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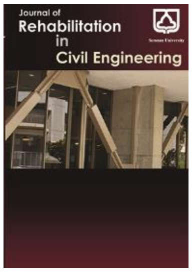


# Achievement of Minimum Seismic Damage for Zipper Braced Frames Based on Uniform Deformations Theory

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## ABSTRACT

When structures are subjected to severe ground excitations, structural elements may be prone to yielding, and consequently experience significant levels of inelastic behavior. The effects of inelastic behavior on the distribution of peak floor loads are not explicitly accounted for in current seismic code procedures. During recent years, many studies have been conducted to develop new design procedures for different types of buildings through proposing improved design lateral load patterns. One of the most important parameters of structural damage in performance-based seismic design is to limit the extent of structural damages (maximum inter-story ductility ratio) in the system and distribute them uniformly along the height of the structures. In this paper, a practical method is developed for optimum seismic design of zipper-braced frames (ZBF) subjected to seismic excitations. More efficient design is obtained by redistributing material from strong to weak parts of a structure until a state of uniform ductility ratio (damage) prevails. By applying the proposed design algorithm on 5, 10 and 15-storey zipper-braced frames subjected to 10 synthetic seismic excitations, the efficiency of the proposed method is investigated for specific synthetic seismic excitations. The results indicate that, for a constant structural weight, the structures designed according to the proposed optimization algorithm experience up to 50% less global ductility ratio (damage) compared with code-based design structures.

## 1. Introduction

In the recent earthquakes, the structures designed based on the new terms of seismic design have an appropriate performance in the safety of occupants; however, the extent of damage and economic losses in these structures were unexpected. It is well known that the structures designed in accordance with the current seismic provisions may experience extreme damages under severe earthquakes [1-4]. In the current seismic design codes, lateral-load resisting systems for regular structures may be designed based on the equivalent lateral force procedure [5-7]. A fundamental component of the equivalent lateral force procedure is the utilization of design lateral load patterns to determine the strength and the stiffness characteristics of structure. These code-specified design lateral load patterns were set up based on the dynamic behavior of elastic structural systems. Therefore, the design lateral load patterns of this procedure do not explicitly account for the inelastic response of the structural system. If the structure is expected to experience significant levels of inelasticity, code-specific lateral load distributions may not provide an accurate representation of the story shear strength demands applied to the structural system. Thus, a designer has certain control on the amount of the global structural damage experienced by the structure based on an appropriate selection of stiffness, strength, and ductility requirements in the seismic design stages of a structure. However, a designer has limited control over the distribution of damage, which is mainly caused by load redistribution effects characteristic of inelastic structural response [8]. The total lateral load force proposed by seismic provisions, is generally less than the actual earthquake forces imposed on structures during sever earthquakes and consequently the conventional structures were experienced large deformations and nonlinearity in strong ground motions. Therefore, the design of structures based on elastic vibration modes is not logical as the actual earthquake force is a function of structural dynamic characteristics such as yield shear strength and inter-story ductility ratio [9].

Many researchers have recommended improved seismic design load patterns for multistory structures.

Leelataviwat et al. [10] evaluated the seismic demands of mid-rise moment-resisting frames designed in accordance to UBC 94. They proposed improved load patterns using the concept of energy balance applied to moment-resisting frames with a pre-selected yield mechanism. Lee and Goel [11] also proposed new seismic lateral load patterns by using high-rise moment-resisting frames up to 20-story with the same concept which Leelataviwat et al. [10] used. In a more comprehensive research, Mohammadi et al. [12] investigated the effect of lateral load patterns specified by the United States seismic codes on drift and ductility demands of fixed-base shear building structures under 21 earthquake ground motions, and found that using the code-specified design load patterns do not lead to a uniform distribution and minimum ductility demands. Ganjavi et.al [13] investigated the effect of equivalent static and spectral dynamic lateral load patterns specified by the major seismic codes on height-wise distribution of drift, hysteretic energy and damage subjected to severe earthquakes in fixed-base reinforced concrete buildings. More recently, several studies have been conducted by researchers to evaluate and improve the code-specified design lateral load patterns based on the inelastic behavior of the structures [8, 14-18].

As stated in the literature, considerable effort have been made on the optimum seismic design of different types of structures such as shear buildings, steel and concrete moment-resistant frames, concentrically- and eccentrically- braced frames and etc. over the last decade. Zipper-braced frame (ZBF) is one of the innovative load-resisting systems first introduced by Khatib et al. [19], and developed by other researchers during the last decade [20, 21]. This system has a special seismic behavior than other load-resisting systems as it depends on buckling behavior of braces in the height of the structure. In the present study, a large number of nonlinear dynamic analyses are performed to achieve the uniform deformation over height of the ZBF models. In this regard, 5, 10 and 15 story of ZBF models with different characteristics which will be explained in the next section are modeled and the optimization technique proposed by and Moghaddam [14] and Ganjavi and Hao [17] for shear-building systems are modified and developed for ZBF systems. Based on the proposed optimization algorithm and by adopting the stories ductility ratio as a damage criterion, the distribution of stories ductility ratio over height of the structures will be more uniform, leading considerable decrease of the maximum ductility ratio of ZBF the structure. Finally, the efficiency of the proposed optimization algorithm is demonstrated through several examples. It is shown that with assumption of constant structural weight, the seismic performance of such structures is near optimum such that they undergo less global damage when compared to code-based structures.

## 2. Structures modeling and assumptions

The behavior of concentrically braced frame (CBF) in chevron configuration is controlled by the buckling of the first story braces in compression. This will result in a localization of the failure and loss of lateral resistance. To overcome the adverse effect of this behavior, Khatib et al. [19] proposed to link all beam-to-brace intersection points of adjacent floors and to transfer the unbalanced load to the vertical member called “zipper column” and this new structural system called “zipper-braced frame”. The main application of zipper braced frame (ZBF) is to tie all brace-to-beam intersection points together, and force all compression braces in a braced bay to buckle simultaneously. This configuration will result in a better hysteretic response and more uniform energy dissipation (i.e., uniform damage distribution) over the height of the structure. With the aim of avoiding storey mechanism formation, Sabelli [22] has carried out a study on the design and behavior of ZBF systems. Later on, Tremblay and Tirca [20] proposed a ZBF system with elastic zipper columns, while braces and beams were designed to undergo plastic deformations. Similarly, a ZBF system with suspended struts was proposed by Yang et al. [21]. This system consists of adding an elastic truss at the top floor level where braces were designed to behave elastically in order to avoid the full-height zipper mechanism formation. All the remaining braces were proportioned to buckle and zippers to yield. In fact, they proposed a new design procedure and configuration of ZBF system called suspended zipper braced frame (S-ZBF).

In this paper, three zipper-braced frames (ZBFs) models with 5, 10 and 15 stories with the fundamental periods of 0.4, 0.6 and 0.8 sec, respectively are seismically loaded based on ASCE7-10 lateral load pattern [23] and are designed based on AISC-LRFD [24]. They are then subjected to 20 earthquake ground motions through performing nonlinear dynamic analyses. The geometric configurations of these models are shown in Figure 1. The general formulation of the lateral load pattern specified by the ASCE7-10 is defined as [23]:

$$F_x = \frac{W_x h_x^k}{\sum_{i=1}^{n} W_i h_i^k} . V \; ; \qquad x = 1,2,...,n \; ; \qquad k = \begin{cases} 1 & T \le 0.5 \\ 0.5T + 0.75 \; ; & T \le 0.5 \le 2.5 \\ 2 & T \ge 2.5 \end{cases} \qquad (1)$$

where $F_x$ and $V$ are respectively the lateral load at level $x$ and the design base shear; $w_i$ and $w_x$ are the portion of the total gravity load of the structure located at the level $i$ or $x$; $h_i$ and $h_x$ are the height from the base to the level $i$ or $x$; $n$ is the number of stories; and $k$ is an exponent that differs from one seismic code to another. Figure 1 shows a typical ZBF model used in this study.

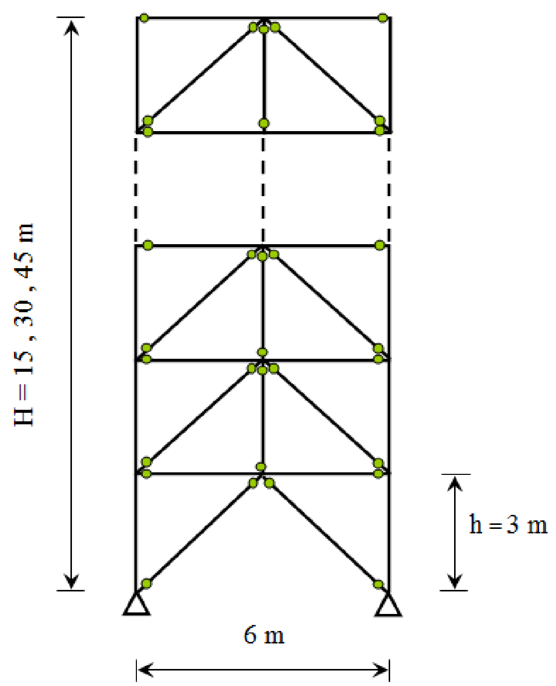



**Figure 1.** Typical ZBF model

All the nonlinear dynamic analyses have been performed by OPENSEES [25], which allows users to create finite element applications for simulating the response of structural and geotechnical systems subjected to earthquakes. To simulate the buckling behavior of a brace under compression for the hysteretic response of the zipper frame model, a brace model with a small initial imperfection has been defined [26]. Five percent Rayleigh damping was assigned to the first mode and the mode in which the cumulative mass participation was at least 95%. Figure 2 shows Schematic graph of a brace model in ZBF structures.

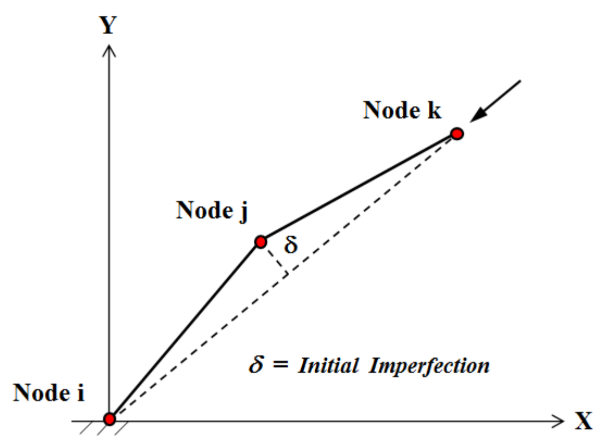



**Figure 2.** Schematic graph of a brace model.

## 2. Earthquake records used in this study

To achieve the uniform deformations along the height of structures, 10 earthquake ground motions with different characteristics recorded on very dense soil (soil type $C$, with shear wave velocity between 360 m/s and 750 m/s) according to the IBC-2012 [6] are selected. The main characteristics of these ground motions are listed in Table 1. All the selected ground motions are obtained from earthquakes with magnitude greater than 6 having closest distance to fault rupture more than 30 km without pulse in velocity time history. To be consistent, using SeismoMatch [27] software the selected seismic ground motions are adjusted to the elastic design response spectrum of IBC-2012 [6] with soil type *C*. SeismoMatch [27] is an application capable of adjusting earthquake accelerograms to match a specific target response spectrum using wavelets algorithm. Figure 3 shows a comparison of the 10 synthetic ground motion spectra with the target elastic design response spectrum of IBC-2012 [6].

Table1. Selected ground motions soil type *C* on the basis of USGS site classification.

| ***Earthquake*** | ***Year*** | ***Station*** | ***Component*** | ***Distance (km)*** | ***Soil Type*** | ***PGA (g)*** |
|---|---|---|---|---|---|---|
| Borrego Mtn | 1968 | 117 El Centro Array #9 | 180 | 46 | C | 0.130 |
| Kocaeli (180) | 1999 | Iznik | 180 | 31.8 | C | 0.098 |
| Kocaeli (90) | 1999 | Iznik | 90 | 31.8 | C | 0.136 |
| Landers | 1992 | 12025 Palm Springs Airport | 0 | 37.5 | C | 0.076 |
| Loma Prieta (160) | 1989 | 47179 Salinas - John & Work | 160 | 32.6 | C | 0.091 |
| Loma Prieta (250) | 1989 | 47179 Salinas - John & Work | 250 | 32.6 | C | 0.112 |
| Morgan Hill | 1984 | 1028 Hollister City Hall | 271 | 32.5 | C | 0.071 |
| N. Palm Springs (270) | 1986 | 12331 Hemet Fire Station | 270 | 43.3 | C | 0.144 |
| N. Palm Springs (360) | 1986 | 12331 Hemet Fire Station | 360 | 43.3 | C | 0.132 |
| Victoria | 1980 | 6621 Chihuahua | 192 | 36.6 | C | 0.150 |

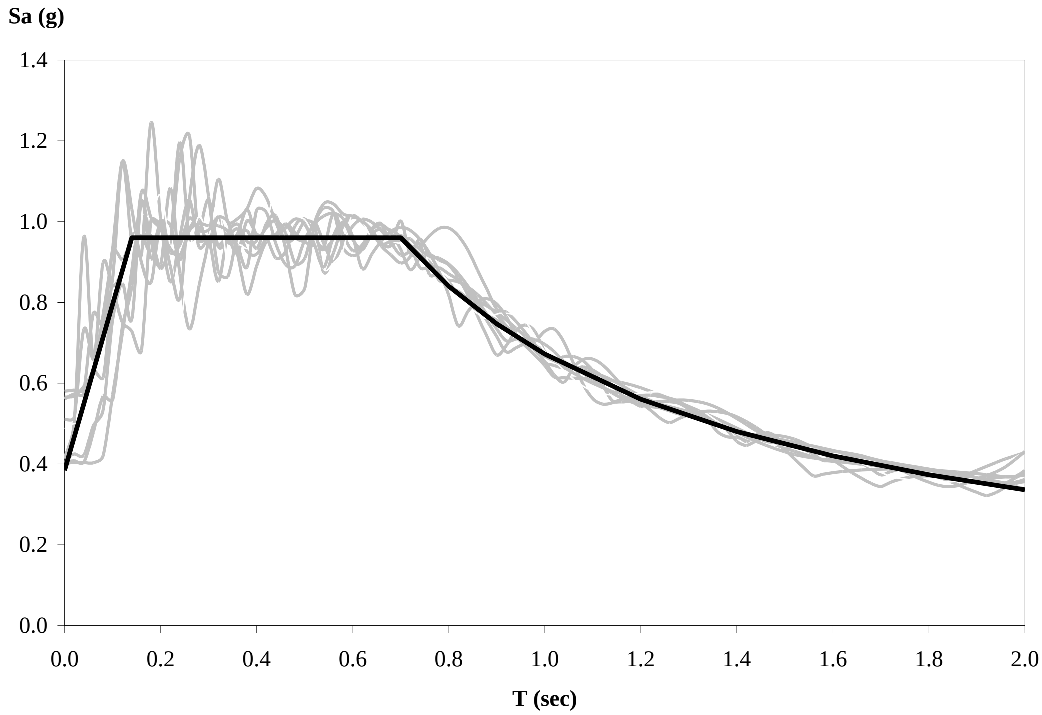



**Figure 3.** IBC-2012 [6] design spectrum for soil type C and response spectra of 10 earthquakes (5% damping) for selected ground motions.

## 3. Uniform deformation theory

Moghaddam and Hajirasouliha [14] showed that using the common seismic design method would not lead to the uniform distribution of ductility demands over the height of the structures. They concluded that when the lateral displacement increases, the strength would generally decrease in nonlinear region. Therefore, the seismic performance of such structures can be improved by substituting the strong parts of the structure to the weaker ones. This causes more uniform distribution of deformations along the height of the structures and consequently the maximum (overall) deformation decreases. According to this theory, lateral resistant factors of structures can be distributed such that they exhibit more uniform deformations. In fact, the lateral load pattern determines how the lateral resistant factors should be distributed along the height of structures. In the present paper, by utilizing this theory an optimization algorithm is developed to obtain a new lateral load pattern to improve the seismic performance of zipper-braced frames.

## 4. Damage index

In recent years, almost all of the design procedures of structures attempted to quantitatively estimate the earthquake-induced damage in structures. Although the damage caused by the nonlinear response of the structure under earthquake excitation depends on many factors, for practical purposes most researchers consider maximum deformation as the main factor of structural and non-structural damages [28]. It means that if the maximum deformation of structure exceeds from allowable value, the structure will fail. Some researchers proposed the stories drift as the damage criteria and some of them preferred stories ductility, since the later criterion can take into account for the energy absorbed by the structure even indirectly. In this paper, the storey ductility has been considered as the structural damage index. In performance-based design methods, a structure may be designed based on two criteria: 1: "*Minimum Seismic Weight*" with specific performance level (target ductility). 2: "*Minimum Structural Damage*" with constant seismic weight. In the present study, the second procedure is regarded as the optimization criterion to reduce the global damage in the structures. The ductility ratio ($\mu$) is defined as the ratio of the maximum value of relative displacement of the story to the yield displacement of a story which can be presented as follows:

$$\mu = \frac{|\Delta_{max}|}{\Delta_y} \quad (2)$$

Where $|\Delta_{max}|$ and $\Delta_y$ are the maximum inter-story displacement demand and the yield inter-story displacement of the same story for a given earthquake ground motion, respectively.

## 5. Proposed procedure to achieve the uniform ductility

The adopted ZBF models introduced in the previous sections are used directly for nonlinear dynamic analyses. In ZBF systems, lateral resistance (total shear strength) of each story depends on the axial strength of the tension and compression braces. When the lateral displacement of the structure is increased, the tension brace is yielded and the compression braces are buckled. Figure 4 shows the behavior of ZBF systems when subjected to a lateral load. Since all beams are connected to columns by pin in the ZBF structure, the shear forces of columns are negligible. Thus, the lateral resistance of each story can be calculated by Equation (3).

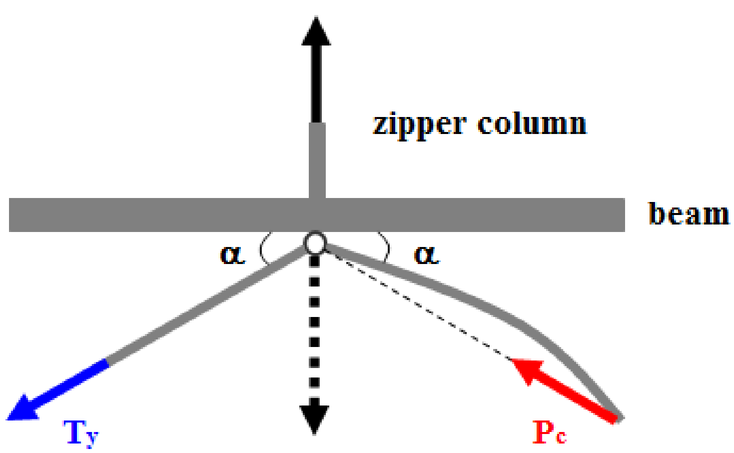



**Figure 4.** Behavior of a ZBF system under lateral load.

$$V_i = (T_{yi} + P_{ci})\cos\alpha = (\phi_n \sigma_y + \phi_c \sigma_{cr})A_i.\cos\alpha \quad (3)$$

Where $V_i$, $T_{yi}$, $P_{ci}$ and $A_i$ are the shear strength of *i*th story, yield strength, buckling strength and cross section area of *i*th story braces, respectively. According to the uniform deformation theory, to obtain the uniform distribution of deformations over the height of the structure and to reduce the maximum deformation in the structure, it is necessary to substitute the strong parts of the structure by the weaker ones. To this end, the lateral strength of each story should be modified in an iterative procedure such that the uniform distribution of damage along the height of the structure is achieved. For a given fundamental period ($T_i$), it is required to decrease or increase the cross section area of braces to reach the ductility ratio of each story, as damage criterion, to the average target ductility ratio. However, by changing the cross section area of ZBF braces, both the distribution of stiffness over the height of the structure and the structural fundamental period also change. This is inconsistent with the conception of uniform deformation theory and optimum lateral load pattern. The optimum lateral load pattern can be obtained by modifying the stiffness or strength of different stories while the fundamental period remains constant. In order to obtain the average ductility ratio in each story of the ZBF system for a given fundamental period, the braces area moments of inertia (I$i$) are modified instead of the braces cross section area. That is obtained by changing the geometric characteristics of braces section area as the shear strength of each story ($V_i$) depends on yield and critical stresses of braces (i.e., ($\sigma_y$) and ($\sigma_{cr}$) in Equation (3)). In other words, the yield stress ($\sigma_y$) of the braces depends on the material properties of braces while independent of the geometric characteristics of braces section. The critical stress ($\sigma_{cr}$) of the braces, however, is related to both aforementioned parameters through slenderness ratio parameter ($\lambda$). As a result, any modification in the story shear strength can be done by altering the slenderness ratio of the braces without any changes in fundamental period of vibration as follows:

$$\sigma_{cr} = \frac{\pi^2 E}{\lambda^2} = \frac{\pi^2 E}{A.(KL)^2}.I \qquad (4)$$

By substituting the Eq. (4) in Eq. (3):

$$\begin{aligned} & V_i = \phi_n \sigma_y A_i \cos\alpha + \phi_c \cos\alpha \frac{\pi^2 E}{(KL)^2} I_i \\ & \kappa_1 = \phi_n \sigma_y A_i \cos\alpha \\ & \kappa_2 = \phi_c \cos\alpha \frac{\pi^2 E}{(KL)^2} \\ & V_i = \kappa_1 + \kappa_2 . I_i \longrightarrow V_i \propto I_i \end{aligned} \qquad (5)$$

Equation (5) shows that if the total cross sectional area of braces is to be constant, the shear strength of each story would depend on the braces area moment of inertia. By utilizing this strategy, the fundamental period of the ZBF system will be constant and thus it is possible to change the lateral strength of each story (i.e., base shear) to achieve the average ductility ratio simultaneously. In the present study, the proposed method by Moghadam and Hajirsouliha [14] for shear building systems is developed for ZBF systems to reduce the maximum global damage and to obtain the uniform distribution of ductility ratio along the height of the structure in order to minimize the iteration steps:

1. Design the ZBF model based on the ASCE7-10 [23] lateral load pattern.
2. Select an earthquake ground motion.
3. Select a fundamental period of structure, and scale the total stiffness without altering the stiffness distribution pattern such that the structure has a specified target fundamental period based on proposed Equations of 4 and 5. Since the fundamental period of structure directly depends on cross section area of braces, the following equation is used for scaling the stiffness to reach the target period by just one step:

$$(A_j)_{i+1} = \left(\frac{T_i}{T_{target}}\right)^{\alpha} .(A_j)_i \qquad (6)$$

Where $A_j$, $T_i$ and $T_{target}$ are the cross section area of braces in the $j$th story, fundamental period in the $i$th step and the target period, respectively.$\alpha$ is iteration power, which is more than zero. Results of this study indicate that minimum iteration steps and fast convergence can be obtained for $\alpha$ equal to 2.

4. The ZBF structure is excited by a given earthquake ground motion. Then, the inter-story displacement ductility ratio of each story can be computed by dividing the maximum elastic inter-story displacement demand into the maximum inelastic inter-story displacement demand. Calculate the coefficient of variation (COV) of story ductility distribution along the height of the structure and compare it with the target value of interest, which is set here as 0.05. If the value of COV is less than the presumed target value, no iteration is necessary. Otherwise, total base shear strength must be scaled (by either increasing or decreasing) until a uniform distribution of ductility ratio along the height of the structure is achieved. As explained in Equation (5), due to direct relationship between the story shear strength and the area moment of inertia of each story braces, the following equation is proposed:

$$(I_j)_{i+1} = \left(\frac{\mu_{\max}}{\mu_{ave}}\right)^{\beta} .(I_j)_i \qquad (7)$$

Where $(I_j)_i$ is the area moment of inertia of braces in the $j$th story at the $i$th iteration. $\beta$ is iteration power, which is more than zero. Results of this study indicate that $\beta$ can be considered from 0.1 to 0.2 which to large extent depends on to the earthquake ground motion characteristics.

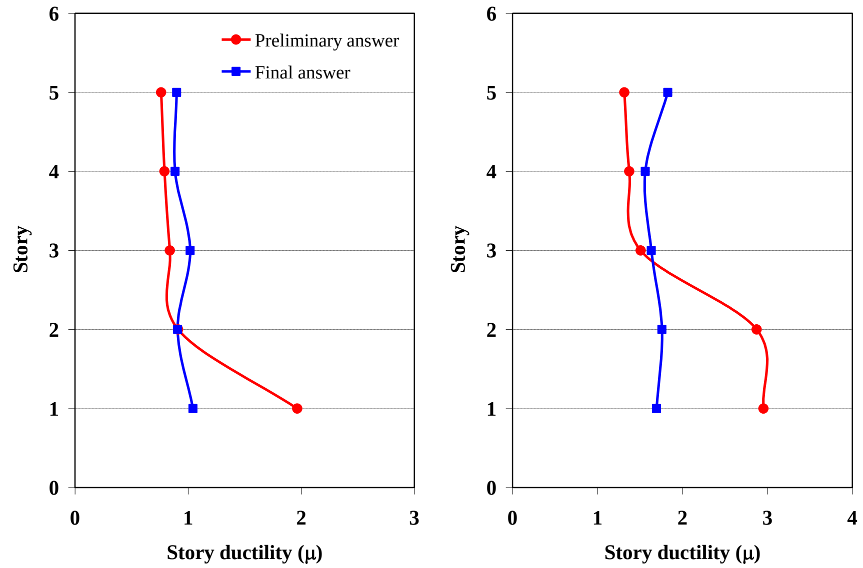
5. Repeat steps 3–4 for different target periods.

6. Repeat steps 2–5 for different earthquake ground motions.

## 6. Results and Discussions

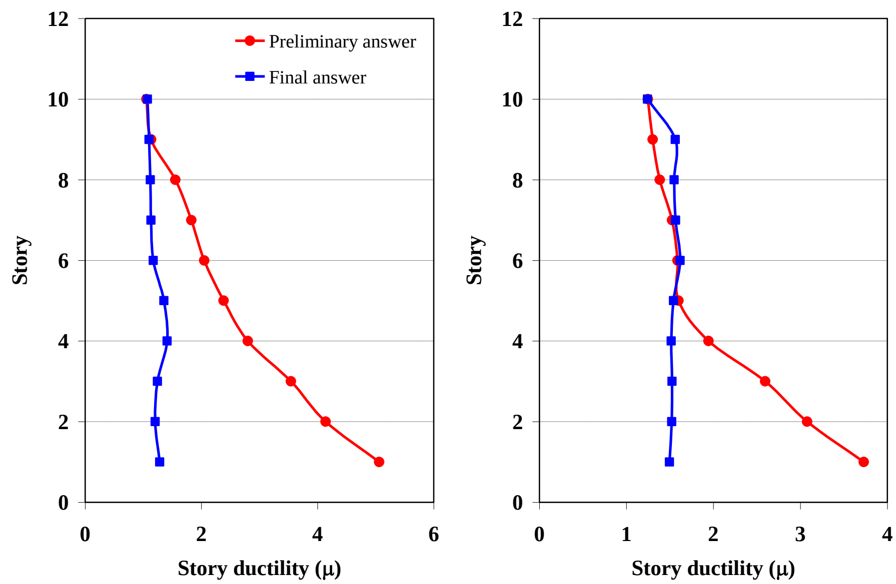
### 6.1. Efficiency of the uniform deformation theory for ZBF systems

As mentioned in the pervious section, the main objective of this study is to decrease the maximum ductility ratio ($\mu_{max}$) and to achieve the uniform ductility ratio ($\mu$) along the height of the ZBF structures. For this purpose, 5, 10 and 15 story ZBF models with the fundamental periods of respectively 0.4, 0.6 and 0.8 sec were designed and thousands of nonlinear dynamic analyses were performed subjected to selected earthquake ground motions. According to the proposed optimization algorithm described in the previous section, the uniform distribution of ductility ratio ($\mu$) along the height of the ZBF systems can be obtained through an iterative procedure. Figure 5-7 show the distribution of ductility ratio ($\mu$) for 5, 10 and 15 story ZBF structures under Landers and Morgan Hill earthquakes.




(a) (b)

**Figure 5.** Distribution of inter-story ductility demand ratio over the height of 5- story ZBF structure under (a) Landers & (b) Morgan Hill earthquakes.




(a) (b)

**Figure 6.** Distribution of inter-story ductility demand ratio over the height of 10- story ZBF structure under (a) Landers & (b) Morgan Hill earthquakes.

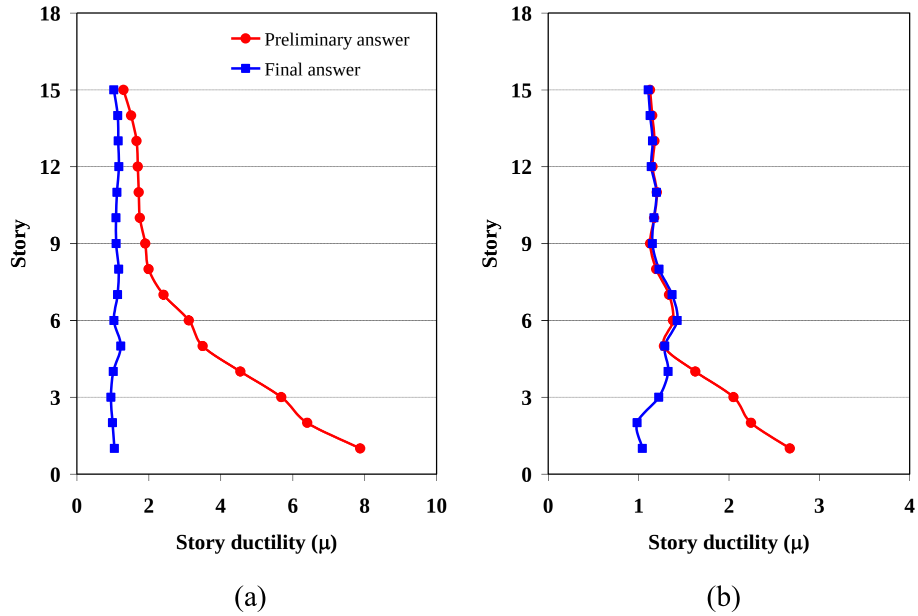



**Figure 7.** Distribution of inter-story ductility demand ratio over the height of 15- story ZBF structure under (a) Landers & (b) Morgan Hill earthquakes.

From these figure, it is found that the maximum ductility ratio in ZBF structures is generally occurred in the firs story. The reason of this result goes back to the hysteretic behavior of ZBF structures. As mentioned earlier, the hysteretic behavior of ZBF structures is controlled by the buckling behavior of compression braces over the height of the structure and this mechanism is initiated from the first story and will be extended over the height of the structure. Therefore, the distribution of damage along the height of the structure is non-uniform and the maximum damage occurs in the lowest story, which implies that the ZBF structure cannot exhibit its maximum capacity of energy dissipation. On the other hand, the results of this study show that by using the proposed uniform deformation theory the capacity of energy dissipation in ZBF structures significantly increases as shown in Figure 8. Results are provided for the mean distribution of ductility ratio ($\mu$) of 5-, 10- and 15-story ZBF structures subject to the 10 records of earthquake ground motions listed in Table 1. The results demonstrate the efficiency of uniform deformation theory for ZBF systems such that the reduction of mean maximum ductility ratios ($\mu_{max}$) for 5-, 10- and 15-story ZBF structures are %26.1, %55.4 and %52.7, respectively. Also, the C.O.V (%) of 5-, 10- and 15- story ZBF structures changes from %26.7, %27.8 and %25.6 for the initial structures to %4.3, %3.3 and %4.4 for optimum structures, respectively, which demonstrates the efficiency of the proposed algorithm.

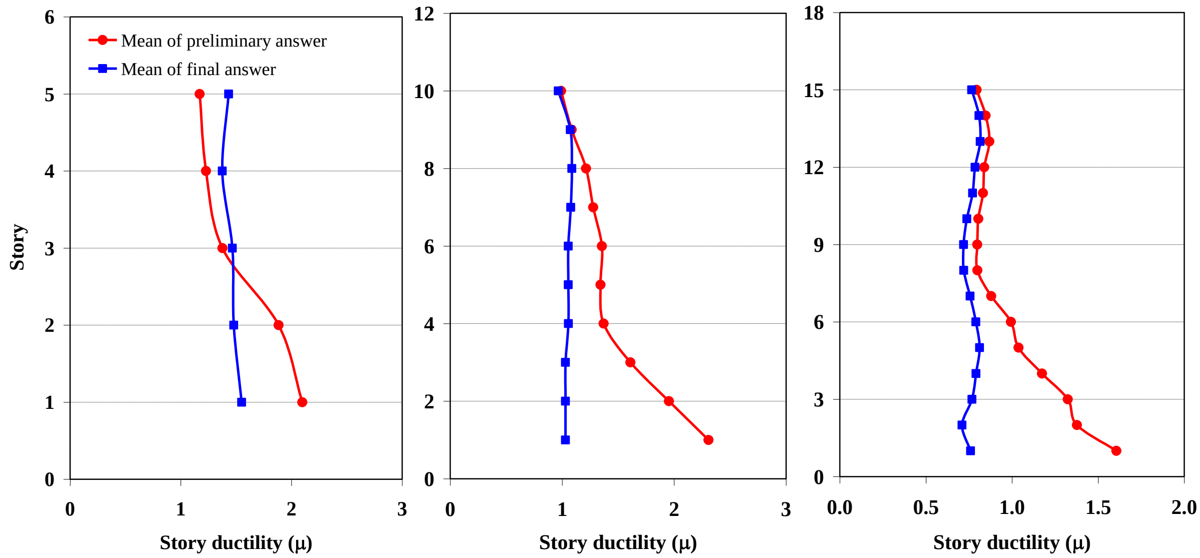



**Figure 8.** Distribution of ductility ratio in high of the 5-, 10- and 15- story ZBF structures; average of 10 earthquake ground motions.

## 6.2. Reduction of maximum damage

As mentioned earlier, to assess the damage states the maximum ductility ratio ($\mu_{max}$) can be considered as damage index for ZBF structures. Figures 9-11 show the variation of the maximum ductility ratio ($\mu_{max}$) and COV of stories ductility ratio ($\mu$) over the height of the structure under Landers earthquake for 5-, 10- and 15- story ZBF structures in each step.The results show that for the structure with constant structural weight the maximum ductility ratio ($\mu_{max}$) and COV decrease in each itération step. This implies That generally decreasing the structural damage index is always accompanied by reduction of the COV (i.e., more uniform damage distribution over height and less global damage). Therefore, the value of COV is directly related to the optimum lateral load pattern. It can be observed that the reduction amount of the maximum ductility ratio ($\mu_{max}$) under Landers earthquake for 5-, 10- and 15- story ZBF structures are %47, %72 and %66, respectively.

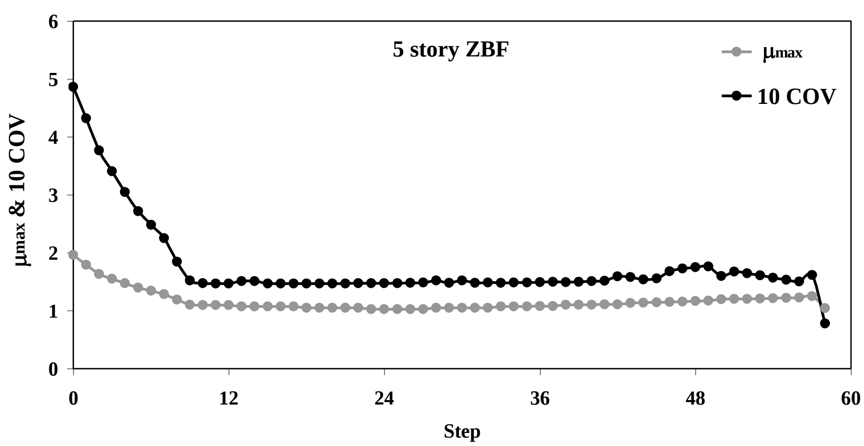



**Figure 9.** Variation of maximum ductility ratio and COV of 5-story ZBF system under Landers earthquake

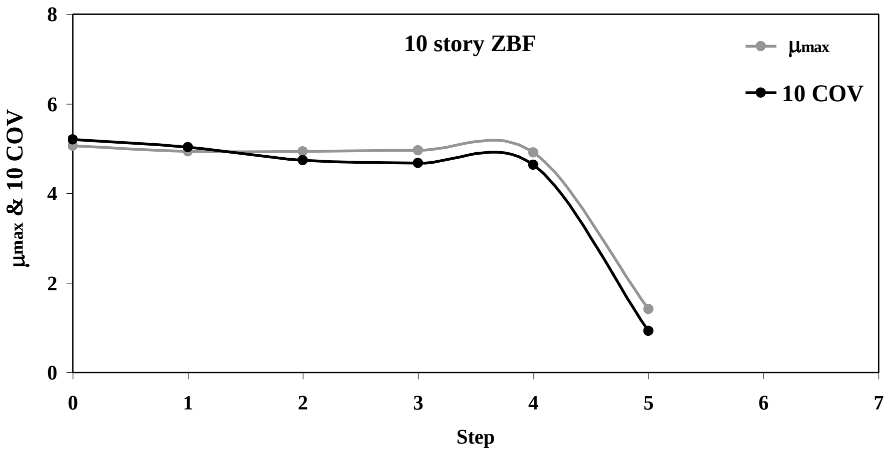



**Figure 10.** Variation of maximum ductility ratio and COV of 10-story ZBF system under Landers earthquake

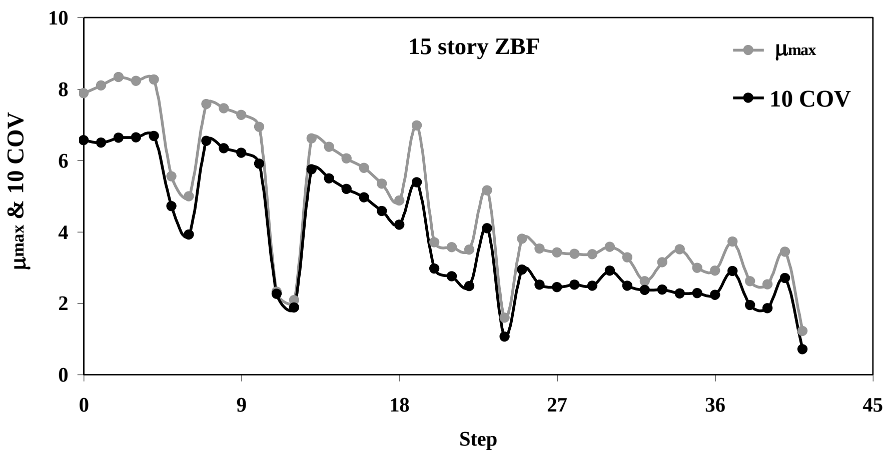



**Figure 11.** Variation of maximum ductility ratio and COV for 15- story ZBF system under Landers earthquake

## 6.3. Variation of structural weight

The main objective of the present study is to achieve uniform ductility ratio along the height of the ZBF structures while the maximum ductility ratio is decreased and the seismic weight is remained constant. It is assumed that the weight of the lateral load-resisting system at each story, $W_{Ei}$, is proportional to the story shear strength, $S_i$. Therefore, the total weight of the seismic resistant system, $W_E$, can be calculated as:

$$W_E = \sum_{i=1}^{n} W_{Ei} = \sum_{i=1}^{n} \lambda . S_i = \lambda . \sum_{i=1}^{n} S_i \qquad (8)$$

Where, λ is the proportioning coefficient. If the values of total seismic weight of the ZBF structure in initial and final steps are assumed $(W_E)_I$ and $(W_E)_F$ ,respectively, the relative weight (*RW*) will be defined as:

$$RW = \frac{(W_E)_F}{(W_E)_I} \tag{9}$$

To evaluate the variation of the ZBF structural weight, the Landers and Morgan Hill earthquakes were selected and the *RW* values 5-, 10- and 15- story ZBF models were calculated and the results are depicted in Figure 12.

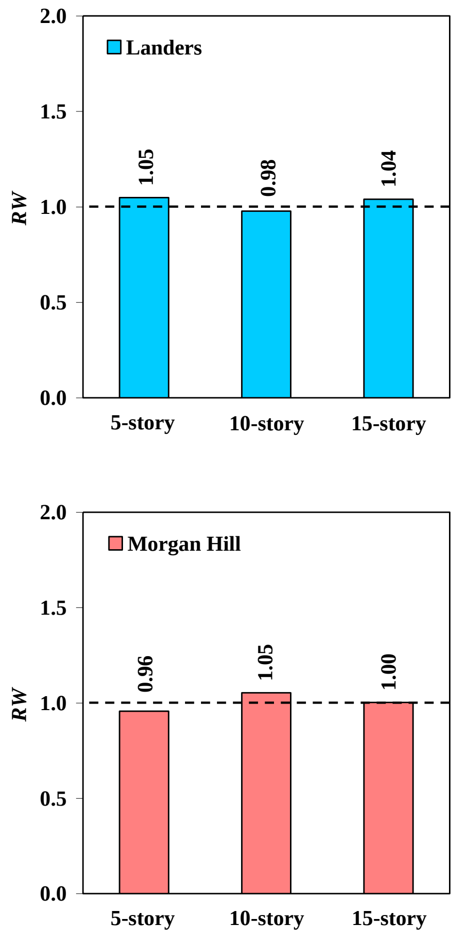



**Figure 12.** Variation of relative weight of 5-, 10- and 15- story ZBF structures under Landers and Morgan Hill earthquakes

It is clear that when the values of *RW* are equal to 1, the variation of structural weight during the achievement of uniform ductility ratio is negligible, and the structural weight is approximately constant. The results of Figure 12 show that the maximum variations of *RW* for 5-, 10- and 15- story ZBF structures are less than %5. It can be concluded that in the present study, the total weights of the ZBF structures to achieve the uniform distribution of ductility ratios will be constant, confirming the concept of the selected damage index for the current study.

## 6.4. Variation of iteration power (β)

Iteration power (β) is a key factor of convergence rate to achieve the uniform deformation along the height of the structure. In this study, the initial value of iteration power (β) is assumed 0.1 and, then, during the iteration process this factor is automatically modified in each step such that the most suitable convergence power can be obtained. Figure 13 illustrates the variation of iteration power (β) in each step for 10-story ZBF structure under Borrego Mtn, Loma prieta and Morgan Hill earthquakes. It is found that: (1) the variation of iteration power (β) strongly depends on the characteristics of each earthquake, (2) the variation of the iteration power (β) pattern is very non-uniform when the β value is selected greater than 0.2. The reason of the high sensitivity of the iteration power (β) may go back to the buckling behavior of ZBF structures.

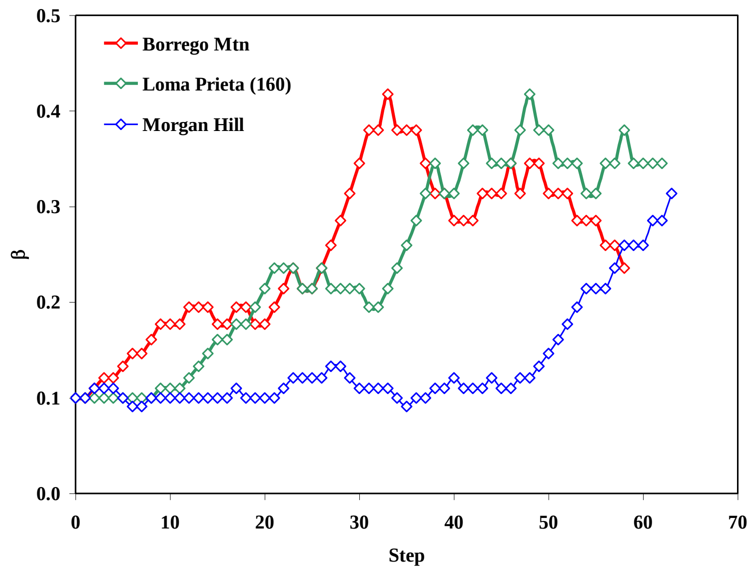



**Figure 13.** Variation of the iteration power for 10- story ZBF structure under Borrego Mtn, Loma prieta (160) and Morgan Hill earthquakes

To compare the iteration power (β) of 5, 10 and 15 stories ZBF models subjected to the 10 earthquake ground motions listed in Table 1, a column chart was developed. Figure 14 shows the variation of mean iteration power for 5, 10 and 15 stories ZBF structures. As a mentioned above, the variation of iteration power (β) strongly depends on the characteristics of each earthquake while it is observed that in most of earthquakes the mean iteration power (β) between 0.1 and 0.2 provides an appropriate convergence.

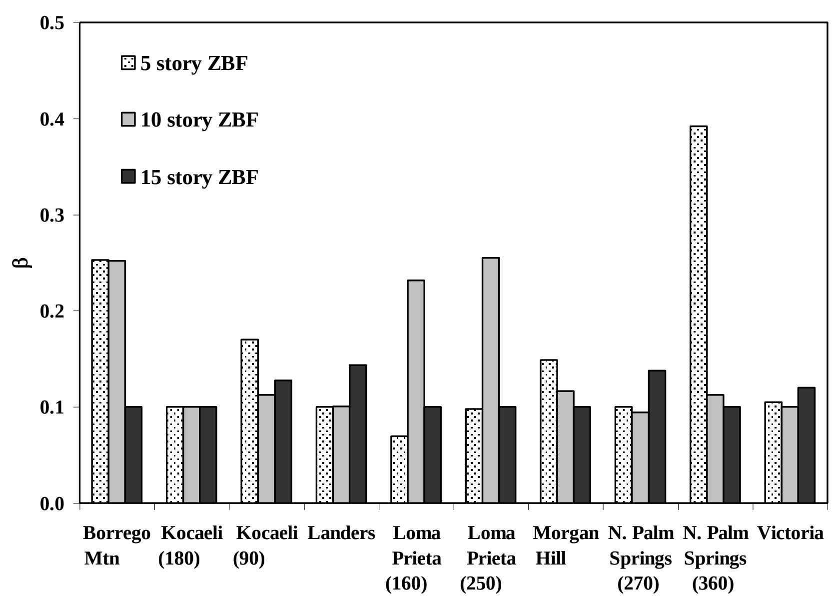



**Figure 14.** Variation of the mean iteration power for 5-, 10- and 15- story ZBF structures under 10 earthquake ground motions

## 7. Conclusions

This paper developed a Performance-Based Optimization algorithm for Zipper-Braced Frames. Five- ten- and fifteen-story steel Zipper-Braced Frame (ZPF) systems with constant structural weight were considered. Since the seismic behavior of ZBF structures and their structural damages significantly depend on behavior of story braces, by modifying the braces characteristics along the height of the structure, the stories lateral strength were tuned such that inter-story ductility ratios over the height of the structure are distributed more uniformly. By using the proposed optimization theory the capacity of energy dissipation in ZBF structures significantly increases, and consequently the designed structure would be more cost-efficient compared to corresponding code-based structures.The main objective of this study is to obtain uniform deformations and decrease maximum structural damage in ZBF structures. According to the results of this study, the following conclusions are made:

- An optimization algorithm for optimum seismic design of zipper braced frames considering both inelastic and buckling behaviors has been developed in the present study. The proposed optimization procedure is based on the constant structural weight criterion to achieve uniform height-wise distribution of inter-story ductility ratio for decreasing the global structural damage. Results demonstrate the efficiency of the proposed algorithm for ZBF systems.
- The results indicate that for constant structural weight, structures designed based on the proposed algorithm experience up to 50% less global ductility ratio (damage) compared with code-based structures.
- For the structure having constant weight the maximum ductility ratio ($\mu_{max}$) and COV decrease in each iteration step. This implies that generally decreasing the structural damage index is always accompanied by reduction of the COV (i.e., more uniform damage distribution over the height and less global damage).
- The variation of iteration power ($\mu$) strongly depends on the characteristics of each earthquake while it is observed that in most of earthquakes, in average, the iteration power ($\mu$) between 0.1 and 0.2 provides an appropriate convergence.
- Based on the proposed optimization algorithm, the variation of structural weight in ZBF structures is negligible and can be assumed to be constant during the achievement of the uniform ductility ratios along the height of the ZBF structure. This result confirms the concept of the selected damage index for the current study.

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