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OPTIMUM SEISMIC LOAD DISTRIBUTION FOR PERFORMANCE-BASED DESIGN OF MULTI-STOREY STRUCTURES ON DIFFERENT SOIL PROFILES

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Abstract

Structural configuration plays an important role on the seismic behaviour of structures. In recent earthquakes, structures with inappropriate distributions of strength and stiffness had inadequate performance due to configuration problems or wrong conceptual design. In the conventional seismic design methods, height-wise distribution of equivalent seismic loads seems to be related implicitly on the elastic vibration modes. Therefore, the employment of such a load pattern does not guarantee the optimum use of materials in the nonlinear range of response. In this study, a new optimisation method is used to find optimum lateral force distribution for seismic design of regular and irregular shear-buildings to achieve minimum structural damage. The proposed approach is based on the concept of uniform distribution of damage where the structural properties are modified so that inefficient material is gradually shifted from strong to weak areas of a structure. It is shown that the seismic performance of such a structure is better than those designed conventionally. By conducting the optimisation algorithm on shear-building models with various dynamic characteristics subjected to 75 synthetic spectrum-compatible earthquakes, the effects of target ductility demand, fundamental period, seismic excitation, number of storeys, damping ratio, ground motion intensity and soil profiles are investigated on the optimum distribution pattern. Based on the results of this study, a general load pattern is proposed for seismic design of regular and irregular building structures that is a function of soil type, fundamental period of the structure and the target ductility demand. It is shown that using the proposed load pattern leads to a more efficient use of structural materials and better seismic performance.

Keywords: Seismic Design; Optimisation; Ductility; Load Distribution

1. Introduction

The preliminary design of most building structures is commonly based on the equivalent static force approach, in which the dynamic inertial forces due to seismic vibrations are represented by equivalent static forces. The height-wise distribution of these static forces is implicitly based on the fundamental elastic vibration modes [1]. Considering that structures do not remain elastic during severe earthquakes, the current capacity design approach in general does not lead to a uniform distribution of ductility demands and optimum use of structural materials [2, 3, 4]. The seismic behaviour of code-based designed structural systems has been extensively investigated both theoretically and experimentally [e.g. 5, 6, 7, 8]. The results of these studies showed that in general buildings that comply with new code requirements satisfy the collapse prevention and immediate occupancy performance levels; however, they may exhibit extensive damage during strong earthquakes.

In one of the early attempts to find optimum distribution of structural properties, Takewaki [9] developed an analytical method to find stiffness (and strength) distribution that leads to a constant storey-ductility demand for a shear-building structure subjected to a given design spectrum. This method is based on an elastic equivalent linearization technique, and the results showed that for tall buildings it does not lead to a uniform ductility demand distribution when the structure is subjected to a time-history excitation.

Chao et al. [10] analysed a series of steel moment and braced frames subjected to various earthquake excitations to find more efficient seismic load patterns. They showed that in general there is a discrepancy between the earthquake induced shear forces and the forces determined by assuming code-based design load distribution patterns. Based on the results of their studies, they suggested a new lateral force distribution for seismic loads to address the influence of increasing higher mode effects in the inelastic state. However, the effects of ground motion characteristics and the degree of nonlinearity were not considered in their suggested load distribution.

Moghaddam and Hajirasouliha [4] and Hajirasouliha and Moghaddam [11] developed an effective optimisation method, based on the concept of uniform distribution of deformation, to find optimum lateral load distribution for seismic design of regular shear-building structures to obtain uniform storey ductility. They showed that, for the same target storey-ductility demand, structures designed with the average of optimum load patterns for a set of earthquakes with similar characteristics, have relatively lower structural weight compared to those designed conventionally. Based on the results of their study on a set of real earthquake excitations recorded on stiff soil profiles, they proposed a new design load pattern that is a function of fundamental period of the structure and the target ductility demand. However, the load pattern adopted cannot be used directly in practical design of structures, as the utilized seismic records were not compatible with modern building code design spectra (such as IBC-2012 [12]), and the effect of site soil profile was not considered in their proposed equation.

In this study, the optimisation method proposed by Hajirasouliha and Moghaddam [11] is further developed to obtain the best lateral load distribution for seismic design of shear-building structures to exhibit minimum structural damage under a design spectrum. First the effects of target ductility demand, fundamental period, seismic excitation, number of storeys, damping ratio and ground motion intensity are investigated on the optimum distribution patterns for a set of real earthquakes. Subsequently, by using 200 shear-building models subjected to 75 synthetic IBC-2012 spectrum compatible earthquakes, optimum design load patterns are obtained for different site soil classifications. The results are then used to develop a more realistic lateral design load distribution, which leads a more efficient use of structural materials and better seismic performance.

2. Structural models

In spite of some drawbacks, shear-building models have been widely used to study the seismic response of multi-storey buildings because of simplicity and low computational effort that enables a wide range of parametric studies [13]. The shear-building model is capable of considering both non-linear behaviour and higher mode effects for the first few effective modes. The parameters required to define a shear-building model corresponding to a full-frame model can be determined by performing a single pushover analysis [14]. In shear-building models, the strength of each floor is obtained from the corresponding storey shear force, and therefore, the height-wise distribution of storey strengths can be easily converted to the height-wise distribution of lateral forces. This makes shear-buildings a very suitable model for calculating the optimum seismic design load pattern for multi-storey structures with different dynamic characteristics and performance targets. In the present study, 200 shear-building models with fundamental period ranging from 0.1 sec to 3 sec, and maximum ductility demand equal to 1, 1.5, 2, 3, 4, 5, 6 and 8 were utilized.

To predict the seismic response of the shear-building models, nonlinear time-history analyses were carried out using computer program DRAIN-2DX [15]. The Rayleigh damping model with a constant damping ratio of 0.05 was assigned to the first mode and to the first mode at which the cumulative mass participation exceeds 95%. To investigate the effects of different soil profiles on the optimum design load distributions, five sets of spectrum-compatible synthetic earthquakes were generated using the SIMQKE program [16] to represent the elastic design response spectra of IBC-2012 soil types A, B, C, D and E (see Table 1). These design response spectra are assumed to be an envelope of the many possible ground motions that could occur at the site. To include the ground motion variability, each set of synthetic earthquakes consists of 15 generated seismic excitations, with a PGA of 0.4g. It is shown in Fig. 1 that the average acceleration response spectrum of each set of synthetic earthquakes compares well with its corresponding IBC-2012 design spectrum.

Table 1- Site soil classifications according to IBC-2009

Site class	Soil profile name	Soil shear wave velocity
A	Hard rock	> 1500 m/s
B	Rock	760 to 1500 m/s
C	Very dense soil and soft rock	370 to 760 m/s
D	Stiff soil profile	180 to 370 m/s
E	Soft soil profile	< 180 m/s

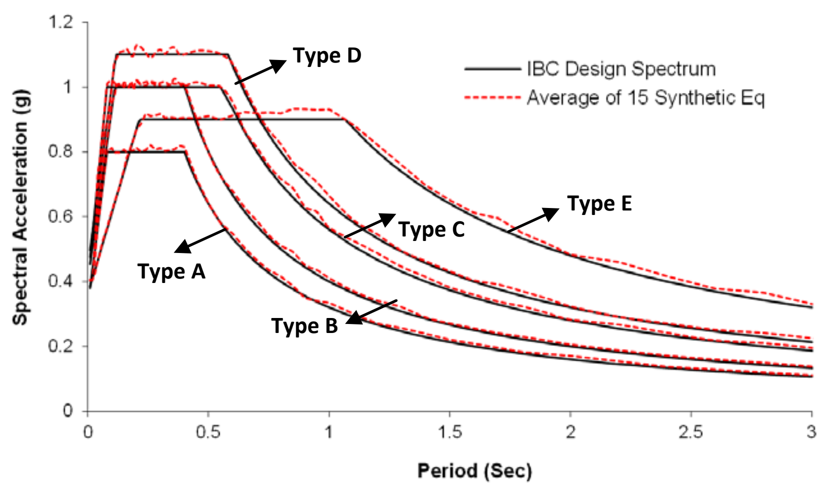

Fig. 1- IBC-2012 design spectrum and average response spectra of 15 synthetic earthquakes

3. Conventional lateral loading patterns

In most seismic building codes (e.g. Eurocode 8 [17], IBC-2012 [12]), the height-wise distribution of lateral forces is to be determined from the following typical relationship:

$$F_i = \frac{w_i h_i^k}{\sum_{j=1}^{n} w_j h_j^k} \cdot V \tag{1}$$

where V is the base shear; w_i and h_i are the weight and height of the i^{th} floor above the base, respectively; n is the number of storeys; and k is the power that differs from one seismic code to another. In most earthquake design guidelines, k increases from 1 to 2 as period varies from 0.5 to 2.5 second.

4. Optimum lateral loading pattern for a design earthquake

In this study, the optimisation target is to obtain a seismic design load that leads to minimum structural damage (i.e. optimum distribution of structural material) using a fixed amount of structural material. As discussed before, during strong earthquakes the deformation demand in code-based designed structures is not usually uniform [1, 2, 4]. As a result, in some parts of the structures, the maximum level of seismic capacity is not necessarily utilized. If the strength of underused elements is decreased incrementally, for a ductile structure, it is expected to eventually obtain a status of uniform damage distribution. In such a case, the dissipation of seismic energy in each structural element is maximised and the material capacity is fully exploited. Therefore, in general, it can be assumed that a status of uniform distribution of structural damage is a direct consequence of the optimum use of material. This concept can significantly simply the complex optimisation of non-linear structure subjected to dynamic excitations.

In the present study, in an attempt to reach uniform damage distribution through the structure, the following optimisation procedure is adopted:

1- The initial structure is designed for seismic loads based on design guidelines, such as IBC-2012 [12]. The distribution of storey shear strength along the structure is then determined.

2- A model of the structure is subjected to the design seismic excitation, and a suitable local damage index (such as storey ductility, inter-storey drift and cumulative damage) is calculated for all stories.

3- The Coefficient of Variation (COV) of damage indices of all stories is calculated. If this COV is small enough (e.g. less than 0.1), the structure is considered to be practically optimum. Otherwise, the optimisation algorithm proceeds to iterations.

4- During the iterations, the distribution of storey shear strength is modified. The shear strength is reduced in the stories with lower-than-average damage index and increased in the stories which experienced higher-than-average damage. To obtain convergence in numerical calculations, this alteration needs to be applied incrementally using the following equation:

$$(S_i)_{n+1} = \left[\frac{DI_i}{DI_{ave}}\right]^{\alpha} (S_i)_n \tag{2}$$

where $(S_i)_n$ is the shear strength of the i^{th} storey at n^{th} iteration, DI_i and DI_{ave} are damage index for the i^{th} storey and average of damage indices for all stories, respectively. α is convergence parameter ranging from 0 to 1. Analyses carried out on different models and seismic excitations indicated that an acceptable convergence is usually obtained by using α values of 0.1 to 0.2 [18]. The results presented in this paper are based on α value of 0.15.

5- The total structural weight is considered proportional to the sum of all storey shear strengths [4, 11]. Therefore, the storey shear strengths are scaled such that the sum of storey shear strengths (and structural weight) remains unchanged. The optimisation procedure is then repeated from step 2 until the COV of damage indices become small enough. The final solution is considered to be practically optimum. Analyses carried out by the authors showed that the optimum distribution of storey shear strengths is independent of the seismic load distribution used for the initial design.

In performance-based design methods, design criteria are expressed in terms of achieving specific performance targets during a design level earthquake. Performance targets could be satisfied by controlling the level of stress, displacement or structural and non-structural damage. While the proposed method can optimise the design using different types of performance parameters, here storey ductility is considered as the damage index in the optimisation process (i.e. the damage index DI in Eq. 2).

4.1. Effect of target ductility demand

In order to study the effect of target ductility demand on the optimum distribution patterns, 10 storey shear-building models with fundamental period (T) of 1 sec and target ductility demand (μ_t) of 1.5, 2, 4 and 8 are considered. Using the above mentioned optimisation method, optimum lateral load patterns are derived for each model subjected to Northridge 1994 (CNP196) ground motion. Fig. 2 shows the effect of target ductility demand on the optimum distribution of seismic loads. The results indicate that optimum distribution is highly dependent on target ductility demand of the structure. In general, increasing the ductility demand is accompanied by decreasing the optimum design loads at the top storeys and increasing the loads at the lower levels. However, the seismic design load patterns suggested by most seismic codes do not take into account the expected level of ductility under design earthquakes.

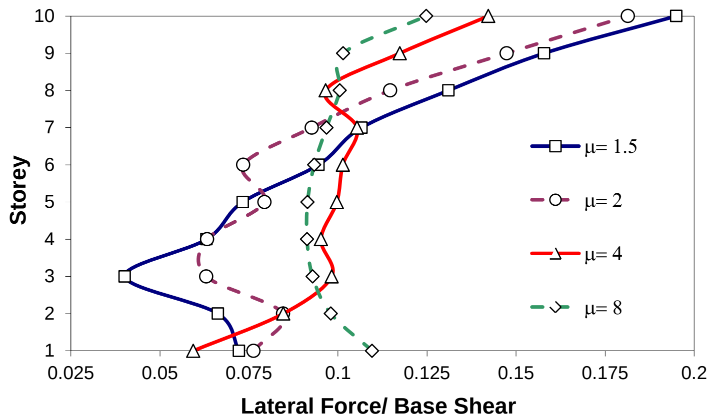

Fig. 2- Optimum lateral force distribution for different target ductility demands, 10-storey building with T=1 Sec, Northridge 1994 (CNP196)

4.2. Effect of fundamental period

To investigate the effect of fundamental period on the optimum distribution patterns, 10-storey shear buildings with target ductility demand (μ_t) of 4 and fundamental periods of 0.2, 0.6, 1 and 2 sec are used in this section. For each case, the optimum lateral load pattern is obtained for Northridge 1994 (CNP196) earthquake event. The comparison of the optimum lateral load patterns is presented in Fig. 3. As shown in this figure, the optimum distribution of seismic loads is a function of fundamental period of the structure. The results of this study indicate that increasing the fundamental period is usually accompanied by increasing the loads at the top storeys caused by the higher mode effects.

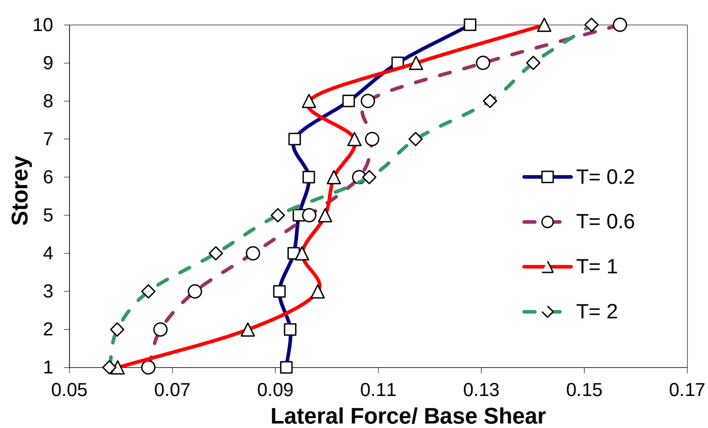

Fig. 3- Optimum lateral force distribution for different fundamental periods, 10-storey building with μ_t=4, Northridge 1994 (CNP196)

4.3 Effect of seismic excitation

The effect of seismic excitation is investigated by comparing the optimum load patterns of the following seismic records: (1) The 1994 Northridge earthquake CNP196 component with a PGA of 0.42g, (2) The 1979 Imperial Valley earthquake H-E08140 component with a PGA of 0.45g, and (3) The 1992 Cape Mendocino earthquake PET090 component with a PGA of 0.66g. All of these seismic excitations were recorded on site soil profiles similar to the type D of IBC-2012. Fig. 4 compares the optimum load patterns for a 10-storey shear buildings with target ductility demand of 4 and fundamental periods of 1 subjected to these earthquakes. While it is shown in this figure that every seismic excitation has a unique optimum distribution of structural properties, the results indicate that there is not a big discrepancy between different optimum load patterns for the seismic excitations recorded on similar soil profiles.

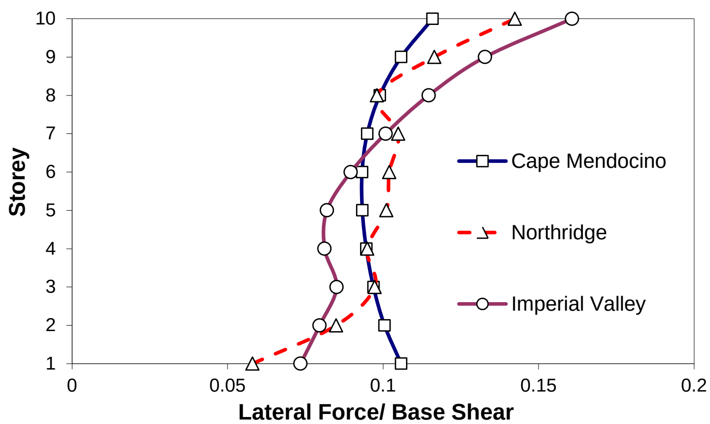

Fig. 4- Optimum lateral force distribution for different earthquake records, 10-storey building with T=1 sec and μ_t=4, Northridge 1994 (CNP196)

4.4 Effect of number of Storeys

To study the effect of number of storeys on the optimum distribution pattern, the proposed optimisation algorithm was conducted on 5, 7, 10 and 15-storey shear-building models subjected to Northridge 1994 (CNP196) earthquake event. For each model, the optimum lateral load patterns were obtained for two different cases: (a) fundamental period of 1 and target ductility demand of 4, (b) fundamental period of 1.5 and target ductility demand of 6. It is shown in Fig. 5 that for a specific fundamental period and target ductility demand, optimum load patterns have a similar trend regardless of the number of storeys. Therefore, optimum design load patterns can be efficiently considered to be independent of the number of storeys.

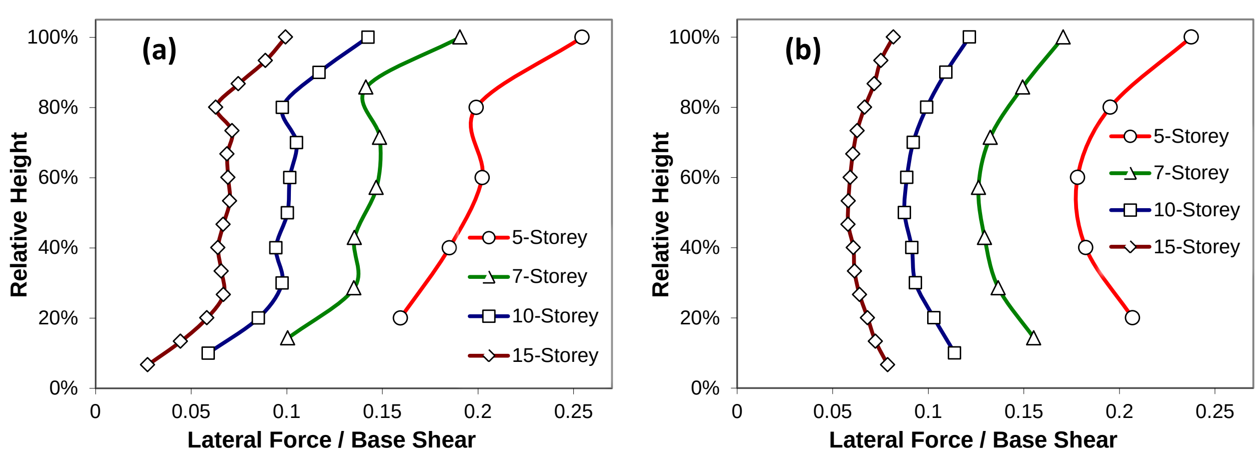

Fig. 5- Optimum lateral force distribution for 5, 7, 10 and 15-storey shear-buildings: (a) T=1 sec and μ_t=4, (b) T=1.5 sec and μ_t=6, Northridge 1994 (CNP196)

4.5 Effect of damping ratio

The effect of damping ratio on the optimum load distribution patterns is illustrated in Fig. 6 for a 10-storey shear-building with target ductility demand of 4 and fundamental period of 1 sec subjected to Northridge 1994 (CNP196) event. As shown in this figure, optimum lateral forces corresponding to the top floors decrease with an increase in damping ratios. This can be explained by the fact that increasing damping ratio is usually accompanied by decreasing the higher mode effects which mainly affect loads at the top storeys. It can be noted from Fig. 6 that optimum load patterns are relatively insensitive to the variation of damping ratios greater than 3%. Hence, for practical purposes, optimum lateral seismic design load patterns can be considered independent of the damping ratio.

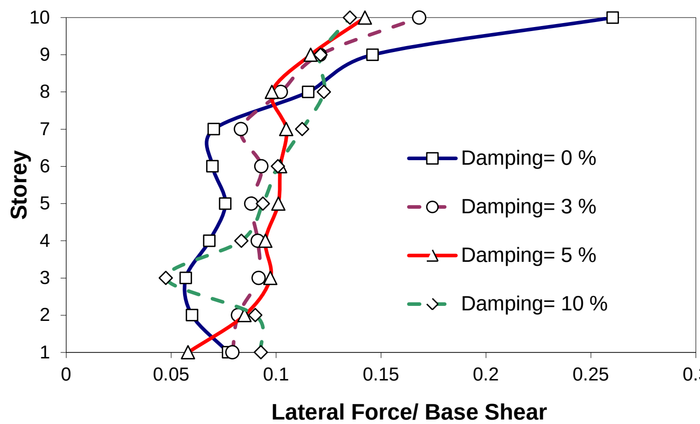

Fig. 6- Optimum lateral force distribution for different damping ratios, 10-storey shear building with T=1 Sec and μ_t=4, Northridge 1994 (CNP196)

4.6 Effect of ground motion intensity

To investigate the effect of ground motion intensity on the optimum lateral seismic design load distribution, 10-storey shear building models with fundamental period of 1 sec and target ductility demand of 4 were subjected to the Northridge earthquake of 1994 (CNP196) scaled by 0.5, 1, 1.5, 2 and 3 factors. For each ground excitation, the optimum load distribution pattern was determined and compared as shown in Fig. 7. The results indicate that for a specific fundamental period and target ductility demand, the optimum load pattern is completely independent of the ground motion intensity.

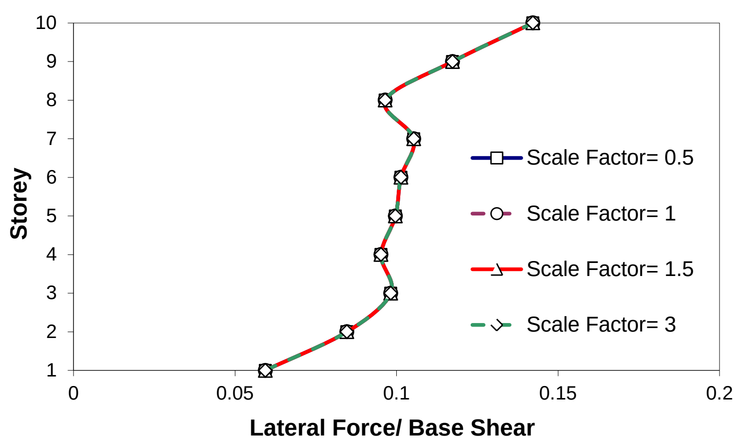

Fig. 7- Optimum lateral force distribution for different ground motion intensities, 10-storey building with T=1 Sec and μ_t=4, Northridge 1994 (CNP196)

5. Optimum lateral loading pattern for a code design spectrum

Based on the work presented in the previous sections, it was found that for every building there is a specific optimum load distribution that leads to optimum seismic performance during the design earthquake. This optimum pattern depends on the characteristics of the design earthquake, and therefore, varies from one earthquake to another. However, there is no guarantee that the structure will experience seismic events with the exact characteristics of the design ground motion. Therefore, for practical applications, appropriate design load distributions should be developed for typical building code design spectra.

Using the proposed optimisation algorithm, the optimum load distribution patterns were calculated for the 200 shear-building models presented earlier under the five sets of selected synthetic earthquakes representing different soil types. The average of the optimum load patterns for each set of synthetic records was then used to design new shear-buildings. For each seismic excitation, the required structural weight was determined to obtain a target storey-ductility demand for the shear-buildings designed with IBC 2012 seismic design load pattern, average of the optimum load patterns and loading patterns with one, two, and three modes included.

Fig. 8 compares the ratio of required to optimum structural weight for structures with fundamental period of 0.5 and 1 sec and maximum ductility demands of 1 to 8 designed with different load patterns. This figure is based on the average weights required for each of the 15 synthetic earthquakes representing soil type C. It is shown that in the elastic range of response (i.e. μ_t=1), the total structural weight for the models designed according to IBC-2012 seismic guidelines are on average around 8% above the optimum value. Therefore, it is confirmed that using conventional loading patterns leads to acceptable designs for elastic structures. However, increasing the ductility demand is generally accompanied by increasing the structural weight required for the conventionally designed models compared to the optimum ones. This implies that conventional loading patterns lose their efficiency in nonlinear ranges of vibration.

It is illustrated in Fig. 8 that for high levels of ductility demand the required structural weight for the models designed according to IBC-2012 could be more than 50% above the optimum weight. The required structural weight for models designed according to IBC-2012 in general is smaller that those designed with the loading patterns with one, two or three modes included. It is shown that significant improvement is achieved by including response contributions due to the second mode; however, the third mode contributions do not seem especially important.

It is shown in Fig. 8 that structures designed with the average of the optimum load distributions always have less (up to 40%) structural weights compared to IBC-2012 designed structures. It is also shown that the efficiency of the average load pattern does not decrease by increasing the target ductility demand. This implies that the average of the optimum load distributions for a set of design spectrum compatible earthquakes can be efficiently used for performance-based seismic design of buildings in a wide range of target ductility demands (i.e. different performance targets).

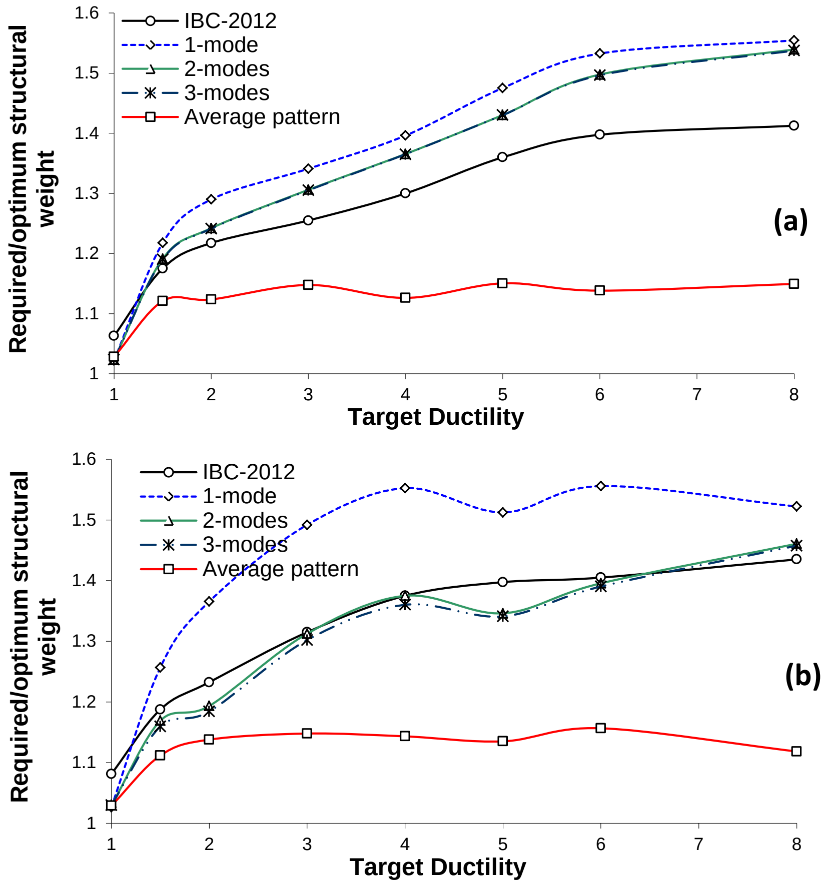

Fig. 8- The ratio of required structural weight to the optimum weight for the models designed according to different load patterns, average of 15 synthetic earthquakes (soil type C)

6. More efficient seismic design load pattern for non-linear structures

Calculation of the average load patterns requires significant computational effort. Therefore, for practical design purposes, it is necessary to develop a simple method to estimate the average of optimum load patterns for different structures and performance targets.

6.1 Practical equation

The results of this study showed that, despite obvious variation between optimum load patterns for different conditions, for each storey there is generally a specific relationship between the optimum lateral load and fundamental period of the structure and target ductility demand. Based on the results of this study, the following equation has been suggested to estimate the optimum load patterns corresponding to a design spectrum:

$$\begin{cases} P_i = (a_i T + b_i)\mu_t^{(c_i T + d_i)} \\ \phi_i = \dfrac{P_i}{\sum_{j=1}^{n} P_j} \end{cases} \tag{3}$$

where ϕ_i is the ratio of optimum design force at i^{th} storey to the base shear for a structure with fundamental period of T and maximum ductility demand of μ_t ; and a_i, b_i, c_i, and d_i are constant coefficients at i^{th} storey.

The results of this study show that Eq. (3) can be adopted to represent the average of optimum load patterns corresponding to different building code design spectra. For this purpose, the constant coefficients a_i, b_i, c_i, and d_i should be calculated based on the average of the results for a set of synthetic spectrum-compatible earthquakes representing a specific design spectrum.

Fig. 9 compares the load distributions calculated by using Eq. (3) and the corresponding load distributions obtained from nonlinear dynamic analysis. The results of the proposed equation compare very well with the analytical results, and the equation works well for different periods and ductility demands. It should be noted that the proposed equation is a function of structural performance level (i.e. storey ductility) and therefore is suitable for performance-based seismic design of structures.

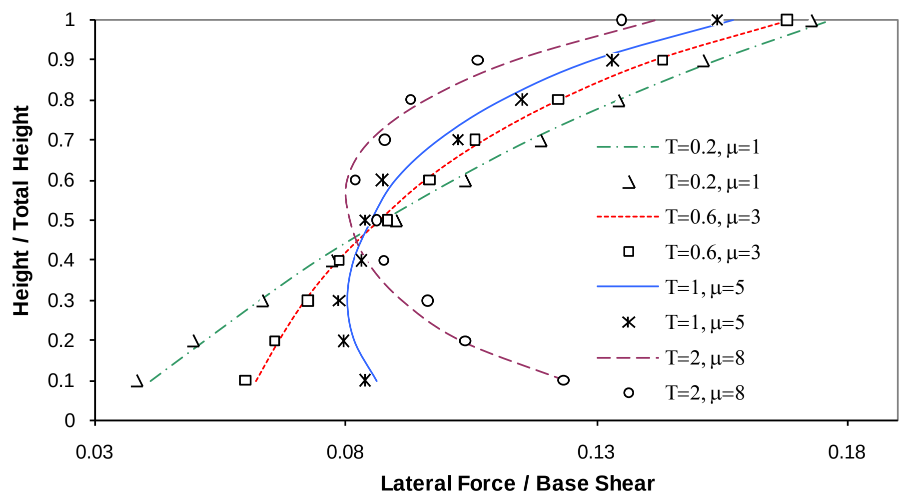

Fig. 9- Correlation between Eq. (3) and analytical results, average of 15 synthetic earthquakes (soil type C)

6.2. Effect of site soil profile

To investigate the effect of site soil classification on the optimum seismic design load distribution, five sets of 15 synthetic earthquakes were considered as introduced in section 2. For each synthetic ground motion record, the optimum design load distribution was derived for the 200 shear-building models with different fundamental periods and target ductility demands. Using the suggested formula for optimum design load distributions (Eq. 3), the constant coefficients a_i, b_i, c_i, and d_i were determined for each group of synthetic earthquakes representing a design spectrum. Fig. 10 compares the constant coefficients corresponding to different soil profiles. It is shown that the optimum load distributions for structures with similar fundamental period and maximum ductility demand sited on soil profiles type A, B, C and D are practically identical. However, the optimum load distributions for soft soil profiles (type E) are slightly different. Therefore, for practical applications, it is suggested to provide two sets of coefficients a_i, b_i, c_i, and d_i for hard rock to stiff soil profiles and for soft soil.

The general loading pattern proposed in this paper is efficient for structural systems that exhibit shear-building like behaviour, such as buckling-restrained braced frames and moment resisting frames with high beam-to-column stiffness ratio. The efficiency of the proposed load pattern reduces slightly for conventional concentrically braced frames, since the seismic behaviour of the frames is significantly influenced by the slenderness of the brace elements [19]. However, the proposed load pattern can still improve the seismic performance of the designed frames, and should prove useful in the conceptual design phase.

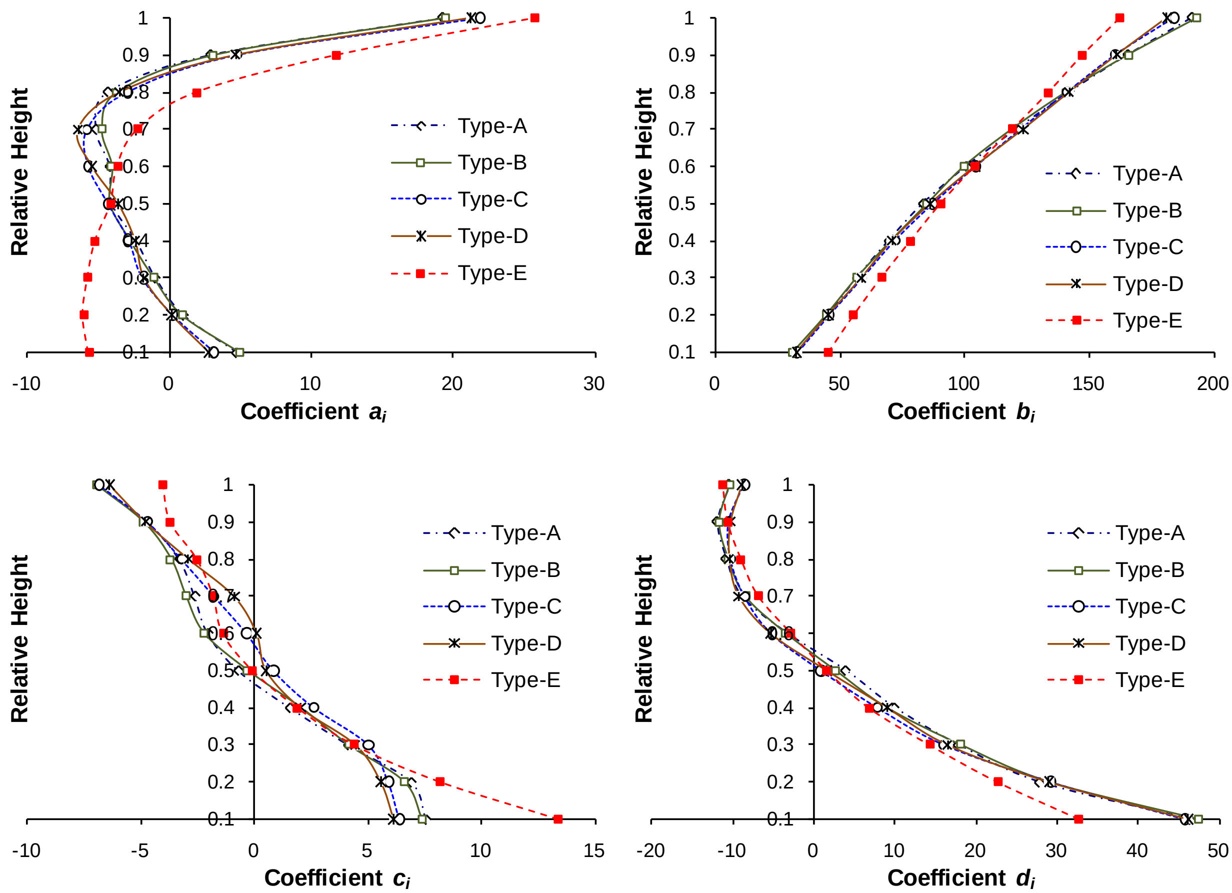

Fig. 10- Constant coefficients a_i, b_i, c_i, and d_i (Eq. 3) for different site soil classifications

7. Conclusions

A method based on the concept of uniform distribution of damage is adopted for optimum seismic design of structures subjected to a design seismic excitation. It is shown that, for the same structural weight, structures designed with the optimum load distribution exhibit significantly less storey-ductility demands compared to their code-based design counterparts.

The results indicate that the optimum load distribution is highly dependent to fundamental period of the structure, target ductility demand and earthquake excitation. However, for practical purposes, optimum patterns can consider to be independent of ground motion intensity, number of storeys and damping ratio.

For a set of synthetic earthquakes representing a typical building code design spectrum, optimum seismic design load distributions were determined. It is shown that structures designed with the average of optimum load distributions have up to 40% less structural weight compared to similar conventionally designed structures.

As shown by the results, the optimum load distributions for structures with similar fundamental period and maximum ductility demand sited on IBC-2012 soil profiles type A, B, C and D (hard rock to stiff soil) are almost identical. However, the optimum load distributions for soft soil profiles (type E) are slightly different.

Based on the results of this study, a general load distribution is introduced for seismic design of shear-building type structures that is a function of soil type, fundamental period of the structure and maximum ductility demand. It is shown that using the proposed loading pattern leads to a more efficient use of structural materials, and therefore, better seismic performance.

8. References

[1] Chopra AK (2012): *Dynamics of Structures/Theory and Applications to Earthquake Engineering*, Prentice Hall Inc., 4th edition, London.

[2] Karami Mohammadi R, El Naggar MH, Moghaddam H (2004): Optimum strength distribution for seismic resistant shear buildings, *International Journal of Solids and Structures*, **41** (22-23), 6597-6612.

[3] Priestley MJN, Calvi MC, Kowalsky MJ (2007): *Displacement-based Seismic Design of Structures*. IUSS Press, Pavia.

[4] Moghaddam H, Hajirasouliha I (2006): Toward more rational criteria for determination of design earthquake forces, *Internatioanl Journal of Solids and Structures*, **43** (9), 2631-2645.

[5] Anderson J C, Miranda E, Bertero VV (1991): Evaluation of the seismic performance of a thirty-story RC building", *Technical Report UCB/EERC-91/16*, Pacific Earthquake Engineering Research, Berkeley, USA.

[6] Lee K, Foutch DA (2002): Performance evaluation of new steel frame buildings for seismic loads, *Earthquake Engineering & Structural Dynamics*, **31** (3), 653-670.

[7] Koboevic SM, Rozon J, Tremblay R (2012): Seismic Performance of Low-to-Moderate Height Eccentrically Braced Steel Frames Designed for North American Seismic Conditions, *Journal of Structural Engineering ASCE*, **138** (12), 1465-1476.

[8] Garcia R, Hajirasouliha I, Guadagnini M, Helal Y, Jemaa Y, Pilakoutas K, Mongabure P, Chrysostomou C, Kyriakides N, Ilki A, Budescu M, Taranu N, Ciupala MA, Torres L & Saiidi M (2014): Full-scale shaking table tests on a substandard RC building repaired and strengthened with post-tensioned metal straps, *Journal of Earthquake Engineering*, **18** (2), 187-213.

[9] Takewaki I (1996): Design-oriented approximate bound of inelastic responses of a structure under seismic loading, *Computer and Structures*, **61** (3), 431-440.

[10] Chao SH, Goel SC, Lee SS (2007): A seismic design lateral force distribution based on inelastic state of structures, *Earthquake Spectra*, **23** (3), 547-569.

[11] Hajirasouliha I, Moghaddam H (2009): New lateral force distribution for seismic design of structures, *Journal of Structural Engineering ASCE*, **135** (8), 906-915.

[12] IBC-2012 (2012): *International Building Code*. International Code Council, Country Club Hills, USA.

[13] Lu Y, Hajirasouliha I, Marshall AM (2016): Performance-based seismic design of flexible-base multi-storey buildings considering soil–structure interaction, *Engineering Structures*, **108**, 90-103.

[14] Hajirasouliha I, Doostan A (2010): A simplified model for seismic response prediction of concentrically braced frames, *Advances in Engineering Software*, **41**(3), 497-505.

[15] Prakash V, Powell GH, Filippou FC (1992): DRAIN-2DX: base program user guide. *Technical Report UCB/SEMM- 92/29*, Earthquake Engineering Research Centre, University of California, Berkeley.

[16] Vanmarke EH (1976): *SIMQKE-A Program for Artificial Motion Generation*, User's Manual and Documentation. Department of Civil Engineering, Massachusetts Institute of Technology.

[17] CEN Eurocode 8 (2004): *Design provisions of structures for earthquake resistance*. European Committee for Standardization. Brussels.

[18] Hajirasouliha I, Pilakoutas K (2012): General seismic load distribution for optimum performance-based design of shear-buildings, *Journal of Earthquake Engineering*, 16(4), 443-462.

[19] Karavasilis TL, Bazeos N, Beskos DE (2007): Estimation of seismic drift and ductility demands in planar regular X-braced steel frames, *Earthquake Engineering and Structural Dynamics*, **36** (15), 2273-2289.