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Toward more rational criteria for determination of design earthquake forces

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Abstract

The preliminary design of most buildings is based on equivalent static forces specified by the governing building code. The height wise distribution of these static forces seems to be based implicitly on the elastic vibration modes. Therefore, the employment of such a load pattern in seismic design of normal structures does not guarantee the optimum use of materials. This paper presents a new method for optimization of dynamic response of structures subjected to seismic excitation. This method is based on the concept of uniform distribution of deformation. In order to obtain the optimum distribution of structural properties, an iterative optimization procedure has been adopted. In this approach, the structural properties are modified so that inefficient material is gradually shifted from strong to weak areas of a structure. This process is continued until a state of uniform deformation is achieved. It is shown that the seismic performance of such a structure is optimal, and behaves generally better than those designed by conventional methods. By conducting this algorithm on shear-building models with various dynamic characteristics subjected to 20 earthquake ground motions, more adequate load patterns are introduced with respect to the period of the structure and the target ductility demand.

Keywords: Ductility demand; Multi-degree of freedom systems; Optimum strength and stiffness distribution; Seismic codes; Performance-based design

1. Introduction

Seismic design is currently based on force rather than displacement, essentially as a consequence of the historical developments of an understanding of structural dynamics and, more specifically, of the response

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of structures to seismic actions and the progressive modifications and improvement of seismic codes worldwide. Although design procedures have become more rigorous in their application, this basic force-based approach has not changed significantly since its inception in the early 1900s. Consequently, the seismic codes are generally regarding the seismic effects as lateral inertia forces. The height wise distribution of these static forces (and therefore, stiffness and strength) seems to be based implicitly on the elastic vibration modes (Green, 1981; Hart, 2000).

Recent design guidelines, such as FEMA 356 and SEAOC Vision 2000, place limits on acceptable values of response parameters, implying that exceeding of these acceptable values represent violation of a performance objective. Further modifications to the preliminary design, aiming to satisfy the performance objectives could lead to some alterations of the original distribution pattern of structural properties. As structures exceed their elastic limits in severe earthquakes, the use of inertia forces corresponding to elastic modes may not lead to the optimum distribution of structural properties. Many experimental and analytical studies have been carried out to investigate the validity of the distribution of lateral forces according to seismic codes. Lee and Goel (2001) analyzed a series of 2–20 story frame models subjected to various earthquake excitations. They showed that in general there is a discrepancy between the earthquake induced shear forces and the forces determined by assuming distribution patterns. The consequences of using the code patterns on seismic performance have been investigated during the last decade (Anderson et al., 1991; Gilmore and Bertero, 1993; Martinelli et al., 2000). Chopra (2001) evaluated the ductility demands of several shear-building models subjected to the El-Centro Earthquake of 1940. The relative story yield strength of these models was chosen in accordance with the distribution patterns of the earthquake forces specified in the Uniform Building Code (UBC). It was concluded that this distribution pattern does not lead to equal ductility demand in all stories, and that in most cases the ductility demand in the first story is the largest of all stories. Moghaddam (1995, 1999) proportioned the relative story yield strength of a number of shear building models in accordance with some arbitrarily chosen distribution patterns as well as the distribution pattern suggested by the UBC 1997. It is concluded that: (a) the pattern suggested by the code does not lead to a uniform distribution of ductility, and (b) a rather uniform distribution of ductility with a relatively smaller maximum ductility demand can be obtained from other patterns. These findings have been confirmed by further investigations (Moghaddam et al., 2003; Moghaddam and Hajirasouliha, 2004; Karami Mohammadi et al., 2004), and led to the development of a new concept: optimum distribution pattern for seismic performance that is discussed in this paper. An effective optimization algorithm is developed to find more rational criteria for determination of design earthquake forces. It is shown that using adequate load patterns could result in a reduction of ductility demands and a more uniform distribution of deformations.

2. Modeling and assumptions

Among the wide diversity of structural models that are used to estimate the non-linear seismic response of building frames, the shear-beam is the one most frequently adopted. In spite of some drawbacks, it is widely used to study the seismic response of multi-story buildings because of simplicity and low computer time consumption (Diaz et al., 1994). Lai et al. (1992) have investigated the reliability and accuracy of such shear-beam models.

One hundred and twenty shear-building models of 10-story structures with fundamental period varying from 0.1 s to 3 s, and target ductility demand equal to 1, 1.5, 2, 3, 4, 5, 6 and 8 have been used in the present study. It should be noted that the range of the fundamental period considered in this study is wider than that of the real structures to cover all possibilities. In the present shear-building models, each floor is assumed as a lumped mass that is connected by perfect elastic–plastic shear springs. The total mass of the structure is distributed uniformly over its height as shown in Fig. 1. The Rayleigh damping is adopted with

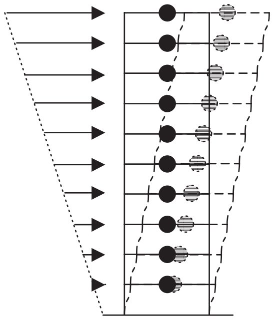

Fig. 1. Typical 10-story shear building model.

a constant damping ratio 0.05 for the first few effective modes. In all MDOF models, lateral stiffness is assumed as proportional to shear strength at each story, which is obtained in accordance with the selected lateral load pattern.

Twenty selected strong ground motion records are used for input excitation as listed in Table 1. All of these excitations correspond to the sites of soil profiles similar to the S_D type of UBC 1997 and are recorded in a low to moderate distance from the epicenter (less than 45 km) with rather high local magnitudes (i.e. $M > 6$). Due to the high intensities demonstrated in the records, they are used directly without being normalized.

The above-mentioned models are, then, subjected to the seismic excitations and non-linear dynamic analyses are conducted utilizing the computer program DRAIN-2DX (Prakash et al., 1992). For each earthquake excitation, the dynamic response of models with various fundamental periods and target ductility demands is calculated.

Table 1
Strong ground motion characteristics

	Earthquake	Station	*M*	PGA (g)	USGS soil
1	Imperial Valley 1979	H-E04140	6.5	0.49	C
2	Imperial Valley 1979	H-E04230	6.5	0.36	C
3	Imperial Valley 1979	H-E05140	6.5	0.52	C
4	Imperial Valley 1979	H-E05230	6.5	0.44	C
5	Imperial Valley 1979	H-E08140	6.5	0.45	C
6	Imperial Valley 1979	H-EDA360	6.5	0.48	C
7	Northridge 1994	CNP196	6.7	0.42	C
8	Northridge 1994	JEN022	6.7	0.42	C
9	Northridge 1994	JEN292	6.7	0.59	C
10	Northridge 1994	NWH360	6.7	0.59	C
11	Northridge 1994	RRS228	6.7	0.84	C
12	Northridge 1994	RRS318	6.7	0.47	C
13	Northridge 1994	SCE288	6.7	0.49	C
14	Northridge 1994	SCS052	6.7	0.61	C
15	Northridge 1994	STC180	6.7	0.48	C
16	Cape Mendocino 1992	PET000	7.1	0.59	C
17	Duzce 1999	DZC270	7.1	0.54	C
18	Lander 1992	YER270	7.3	0.25	C
19	Parkfield 1966	C02065	6.1	0.48	C
20	Tabas 1978	TAB-TR	7.4	0.85	C

3. Conventional lateral loading patterns

In most seismic building codes (Uniform Building Code, 1997; NEHRP Recommended Provisions, 1994; ATC-3-06 Report, 1987; ANSI-ASCE 7-95, 1996; Iranian Seismic Code, 1999), the height wise distribution of lateral forces is to be determined from the following typical relationship:

$$F_i = \frac{w_i h_i^k}{\sum_{j=1}^{N} w_j h_j^k} \cdot V, \quad (1)$$

where w_i and h_i are the weight and height of the ith floor above the base, respectively; N is the number of stories; and k is the power that differs from one seismic code to another. In some provisions such as NEHRP-94 and ANSI/ASCE 7-95, k increases from 1 to 2 as period varies from 0.5 to 2.5 s. However, in some codes such as UBC-97 and Iranian Seismic Code (1999), the force at the top floor (or roof) computed from Eq. (1) is increased by adding an additional force $F_t = 0.07TV$ for a fundamental period T of greater than 0.7 s. In such a case, the base shear V in Eq. (1) is replaced by $(V - F_t)$.

Next we investigate the adequacy of conventional loading patterns concerning the fundamental period of the structures and ductility demand imposed by the ground motion.

4. Adequacy of conventional loading patterns

It is generally endeavored to induce a status of uniform deformation throughout the structure to obtain an optimum design as in Gantes et al. (2000). Karami Mohammadi et al. (2004) showed that for a given earthquake, the weight of seismic resistant system required to reach to the prescribed target ductility is correlated with the cov, the coefficient of variation, of the story ductility demands and the two minimize simultaneously. Therefore, they concluded that the cov of ductilities could be used as a means of assessing the adequacy of design load patterns to optimum use of material.

To investigate the efficiency of conventional loading patterns to lead to the equal ductility demands in all stories, shear-building models with various periods and ductility demands are subjected to 20 selected ground motions (Table 1). In each case, strength and stiffness are distributed within the stories according to the lateral load pattern suggested by UBC 1997. Subsequently, the stiffness pattern is scaled to adjust the prescribed fundamental period. Maximum ductility demand is then calculated by performing non-linear dynamic analysis for the given exaction. By an iterative procedure, the total strength of the model is scaled (without changing its distribution pattern) until maximum ductility demand gets to the target value with less than 1% error. Finally, cov of the story ductility demands is calculated for each case. Fig. 2 illustrates the average of cov obtained in 20 earthquakes versus fundamental period and for various target ductility demands. Based on the results presented in Fig. 2, it is concluded that:

1. Using the strength pattern suggested by UBC 1997 leads to an almost uniform distribution of ductility demands for the structures within the linear range of behaviour. However, the adequacy of conventional load patterns is reduced in non-linear ranges of vibration. It is shown that increasing the target ductility is always accompanied by increasing in cov of story ductility demands.
2. The cov of story ductility demands are especially large in the structures with both short fundamental period and large target ductility demand. It implies that using the conventional loading patterns to design this type of structures do not lead to the satisfactory use of material incorporated in the building construction.
3. In the structures with long fundamental period (i.e. greater than 0.5 s), cov of ductilities is more dependent on the maximum ductility demand than the fundamental period of the structure. However, seismic loading patterns suggested by most seismic codes are not a function of the target ductility.

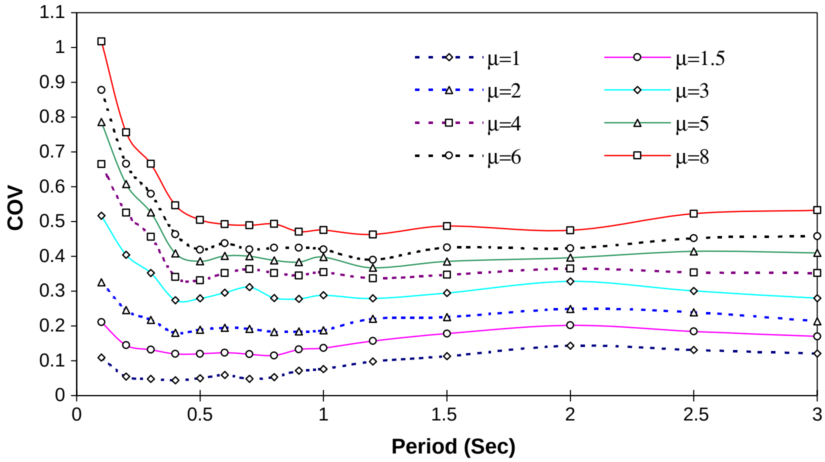

Fig. 2. Cov of story ductility demands, average of 20 earthquakes.

4. When the structures behave linearly or nearly linearly (i.e. ductilities smaller than two), increasing in the fundamental period is generally accompanied by increasing in the cov of story ductility demands. This could be explained by increasing the influence of higher modes as the period of vibration increases.

5. Concept of theory of uniform deformation

As discussed before, the use of distribution patterns for lateral seismic forces suggested by codes does not guarantee the optimum performance of structures. Current study indicates that during strong earthquakes the deformation demand in structures does not vary uniformly. Therefore, it can be concluded that in some parts of the structure, the deformation demand does not reach the allowable level of seismic capacity, and therefore, the material is not fully exploited. If the strength of these strong parts decreases, the deformation would be expected to increase (Riddell et al., 1989; Vidic et al., 1994). Hence, if the strength decreases incrementally, we should eventually obtain a status of uniform deformation. At this point the material capacity is fully exploited. As the decrease of strength is normally obtained by the decrease of material, a structure becomes relatively lighter as deformation is distributed more uniformly. Therefore, in general it can be concluded that a status of uniform deformation is a direct consequence of the optimum use of material. This is considered as the *Theory of Uniform Deformations* (Moghaddam and Hajirasouliha, 2004). This theory is the basis of the studies presented in this paper.

6. Optimum distribution of design seismic forces

The theory of uniform deformation can be easily adapted for evaluation of optimum patterns for shear buildings. It should be noted that there is a unique relation between the distribution pattern of lateral seismic forces and the distribution of strength (as the strength at each floor is obtained from the corresponding story shear force). Hence, for shear buildings, we can determine the optimum pattern for distribution of seismic lateral loads instead of distribution of strength. Let us assume that we want to evaluate the most appropriate lateral load pattern to design a 10-story shear building (Fig. 1) with a fundamental period of 1 s, so that it can sustain the Northridge earthquake 1994 (CNP196) without exceeding a maximum story ductility demand of 4. The following optimization procedure is used:

1. Arbitrary primary patterns are assumed for height wise distribution of strength and stiffness. However, for shear building models we can assume that these two patterns are similar, and therefore, an identical pattern is assumed for both strength and stiffness. Here, the uniform pattern in is chosen for the primary distribution of strength and stiffness.
2. The stiffness pattern is scaled to attain a fundamental period of 1 s.
3. The structure is subjected to the given excitation, and the maximum story ductility is calculated, and compared with the target value. Consequently, the strength is scaled (without changing the primary pattern) until the maximum deformation demand reaches the target value. This pattern is regarded as a feasible answer, and referred to as the first acceptable pattern. For the above example, story strength and maximum story ductility corresponding to the first feasible answer are given in Table 2.
4. The cov (coefficient of variation) of story ductility distribution within the structure is calculated. The procedure continues until cov decreases down to an acceptable level. The cov of the first feasible pattern was determined as 0.719. The cov is high, and the analysis continues.
5. At this stage the distribution pattern is modified. Using the theory of uniform deformation, the inefficient material should be reduced to obtain an optimum structure. To accomplish this, stories where the ductility demand is less than the target values are identified and weakened by reducing strength and stiffness. Experience shows that this alteration should be applied incrementally to obtain convergence in numerical calculations. Hence, the following equation is used in the present studies:

$$[V_i]_{n+1} = [V_i]_n \left[\frac{\mu_i}{\mu_t}\right]^{\alpha}, \tag{2}$$

   where μ_i is the ductility demand at ith story, and μ_t is the target ductility assumed as equal to 4 for all stories. V_i is the shear strength of the ith story. n denotes the step number. α is the convergence coefficient ranging from 0 to 1. For the above example, an acceptable convergence has been obtained for a value of 0.2 for α. Now, a new pattern for height wise distribution of strength and stiffness is obtained. The procedure is repeated from step 2 until a new feasible pattern is obtained. It is expected that the cov of ductility distribution for this pattern is smaller than the corresponding cov for the previous pattern. This procedure is iterated until cov becomes small enough, and a status of rather uniform ductility demand prevails. The final pattern is considered as practically optimum.

Table 2
The preliminary and final arrangement of strength and stiffness

Story	Preliminary arrangement		Final arrangement	
	Story strength (ton f)	Story ductility	Story strength (ton f)	Story ductility
1	1753	4	1435	3.98
2	1753	2.46	1351	3.99
3	1753	1.78	1229	3.99
4	1753	1.41	1089	4.00
5	1753	1.38	953	4.00
6	1753	1.19	808	3.99
7	1753	0.98	662	3.99
8	1753	0.82	512	3.99
9	1753	0.59	371	3.97
10	1753	0.31	204	3.99
Cov		0.719		0.002
Total strength	17,532		8614	

Cov: Coefficient of variation.

Story ductility pattern for preliminary and final answers are compared in Table 2. According to the results, the efficiency of utilizing this method to reach to the structure with uniform ductility demand distribution is emphasized. Fig. 3 illustrates the variation of cov and total strength from first feasible answer toward the final answer. Fig. 3 shows the efficiency of the proposed method that resulted in reduction of total strength by 41% in only five steps. It is also shown in this figure that proposed method has good capability to convergence to the optimum answer without any oscillation. It can be noted from Fig. 3 that decreasing in cov is always accompanied by a decreasing in total strength. Here the total strength is in proportion to the total weight of the seismic resisting system. These results are in agreement with the *Theory of Uniform Deformation*.

Table 2 shows the results of analysis for the first and final step. The height wise distribution of strength can be converted to the height wise distribution of lateral forces. Such pattern may be regarded as the optimum pattern of seismic forces for the given earthquake. As shown in Fig. 4, this would enable the comparison of this optimum pattern with the conventional lateral loading patterns suggested by seismic design codes. The results indicate that to improve the performance under this specific earthquake, the frame should be designed in compliance with a new load pattern different from the conventional UBC pattern.

As described before, an initial strength distribution is necessary to begin the optimization algorithm. In order to investigate the effect of this initial load (or strength) pattern on the final result, for the previous example four different initial load patterns have been considered:

1. A concentrated load at the roof level.
2. Triangular distribution similar to the UBC code of 1997.
3. Rectangular distribution.
4. An inverted triangular distribution with the maximum lateral load at the first floor and the minimum lateral load at the roof level.

For each case, the optimum lateral load pattern was derived for Northridge 1994 (CNP196) event. The comparison of the optimum lateral load pattern of each case is depicted in Fig. 5. As shown in this figure, the optimum load pattern is not dependent on the initial strength pattern; however the speed of conver-

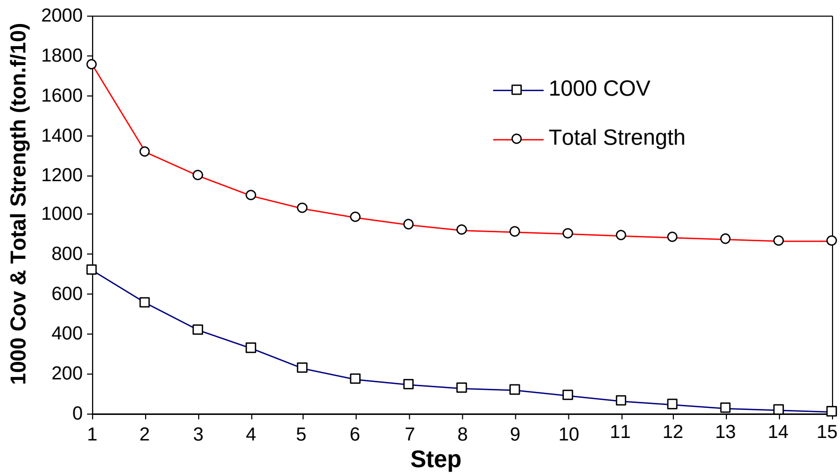

Fig. 3. Cov of story ductility demands and total story strength for feasible answers, 10-story shear building with $T = 1$ s and $\mu_{ti} = 4$, Northridge 1994 (CNP196).

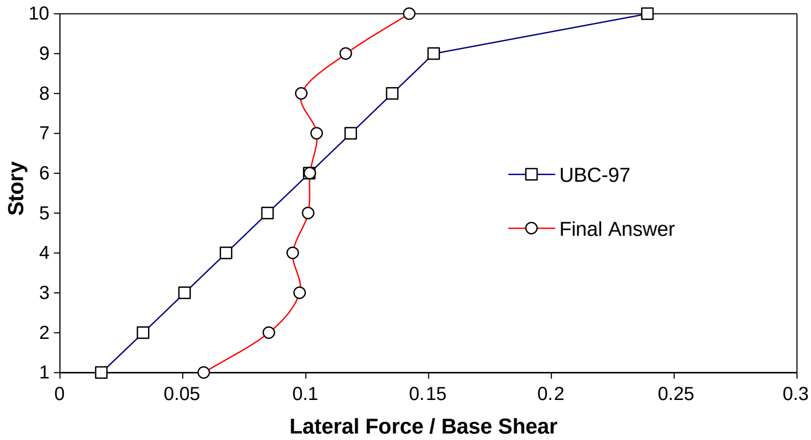

Fig. 4. Comparison of UBC-97 and optimum lateral force distribution, 10-story shear building with $T = 1$ s and $\mu_{ti} = 4$, Northridge 1994 (CNP196).

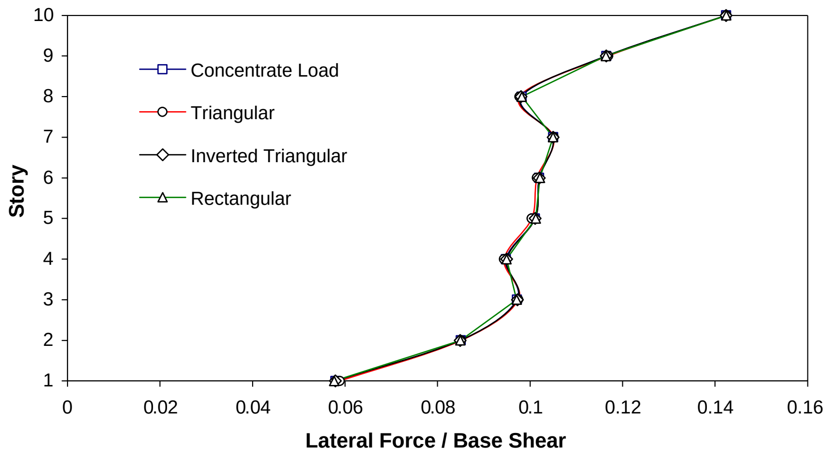

Fig. 5. Optimum load pattern for different initial strength distributions, 10-story shear building with $T = 1$ s and $\mu_{ti} = 4$, Northridge 1994 (CNP196).

gence is to some extent dependant on the initial strength pattern. This conclusion has been confirmed by further analyses on different models and ground motions.

Using the optimization method described above, the adequacy of optimum loading patterns to reduce required structural weight is examined.

7. Adequacy of optimum loading patterns

To investigate the validity and accuracy of the proposed optimization method, the foregoing procedure has been applied to find the optimum pattern for 120 shear-building models with different fundamental periods and target ductility demands subjected to 20 selected earthquakes. In this study, the maximum story ductility is considered as the failure criterion, implying that exceeding of the target ductility represents violation of the performance objective. Therefore, according to the *Theory of Uniform Deformation*, it is expected that seismic performance be improved by a uniform distribution of ductility demands. It is demonstrated in previous section that the proposed method is very efficient to reach to the uniform distribution of ductility demands.

To evaluate the weight of the seismic resistant system for MDOF structures, it is assumed that the weight of lateral-load-resisting system at each story, W_{Ei}, is proportional to the story shear strength, V_i. Therefore, the total weight of the seismic resistant system, W_E, can be calculated as:

$$W_E = \sum_{i=1}^{n} W_{Ei} = \sum_{i=1}^{n} \lambda \cdot V_i = \lambda \cdot \sum_{i=1}^{n} V_i, \tag{3}$$

where λ is the proportioning coefficient. According to Eq. (3), the ratio of total structural weight for the UBC designed models to the optimum models, $(W_E)_{UBC}/(W_E)_{opt}$, has been calculated for all cases. Fig. 6 shows the median values of $(W_E)_{UBC}/(W_E)_{opt}$ as a function of ductility demand, and for different fundamental periods. This figure has been obtained by averaging the responses of 20 earthquakes.

According to the results illustrated in Fig. 6, it is concluded that:

1. Having the same period and ductility demand, structures designed according to the optimum load pattern always have less structural weight compare to those designed conventionally. Therefore, the adequacy of optimum loading patterns is emphasized.
2. In the elastic range of vibration ($\mu = 1$), the total structural weights required for the models designed according to the UBC load pattern are in average 10% above the optimum value. Hence, it can be concluded that for practical purposes, using the conventional loading patterns is satisfying within the linear range of vibrations.
3. Increasing the ductility demand is generally accompanied by increasing in the structural weight required for the conventionally designed models compare to the optimum ones. This implies that conventional loading patterns loose their efficiency in non-linear ranges of vibration. It is illustrated that for conventionally designed structures with high levels of ductility demand, the required structural weight could be more than 50% above the optimum weight.

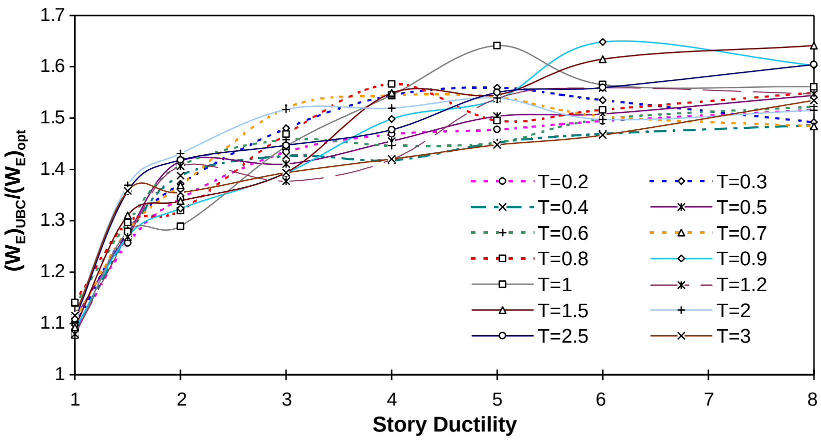

Fig. 6. The ratio of total structural weight for the UBC designed models to the optimum models, $(W_E)_{UBC}/(W_E)_{opt}$, average of 20 earthquakes.

8. More adequate loading patterns

It is well known that there are many uncertainties in seismic loading and seismic design of structures. One of the most random parameters is the seismic event that might occur in a place; therefore, the selection of a ground motion for seismic design of a structure might be at great task. As described before, to improve the performance under a specific earthquake, structure should be designed in compliance with an optimum load pattern different from the conventional patterns. This optimum pattern depends on the earthquake, and therefore, it varies from one earthquake to another. However, there is no guarantee that the frame will experience seismic events, which are the same as the design ground motion. While each of the future events will have its own signature, it is generally acceptable that they have relatively similar characteristics. Accordingly, it seems that the model designed with optimum load pattern is capable to reduce the maximum ductility experienced by the model after similar ground motions. It can be concluded that for general design proposes, the design earthquakes must be classified for each structural performance category and then more adequate loading patterns must be found by averaging optimum patterns corresponding to every one of the earthquakes in each group. To verify this assumption, 20 strong ground motion records with the similar characteristics, as listed in Table 1, were selected. Time history analyses have been performed for all earthquakes and the corresponding optimum pattern has been found for shear-building models with different fundamental periods and target ductility demands. Consequently, 2400 optimum load patterns have been determined at this stage. For each fundamental period and ductility demand a specific matching load distribution has been obtained by averaging the results for all earthquakes. These average distribution patterns used to design the given shear building models. Then the response of the designed models to each of the 20 earthquakes was calculated. In Fig. 7, the ratio of required structural weight to the optimum weight, $(W_E)/(W_E)_{opt}$, for the models designed with the average pattern is compared with those designed conventionally. This figure has been obtained by averaging the responses of shear-building models with fundamental period of 0.1–3 s, subjected to 20 earthquake ground motions. It is illustrated in Fig. 7, having the same period and ductility demand, structures designed according to the average of optimum load patterns require less structural weight compare to those designed conventionally. The efficiency of the average load pattern is more obvious for the models with high ductility demand. As shown in Fig. 7, using this pattern in high levels of ductility demand resulted in more than 30% reduction in the total structural weight

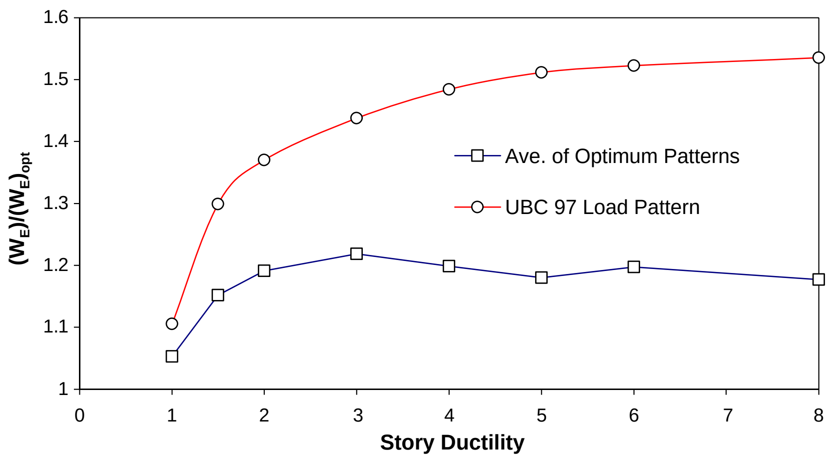

Fig. 7. The ratio of required structural weight to the optimum weight, $(W_E)/(W_E)_{opt}$, for the models designed with the average pattern and those designed conventionally, average of 20 earthquakes.

compared with conventionally designed models. It can be concluded that the proposed approach can be utilized efficiently for any set of earthquakes with similar characteristics.

As mentioned above, using the average of the optimum load patterns results in a better seismic performance in comparison with the conventional patterns. Such a load pattern is designated as 'more adequate load pattern'. At present, the seismic load patterns suggested by most seismic codes do not depend on the ductility. However, the present study shows that more adequate loading patterns are a function of both the period of the structure and the target ductility demand. According to the results of this study, more adequate loading patterns could be illustrated in four different categories as follows:

8.1. Triangular load pattern

As described before, triangular load pattern is suggested by most of the seismic building codes. It is shown in Fig. 8, in average, this load pattern is close to the optimum pattern corresponding to the models with elastic behavior and fundamental period shorter than 1 s. This conclusion is also in agreement with the results shown in Fig. 2. It can be noted from Fig. 8 that, in general, increasing the fundamental period results in increasing the loads at the top stories. This could be explained by increasing the influence of higher modes as the period of vibration increases.

8.2. Trapezoid load pattern

As shown in Fig. 9, trapezoid load pattern is appropriate for models with fundamental period shorter than 0.5 s and small target ductility demand (i.e. $\mu_t \leqslant 3$). It can be noted from Fig. 9 that increasing the ductility demand results in decreasing the loads at the top stories and increasing the loads at the lower stories. It is also shown in Fig. 9 that increasing the fundamental period is generally accompanied by increasing the loads at the top stories. By increasing the ductility demand, this load pattern converts to the parabolic pattern.

8.3. Parabolic load pattern

According to the results of this study, more adequate load patterns are in parabolic shape for a wide range of periods and ductility demands. It seems that the rectangular pattern accompanied by a concen-

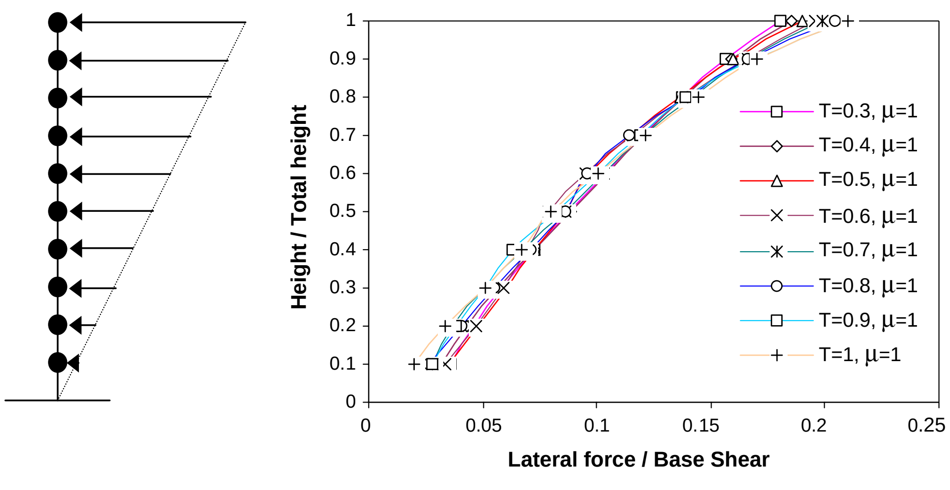

Fig. 8. Triangular load patterns.

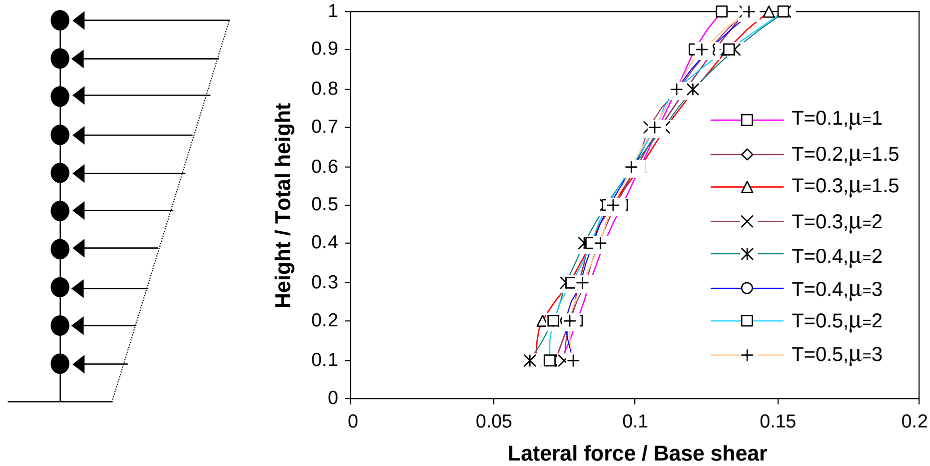

Fig. 9. Trapezoid load patterns.

trated force at the top floor, which is suggested by Karami Mohammadi et al. (2004), also belongs to this category. As shown in Fig. 10, in general, parabolic load patterns are appropriate to design three categories of structures:

- Structures with fundamental period shorter than 0.5 s and high ductility demand ($\mu_t \geqslant 3$).
- Structures with fundamental period longer than 1 s and small ductility demand ($\mu_t \leqslant 3$).
- Structures with fundamental period varying from 0.5 s to 1 s.

As Fig. 10 indicates, for the same ductility demand, loads at the top stories are increasing as the fundamental period of the structure increases. It is also shown in Fig. 10 that increasing the ductility demand results in decreasing the loads at the top stories and increasing the loads at the lower stories. For higher levels of ductility demand, optimum load patterns corresponding to the models with fundamental period longer than 1 s, move toward the hyperbolic pattern.

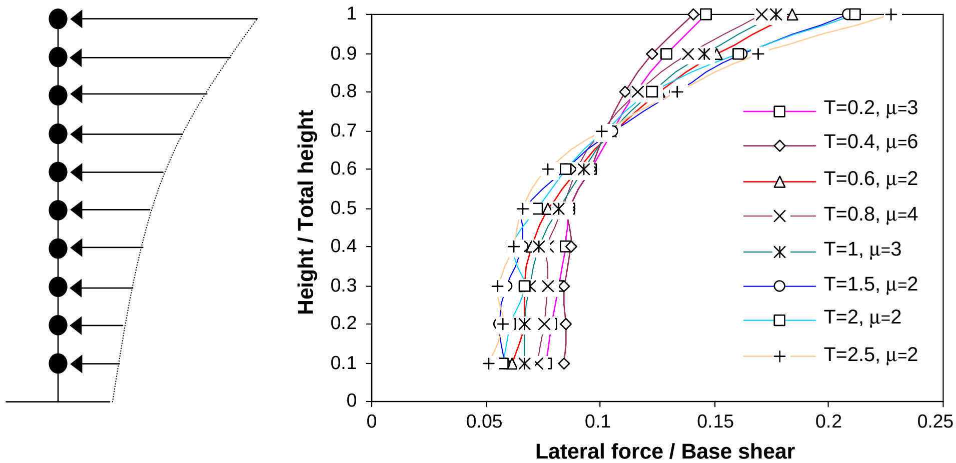

Fig. 10. Parabolic load patterns.

8.4. Hyperbolic load pattern

As illustrated in Fig. 11, more adequate load patterns are in hyperbolic shape for structures with high levels of ductility demand ($\mu_t \geqslant 3$) and fundamental period longer than 1 s. It is also shown in this figure that increasing the ductility demand results in decreasing the loads at the top stories and increasing the loads at the lower stories.

It can be noted from Fig. 11 that for the optimum loading patterns corresponding to the structures with long periods and high levels of ductility demand ($T \geqslant 2.5$ s and $\mu_t \geqslant 5$), loads assigned to the lower stories could be greater than those assigned to the top stories. Therefore in this case, optimum loading patterns are completely different with the lateral loading patterns suggested by the seismic codes (e.g. triangular pattern). However, it should be mentioned that this condition is beyond the most practical designs.

While more adequate load patterns could be very different in their shape, it is possible to establish some general rules. According to the illustrated results, increasing the fundamental period is usually accompanied by increasing the loads at the top stories caused by the higher mode effects. On the other hand, in general, increasing the ductility demand results in decreasing the loads at the top stories and increasing the loads at the lower stories. By changing both the fundamental period of the structure and the target ductility demand, these two contrary effects are combined with each other. It should be noted that there is not a definite boundary between different categories of more adequate load patterns and they convert to each other very smoothly.

To summarize the above discussions, more adequate load patterns are presented in Table 3 with respect to the fundamental period of the structure and the target ductility demand. More adequate load patterns introduced in this paper are based on the 20 selected earthquakes, as listed in Table 1. However, discussed

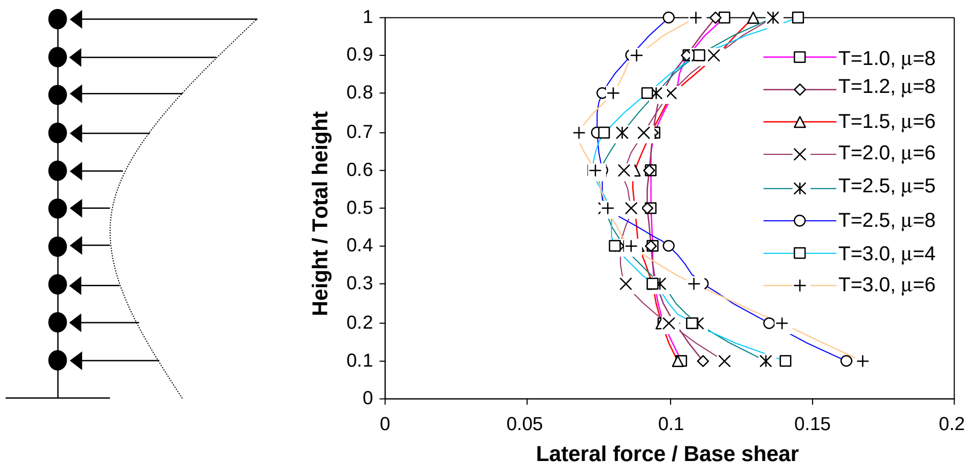

Fig. 11. Hyperbolic load pattern.

Table 3
More adequate load patterns with respect to the target ductility demand and the fundamental period of the structure

	$0.1 \leqslant T \leqslant 0.5$	$0.5 \leqslant T \leqslant 1$	$1 \leqslant T \leqslant 3$
$\mu_t = 1$	Triangular	Triangular	Parabolic
$1 < \mu_t \leqslant 3$	Trapezoid	Parabolic	Parabolic
$3 \leqslant \mu_t \leqslant 8$	Parabolic	Parabolic	Hyperbolic

observations are fundamental and similar conclusions have been obtained by further analyses on different models and ground motions (Hajirasouliha, 2004). It should be noted that the results cannot be directly applied to shear walls, as they behave substantially different from shear-building type of structures. The optimization method proposed in this paper, can be used for any set of earthquakes, and can provide an efficient optimum performance-based seismic design method for building structures. As we know, in performance-based design we consider multiple limit states (e.g. service event, rare event, very rare event). However, different events (earthquakes) would result in different optimum load distributions. In this case, it seems rational to consider the very rare event as the governing criterion for preliminary design, and control the design for other events.

9. Conclusions

1. This paper presents a new method for optimization of dynamic response of structures subjected to seismic excitation. This method is based on the concept of uniform distribution of deformation.
2. It is shown that using the load pattern suggested by seismic codes does not lead to a uniform distribution of deformation demand, and, it is possible to obtain uniform deformation by shifting the material from strong to weak parts. It has been shown that the seismic performance of such structure is optimal. Hence, it can be concluded that the condition of uniform deformation results in optimum use of material. This has been denoted as the *Theory of Uniform Deformation*.
3. By introducing an iterative method, *Theory of Uniform Deformation* has been adapted for optimum seismic design of shear buildings. It is concluded that this can efficiently provide an optimum design. It has been demonstrated that there is generally a unique optimum distribution of structural properties, which is independent of the seismic load pattern used for initial design.
4. For a set of earthquakes with similar characteristics, the optimum load-patterns were determined for a wide range of fundamental periods and target ductility demands. It is shown that, having the same story ductility demand, models designed according to the average of optimum load patterns have relatively less structural weight in comparison with those designed conventionally.
5. Considering the average of optimum patterns, more adequate load patterns have been introduced with respect to the fundamental period of the structure and the target ductility demand. The proposed patterns are illustrated in four categories including triangular pattern, trapezoid pattern, parabolic pattern and hyperbolic pattern. It is shown that, increasing the fundamental period is usually accompanied by increasing the loads at the top stories caused by the higher mode effects. Alternatively, increasing the ductility demand results in decreasing the loads at the top stories and increasing the loads at the lower stories.

References

Anderson, J.C., Miranda, E., Bertero, V.V., Kajima Research Team, 1991. Evaluation of the seismic performance of a thirty-story RC building, UCB/EERC-91/16, Earthquake Engineering Research Center, University of California, Berkeley.

ANSI-ASCE 7-95, 1996. Minimum Design Loads for Building and other Structures.

ATC-3-06 Report, 1987. Tentative provisions for the development of seismic regulations for buildings, San Francisco, California.

Chopra, A.K., 2001. Dynamics of Structures: Theory and Applications to Earthquake Engineering, second ed. Prentice Hall Inc., London.

Diaz, O., Mendoza, E., Esteva, L., 1994. Seismic ductility demands predicted by alternate models of building frames. Earthquake Spectra 10 (3), 465–487.

FEMA 356, 2000. Prestandard and commentary for the seismic rehabilitation of buildings. Federal Emergency Management Agency, Washington, DC.

Gantes, C.J., Vayas, I., Spiliopoulos, A., 2000. Optimum bending and shear stiffness distribution for performance based design of rigid and braced multi-story steel frames. Behavior of Steel Structures in Seismic Areas, 585–592.

Gilmore, T.A., Bertero, V.V., 1993. Seismic performance of a 30-story building located on soft soil and designed according to UBC 1991, UCB/EERC-93/04. Earthquake Engineering Research Center, University of California, Berkeley.

Green, N.B., 1981. Earthquake Resistant Building Design and Construction, second ed. Van Nostrand Reinhold Company, New York.

Hajirasouliha, I., 2004. Optimum strength distribution for seismic design of structures. D.Phil. thesis, Sharif University of Technology, Tehran, Iran.

Hart, G.C., 2000. Earthquake forces for the lateral force code. The Structural Design of Tall Buildings, 49–64.

Iranian Code for Seismic Resistant Design of Buildings, 1999. First ed., Building and Housing Research Center, Tehran.

Karami Mohammadi, R., El Naggar, M.H., Moghaddam, H., 2004. Optimum strength distribution for seismic resistant shear buildings. International Journal of Solids and Structures 41, 6597–6612.

Lai, M., Li, Y., Zhang, Ch., 1992. Analysis method of multi-rigid-body model for earthquake responses of shear-type structure. In: WCEE 10th Conference, Madrid, Spain, pp. 4013–4018.

Lee, S.S., Goel, S.C., 2001. Performance based seismic design of structures using target drift and yield mechanism. In: US Japan Seminar on Advanced Stability and Seismicity Concept for Performance Based Design of Steel and Composite Structures, Kyoto, Japan.

Martinelli, L., Perotti, F., Bozzi, A., 2000. Seismic design and response of a 14-story concentrically braced steel building. Behaviour of Steel Structures in Seismic Areas, 327–335.

Moghaddam, H., 1995. Earthquake Engineering, first ed. RTRC Publications, Tehran (in Persian).

Moghaddam, H., Esmailzadeh Hakimi, B., 1999. On the optimum seismic loading of multistory structures. In: 3rd International Conference on Seismology and Earthquake Engineering, Tehran, Iran, pp. 669–676.

Moghaddam, H., Hajirasouliha, I., 2004. A new approach for optimum design of structures under dynamic excitation. Asian Journal of Civil Engineering 5, 69–84.

Moghaddam, H., Hajirasouliha, I., Doostan, A., 2003. On the optimum strength distribution in seismic design of structures. In: Response of Structures to Extreme Loading (XL2003), Canada, Toronto.

NEHRP, 1994. Recommended Provisions for the Development of Seismic Regulation for New Buildings, Building Seismic Safety Council, Washington, DC.

Prakash, V., Powell, G.H., Filippou, F.C., 1992. DRAIN-2DX: Base program user guide, Report No. UCB/SEMM-92/29.

Riddell, R., Hidalgo, P., Cruz, E., 1989. Response modification factors for earthquake resistant design of short period buildings. Earthquake Spectra 5 (3), 571–590.

SEAOC Vision 2000, 1995. Performance based seismic engineering for buildings. Structural Engineers Association of California, Sacramento, CA.

Uniform Building Code (UBC), 1997. International Conference of Building Officials, vol. 2.

Vidic, T., Fajfar, P., Fischinger, M., 1994. Consistent inelastic design spectra: strength and displacement. Journal of Earthquake Engineering and Structural Dynamics 23, 507–521.