularly appropriate, because of the high sensitivity of the damage distribution respect to the values of the yield-shear coefficient distribution.
Therefore, the procedure is summarized as follows:

- Define an initial benchmark numerical model where α_1 is obtained with Equation (13 and in which the value of γ_1 is obtained with Equation (8 taking into account the value of $\bar{\alpha}_i$ proposed by Akiyama (Equation (9), hereafter referred to as $\bar{\alpha}_{Aki,i}$. Two "approximated" optimum shear force coefficient distributions are used to calculate the values of α_i for the other stories ($\alpha_i = \bar{\alpha}_i \alpha_1$): the aforementioned $\bar{\alpha}_{Aki,i}$ and another one, $\bar{\alpha}_{JBC,i}$, which is obtained using the Japan Building Code (JBC) (Building Research Institute, 2009), , and is given by the following expression:

$$\bar{\alpha}_{JBC,i} = 1 + \left(\frac{1}{\sqrt{\bar{m}_i}} - \bar{m}_i \right) \frac{2T}{1+3T} \tag{15}$$

where $\bar{m}_i = \sum_{j=i}^{N} m_j / M$.

- Set-up the PSM and establish the following constraint for the possible trials of $\bar{\alpha}_i$: (i) its value for the first story (*i*=1) is always equal to 1; (ii) its distribution is monotonic growing with the height of the structure. Fix the maximum and minimum step size and define the increasing and decreasing factor for the step size in successful or unsuccessful evaluation.

- Apply the PSM. The first trial will be $\bar{\alpha}_{Aki,i}$. For the following trials, the test value of $\bar{\alpha}_i$ proposed by the PSM is used. Then, the values of $Q_{y,i}$ are obtained to each one by applying Equation (14, and using the α_1 obtained for the benchmark numerical model. Non-linear time history analysis (NLTHA) is carried out. The η_i distribution is obtained and then its standard deviation. The last one is considered as the objective function.
- Keep iterating until one of the following conditions is met: (i) the standard deviation is null; (ii) the step size attains the minimum limit; (iii) other possible limitations such as the minimum change in two consecutive evaluations of the objective function are attained. Eventually, $\bar{\alpha}_{PSM,i}$ is obtained.

4. CASES STUDIES

4.1 Prototype buildings

Two prototype buildings with N=3 and N=6 stories are considered. The mass m_i of each floor is 450 kN/981 cm/s^2 = 0.458 kNs^2/cm. The distribution of lateral stiffness k_i of the stories is forced to follow a linear law characterized by the ratio k_1/k_T, where k_1 and k_T is the lateral stiffness of the first and top story, respectively. Once M is fixed, it is possible to obtain k_{eq}. On the other hand χ_1 can be approximated with the simplified expression χ_1= 0.52N+0.48 proposed by Akiyama, (1980), and k_1 can be readily obtained as $\chi_1 k_{eq}$. The values of the parameters that characterize the investigated buildings are shown in the Table 1, where m_T is the mass of the top floor.

Table 1. Design data of the prototypes

N	k_1/k_T	m_1/m_T	M (kNs^2/cm)	T (s)	k_{eq} (kN/cm)	χ_1	k_1 (kN/cm)	k_T (kN/cm)
3	1	1	1.38	0.4	339.55	2.04	692.69	692.69
6	1.5	1	2.75	0.8	169.78	3.60	611.19	407.46

4.2 Benchmark numerical models

The two buildings are modeled as MDOF lumped-mass systems with one translational degree of freedom per floor. Two sets of seven ground motion records (for details see the Appendix) representing near and far field earthquakes, are considered. The required yield-shear force at the *i-th* story, Q_{yi} is calculated for each record using the data shown in Table 1 as follows.

Firstly, the elastic input energy V_E is obtained from the input energy spectrum of the record, and then, the value of V_D is calculated by applying Equation (3. Secondly, the value of α_1 is obtained from the Equation (13, using: (i) the optimum distribution $\bar{\alpha}_{Aki,i}$; (ii) the value of γ_1 obtained with Equation (8; and (iii) assuming $\bar{\mu}_1$ = 2.

Eventually, the value of Q_{yi} for each i-th story is obtained from Equation (14, and the counterpart δ_{yi} obtained the quotient Q_{yi}/k_i.

4.3 Pattern Search Method

The PSM is used to improve the initial optimum yield shear force distribution $\bar{\alpha}_{Aki,i}$ imposed to the model, in order to obtain the $\bar{\alpha}_{PSM,i}$ that makes η_i equal at all stories for a given ground motion. The objective function is made up throughout the damage distribution obtained from NLTHA carried out on the numerical models that minimizes the standard deviation of η_i. Therefore, it is not explicitly outlined but it is underlying on them.

4.4 Optimal distribution of the yield-shear force coefficient

Figure 1 shows for the 3-story building the optimal yield-shear force coefficient distributions proposed by Akiyama, the one implemented in Japanese Building Code (JBC) and the one obtained by applying the PSM procedure for each record. It can be noted that the Akiyama's distribution and the JBC one are similar, and they both overestimate the required "exact" lateral strength value especially at the top story. Moreover, distributions obtained with the PSM approach show a lower standard deviation (denoted as σ in the figure) in the case of the near field ground motions than the far field ground motions.

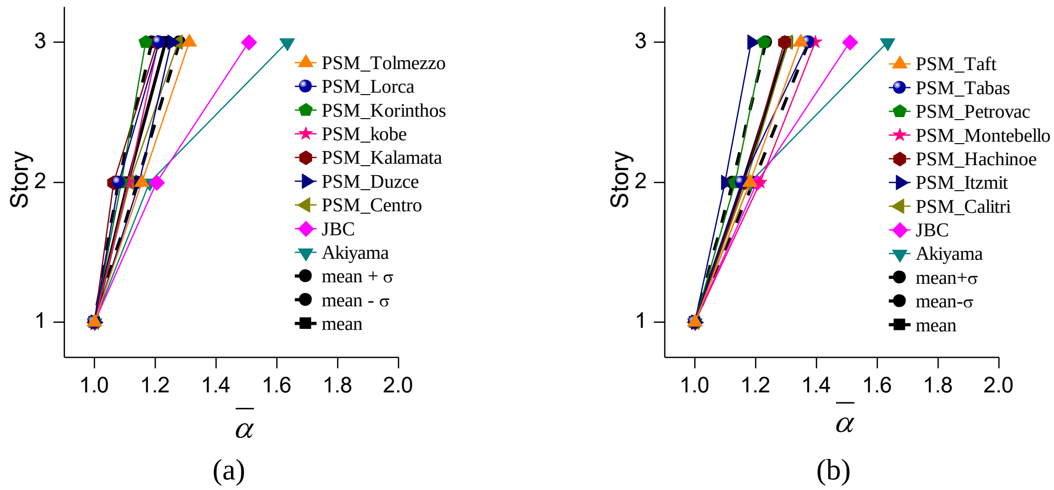


Figure 1. $\overline{\alpha}_i$ obtained for the 3-story building using: (a) near field records; (b) far field records

Figure 2 shows the distribution of the $\overline{\alpha}_{Aki,i} / \overline{\alpha}_{PSM,i}$ ratio. Both the mean and the mean $\pm\,\sigma$ of this ratio are also reported. The observed mean is about 5% and 30% are observed at the second and the third story, respectively. This means that the value of the yield shear force at these stories is larger when the structure is designed using the Akiyama's approach. About the near and far field records, no significant differences in the obtained $\overline{\alpha}_{Aki,i} / \overline{\alpha}_{PSM,i}$ values can be observed.

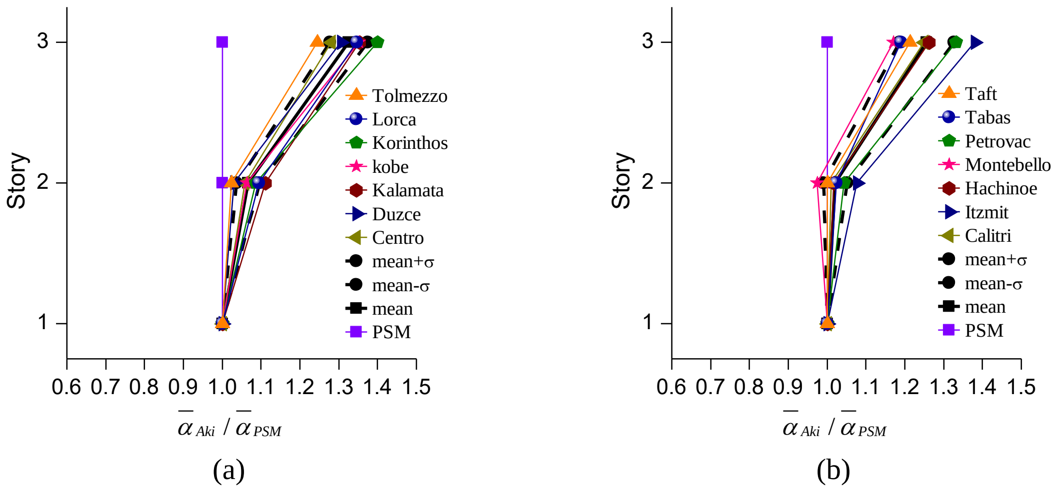
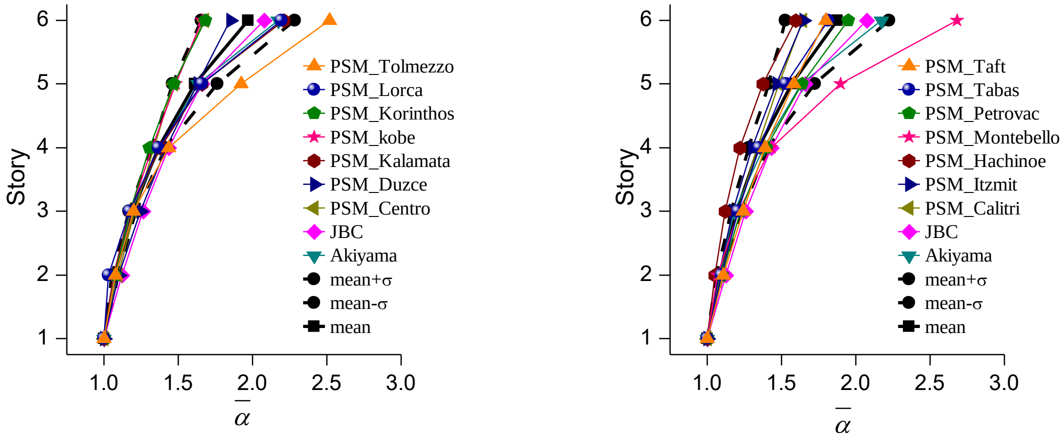


Figure 2. $\overline{\alpha}_{Aki,i}$ normalized by $\overline{\alpha}_{PSM,i}$ for the 3-story building using: (a) near field records; (b) far field records

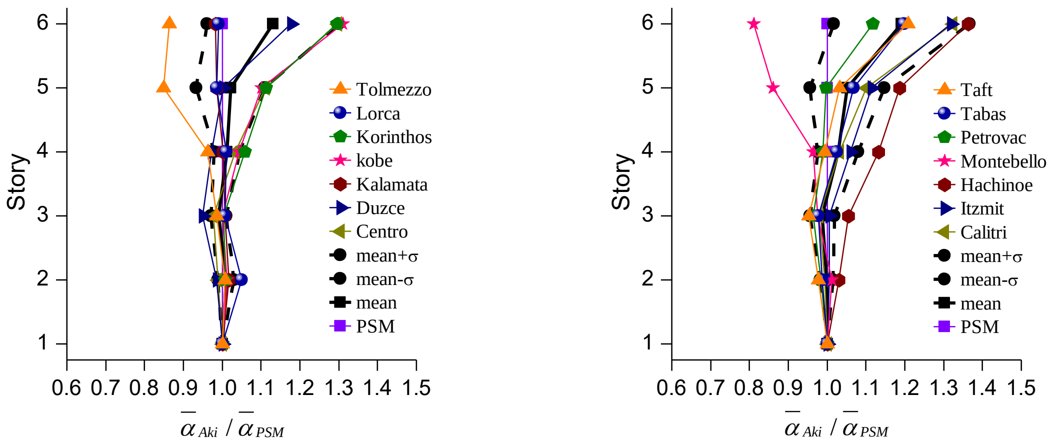
For the 6-story building, the results are lightly different. Figure 3 shows that even though the Akiyama and the JBC distributions provide values that are larger than the mean values obtained with the PSM approach, the observed difference is not significant. The value of σ is again larger for the far field than the near field records. It is worth emphasizing that differences are meaningful only in the upper third of the building height (starting from the 4-th story, in particular), as also noted Akiyama (1980), that is, where the response of the building is more significantly influenced by the higher modes of vibration.



(a) (b)

Figure 3. $\overline{\alpha}_i$ obtained for the 6-story building using: (a) near field records; (b) far field records

Figure 4 shows the ratio between $\overline{\alpha}_{Aki,i}$ and $\overline{\alpha}_{PSM,i}$. For the near field records, the higher deviation of the mean value of the ratio is larger at the top story, being equal to 15%. For the far field records the value is lightly larger, being equal to 20%. However, differences at intermediate stories are more significant, especially in the case of the far field records.



(a) (b)

Figure 4. $\overline{\alpha}_{Aki,i}$ normalized by $\overline{\alpha}_{PSM,i}$ for the 6-story building using: (a) near field records; (b) far field records

4.5 Distribution of damage

Figure 5 and Figure 6 show the damage distribution obtained with the Akiyama's approach, $\eta_{Aki,i}$, normalized by that obtained with the PSM approach, $\eta_{PSM,i}$. It can be observed that by using the Akiyama's approach, damage concentrates at the lower stories in the case of the 3-story building, especially for the near field records (see Figure 5). This is due to the fact that Akiyama's approach tends to overestimate the required lateral strength in the upper stories. This trend is not so evident in the case of 6-story building (see Figure 6) because of the influence of the higher modes of vibration.

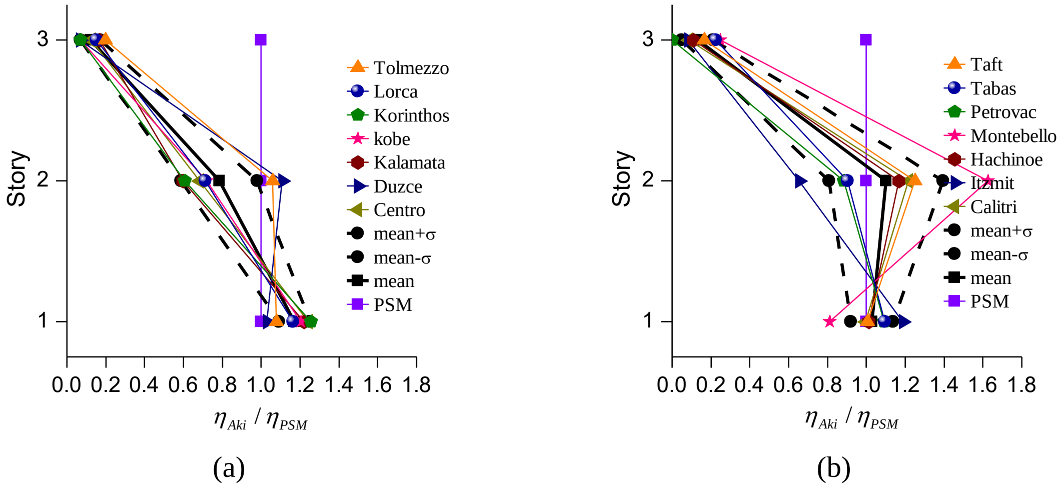


Figure 5. $\eta_{Aki,i}$ normalized by $\eta_{PSM,i}$ for the 3-story building using: (a) near field records; (b) far field records

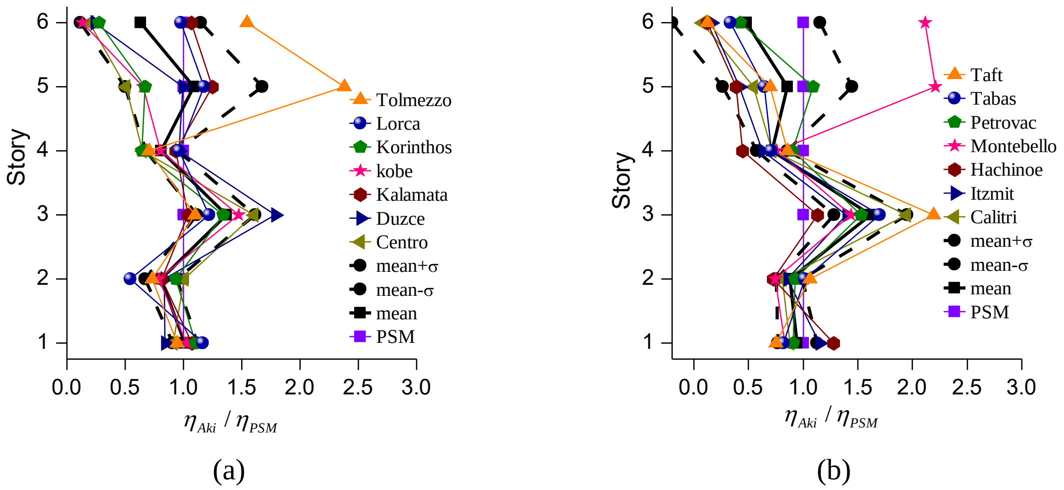


Figure 6. $\eta_{Aki,i}$ normalized by $\eta_{PSM,i}$ for the 6-story building using: (a) near field records; (b) far field records

Table 2 and Table 3 report the coefficient of variation (COV) the damage distribution expressed in terms of η_i. COV_Aki, COV_JBC and COV_PSM denote the values of COV obtained with $\overline{\alpha}_{Aki,i}$, $\overline{\alpha}_{JBC,i}$ and $\overline{\alpha}_{PSM,i}$, respectively. The mean and the standard deviation of COV with respect to the ground motion variability are also included in the tables.

It can be noted that by using the Akiyama's approach larger values of COV are obtained, regardless of the considered exciting ground motion or building. The values obtained by applying the PSM approach are significantly lower than those obtained with both the Akiyama's approach and the JBC.

Table 2. COV of η_i for near field records

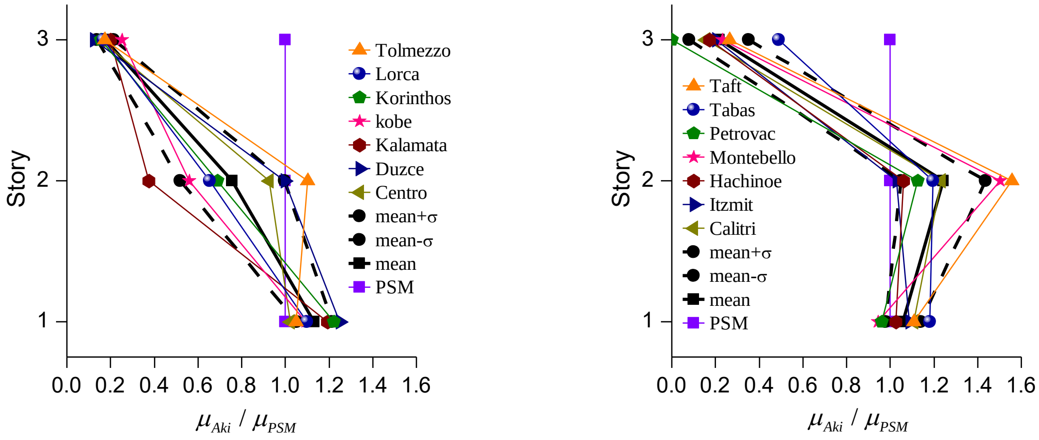
COV	Centro	Duzce	Kalamata	Kobe	Korinthos	Lorca	Tolmezzo	Mean	σ
3-Story									
COV_Aki	0.70	0.64	0.65	0.72	0.76	0.64	0.52	0.66	0.07
COV_JBC	0.61	0.51	0.64	0.66	0.74	0.59	0.41	0.59	0.10
COV_PSM	0.04	0.05	0.01	0.03	0.02	0.04	0.01	0.03	0.01
6-Story									
COV_Aki	0.62	0.48	0.12	0.50	0.42	0.24	0.47	0.41	0.15
COV_JBC	0.36	0.33	0.31	0.42	0.47	0.30	0.55	0.39	0.09
COV_PSM	0.13	0.02	0.02	0.03	0.03	0.04	0.00	0.04	0.04

Table 3. COV of η_i for far field records

COV	Calitri	Itzmit	Hachinoe	Montebello	Petrovac	Tabas	Taft	Mean	σ
3-Story									
COV_Aki	0.64	0.70	0.61	0.63	0.72	0.49	0.64	0.63	0.07
COV_JBC	0.49	0.66	0.46	0.38	0.69	0.31	0.49	0.48	0.13
COV_PSM	0.01	0.01	0.02	0.00	0.02	0.02	0.01	0.01	0.01
6-Story									
COV_JBC	0.68	0.57	0.66	0.45	0.34	0.51	0.66	0.55	0.12
COV_Ec8	0.54	0.58	0.94	0.58	0.19	0.21	0.34	0.48	0.24
COV_PSM	0.06	0.06	0.08	0.09	0.01	0.06	0.03	0.06	0.03

4.6 Distribution of inelastic deformation

Figure 7 and Figure 8 show the maximum inelastic deformation ratio obtained with the Akiyama's approach, $\mu_{Aki,i}$, normalized by that obtained with the PSM approach, $\mu_{PSM,i}$.



(a) (b)

Figure 7. $\mu_{Aki,i}$ normalized by $\mu_{PSM,i}$ for the 3-story building using: (a) near field records; (b) far field records

For the 3-story building (see Figure 7), the $\mu_{PSM,i}$ values at the upper stories are significantly lower than those of $\mu_{Aki,i}$. For the 6-story building (see Figure 8) such differences between $\mu_{PSM,i}$ and $\mu_{Aki,i}$ are larger both at intermediate and upper stories.

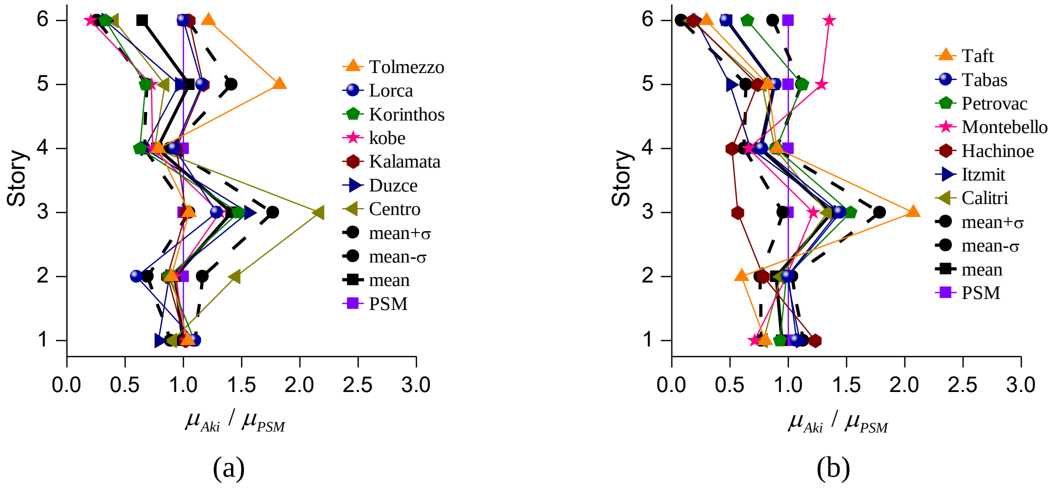


Figure 8. $\mu_{Aki,i}$ normalized by $\mu_{PSM,i}$ for the 6-story building using: (a) near field records; (b) far field records

5. CONCLUSIONS

A new procedure to obtain the optimal lateral shear distribution of a structure subjected to a given ground motion is presented in this study. The procedure uses the Pattern Search Method (PSM) approach for minimizing the variation of the damage distribution across the stories. The procedure involves iterative non-linear time history analyses with MDOF lumped-mass models of the structure until an even distribution of damage among the stories is attained. Damage in a given story is characterized in terms of the amount of energy dissipated through plastic deformations normalized by the product of the yield shear force and the yield displacement of the story. The study shows that the proposed procedure provides a distribution of lateral strength that significantly reduces the COV of the damage distribution among the stories that derives from a lateral strength distribution determined according to the proposal of Akiyama or that by the Japanese Building Code.

6. ACKNOWLEDGMENTS

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APPENDIX

The records used in this study are reported in the following table:

Table 4. Near and far field records used in this study

Near Field					Far Field				
Earthquak e	**Station**	**Countr y**	**Yea r**	**PGA (cm^2/s)**	**Earthquak e**	**Station**	**Countr y**	**Yea r**	**PGA (cm^2/s)**
El Centro	El Centro	EE.UU	1940	341.3	Itzmit	Duzce	Turkey	1999	303.8
Hyogo-k.N.	Kobe	Japan	1995	820.3	Northridge	Montebell o	EE.UU	1994	163.3
Lorca	Lorca	Spain	2011	325.8	Montenegro	Petrovac	Mont.	1979	445.3
Friuli	Tolmezz o	Italy	1976	349.9	Tokachi-Oki	Hachinoe	Japan	1968	224.4
Alkion	Korintho s	Greece	1981	225.7	Kern County	Taft	EE.UU	1952	152.9
Duzce	Duzce	Turkey	1999	369.9	Campano Luc.	Calitri	Italy	1980	155.0
Kalamata	Kalamata	Greece	1986	327.5	Tabas	Tabas	Iran	1978	908.3