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RESEARCH ARTICLE

The Effect of Different Braced Configurations on the Nonlinear Seismic Behavior of Steel Structure

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Abstract

Improvements in construction technologies have allowed steel structural elements to become more frequently used today in order to enable different architectural designs and to meet structural performance more effectively and efficiently. Structural steel has been used for more than a hundred years and has been tested under real earthquakes, which provide the basis of many earthquake-resistant steel construction standards. The major advantage of steel construction material is that it allows for large plastic deformations. Structural deformations vary depending on the deformation capacity of the structural components in addition to the configuration of the structural components. In this study, moment resisting frames (MRF), X braced frame (XBF), Inverse V braced frame (IVBF), K braced frame (KBF), and eccentric inverse V braced frames (EIVBF) were used to examine the effect of different steel braced systems on the plastic deformation capacity of steel structure with the help of nonlinear static pushover analysis. Bilinear material model was utilized to represent nonlinear steel material behavior and inelastic displacement-based frame element were used to represent column and beam element. The analyses' results demonstrated that the braced frame configuration had a significant effect on the lateral response of steel frame structures.

Keywords: Steel Structures, Nonlinear behavior, Pushover analysis, Steel braced configuration

1. Introduction

The steel is one of the most frequently used as a construction material in civil engineering structures due to its strength and ductility properties result in smaller dimensions of the structural elements. The most important feature of the steel frame structure is its ductile behavior and potential to dissipate energy, especially in the case of earthquakes. These characteristics ensure the economical design of the structure and improve the resistance with respect to seismic security [1]. The failure percentage of steel structures has always been quite small in comparison to other construction materials [2].

The lateral load resistance capacity of steel structures depends on the behavior of the material itself, the structural connections and steel braced frames. Moment resisting frames and braced frames has been generally used as lateral load resisting structural elements in steel buildings. Inelastic behavior of braced frames subjected to lateral loads is strongly dependent on the behavior of bracing members. Concentrically-braced frames (CBFs), eccentrically-braced frames (EBFs) and the knee-brace frames (KBFs) are often used systems. Common configurations for CBFs encompass V and inverted-V bracings, K, X and diagonal bracings [3].

Researchers have been focused on the investigation of these effects on steel structural behavior due to their aforementioned characteristics in a potential usage of the seismic resisting system. The bilinear stress-strain and the multisurface plasticity model were used for the material model of steel structures [4]. The bilinear and multisurface model response predictions for cyclic and dynamic tests

on beam-columns were compared to each other. It is concluded that accurate response predictions were obtained from the bilinear model in the absence of material test data under cyclic loading. However, the multisurface model provides a significantly closer response to experimental results, due to its ability to model a yield plateau and a non-linear strain-hardening regime as well as cyclic degradation. The applicability of the usage of stainless steel (SS) in the seismic design of braced frames, either concentrically (CBFs) or eccentrically (EBFs) braced was investigated [5]. A sample of the regular multi-story CBFs and EBFs was created in compliance with modern seismic standards based on capacity-design rules. The results of the pushover and inelastic response history analyses showed that systems utilizing SSs presented enhanced plastic deformations and excellent energy-absorbing capacity with respect to mild steel braced frames. Yoo et al. (2009) [6] performed a comprehensive series of inelastic analyses to better examine the nonlinear, cyclic behavior of the multi-story X-braced frames and their gusset plate connections. Finite-element analyses were developed and verified by comparing the simulated results with cyclic tests and nonlinear analyses of single-story systems. The study shows that the multi-story, X-braced configuration has the potential to reduce the propensity for concentrating inelastic action into a single story, which is a promising solution for seismic design and the design. In addition, the detailing of the gusset plate has an important effect on the seismic performance of the frame.

Asgarian et al. (2011) [7] examined the seismic performance of steel frames equipped with super-elastic shape memory alloy (SMA) braces. Buildings with various stories and different bracing configurations,

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including diagonal, split X, chevron (V and inverted V) bracing. Nonlinear time-history analyses of steel braced frames subjected to three ground motion records have been performed using OpenSees software. The study concluded that using an SMA element increased the dynamic response of structures subjected to earthquake excitations. Also, SMA braces reduced in residual roof displacement and peak inter-story drift compared to the buckling restrained braced frames. A newly developed seismic force-resisting system called the strongback system was studied by Lahi and Mahin (2014) [8]. The system combines aspects of a traditional concentric braced frame with a mast to form a hybrid system in order to obtain improved seismic performance with the goal of preventing deformation concentration in steel-braced frames. The performances of three conventional braced frame systems and three strongback systems were analyzed using static pushover analyses and nonlinear dynamic response history analyses. The study concluded that the seismic force-resisting system can effectively diminish the concentration of deformations using the proposed design strategy.

Baijan et al. (2014) [9] was investigated a mega steel frame-prestressed composite bracing structure with a rigid-flexible composite bracing system composed of rigid Λ -shape steel braces and inverted Λ -shape flexible cable. The structural performance under static load and the energy dissipation, as well as the failure mode under earthquake, were examined for the system. The results showed that the lateral deformation was mainly depended on horizontal load, and the corresponding curve of lateral displacement had the characteristic of flexure mode as a whole. The other study represented the use of SMA bracing and steel bracing (Mega) utilized in steel frames [10]. The effectiveness of these two systems in rehabilitating mid-rise eight-story steel frame was investigated using time-history nonlinear analysis using SeismoStruct software. Results illustrated that both systems made an increase in the strength and stiffness of the original structure. However, because SMA had an excellent behavior in the nonlinear phase and under compressive forces, this system demonstrated much better performance than the rehabilitation system of Mega bracing.

Patil and Sangle (2015) [11] aimed to compare the seismic behavior of different bracing systems, moment-resisting frames. Chevron braced frames, V-braced frames, X-braced frames and zipper braced frames (ZBFs), in high rise 2D steel buildings. Nonlinear static pushover analyses were carried out to evaluate the structural performance on different bracing systems in high rise steel buildings of 15, 20, 25, 30 and 35 stories. The study concluded that the different braced frames performed well in terms of story displacement, inter-story drift ratio, base shear and performance point when compared with the moment-resisting frame in high rise steel buildings. A numerical study [12] was performed to investigate and compare the response of chevron and suspended zipper braced frames. Three and nine-story buildings were designed for both brace configurations and analyzed under static and dynamic loadings. Member deformations, member forces, inter-story drifts, top story drifts, base shares were determined for each analysis. The beams, columns and braces were modeled by using nonlinear force formulation frame elements. The results indicated that the lateral load capacity and drift demands for both low-rise chevron and suspended-zipper braced frames were very similar; however, the mid-rise chevron braced frame had a better performance compared to the mid-rise suspended-zipper braced frame.

A study by Nassani et al. (2017) [13] presented a comparison of the seismic response of steel frames by using different types of bracing systems. The bracing systems are X-braced frames, V braced frames, Inverted V braced frames, Knee braced frames and zipper braced frames. The steel frames consisting of three bays are modeled as four different height levels and nonlinear static and dynamic analyses were performed. The results demonstrated a good improvement in the seismic resistance of frames with the incorporation of bracing. The effect of the bracing configuration on the seismic response of a five-story prototype office building was systematically investigated [14]. Five different bracing configurations were created according to the National Building Code of Canada and CSA S16 standard. Detailed structural responses, initial costs, and life cycle costs of the prototype building with five different bracing configurations were

systematically compared. The results represent that the different bracing configurations have significant effects on sizing the structural members, therefore, the initial material usage and the overall life-cycle cost of the building.

The present study assessed to compare the seismic performance of steel moment-resisting frames and different bracing systems in a 2D steel structure. MRF, XBF, IVF, KBF, and EIVF structural brace configurations were used. The structural response of each bracing system and its effect on the behavior of steel frames under seismic loading has been investigated. Nonlinear static pushover analyses were carried out to assess the structural performance of different bracing systems. Bilinear material model was utilized to represent nonlinear steel material behavior and inelastic displacement-based frame element were used to represent column and beam element. It can be concluded from the comparisons of the obtained results that the use of XBF and KBF has significant increases in the lateral rigidity of the steel structure.

2. Basic Concept of Pushover Analysis

The inelastic static pushover analysis is a method that predicts seismic force and deformation demands, which accounts for an approximate manner for the redistribution of internal forces. In this approach, the behavior of the structure can be related to the response of an equivalent single-degree-of-freedom (SDOF) system. This means that the response is controlled by a single-mode and that the shape of this mode remains constant throughout the time history response. Some researchers [15, 16] have shown that these assumptions conduct to rather good predictions of the maximum seismic response of multi-degree-of-freedom (MDOF) structures, yield their response is controlled by a single-mode. This section explains basic assumptions and equations about the pushover analysis. A more comprehensive explanation about it can be found in the literature [17, 18].

By using the assumption that the deflected shape of the MDOF system can be represented by a shape vector, $\{\phi\}$ that remains constant throughout the time history, regardless of the level of deformation and defining $X = \{\phi\}x_t$, the governing differential equation of an MDOF system can be written as [17];

$$M\{\Phi\}\ddot{x}_t + C\{\Phi\}\dot{x}_t + Q = -M\{1\}\ddot{x}_g \quad (1)$$

By defining the reference SDOF displacement X^* as;

$$x^* = \frac{\{\Phi\}^T M \{\Phi\}}{\{\Phi\}^T M \{1\}} x_t \quad (2)$$

and pre-multiply Eq. (1) by $\{\phi\}^T$ and substitute for x_t using Eq.(2), it can be obtained the following differential equation for the response of the equivalent SDOF system;

$$M^* \ddot{x}^* + C^* \dot{x}^* + Q^* = -M^* \ddot{x}_g \quad (3)$$

M^* , C^* , Q^* denote the properties of the equivalent SDOF system and are expressed by;

$$M^* = \{\Phi\}^T M \{1\} \quad (4)$$

$$C^* = \{\Phi\}^T C \{\Phi\} \frac{\{\Phi\}^T M \{1\}}{\{\Phi\}^T M \{\Phi\}} \quad (5)$$

$$Q^* = \{\Phi\}^T Q \quad (6)$$

By using the assumption that the shape vector is known, the force-deformation characteristics of the equivalent SDOF system can be evaluated from the results of a nonlinear incremental static analysis of the MDOF structure [17].

3. Description of the Analytical Models

In this study, a steel structure designed by considering DBYBHY 2007 Turkish seismic code was used. The structure has six stories consist of four bays in one direction eccentrically braced to carry the lateral wind and seismic load. In addition, moment-resisting frame with three bays is used to carry the lateral load in the other direction.

The building was designed as a typical office building; therefore, gravity load and the live load were chosen as 4.9 kN/m² and live load 2.0 kN/m², respectively. Seismic loads were calculated according to DBYBHY 2007 by considering effective ground acceleration coefficient, A₀, as 0.4, building importance factor, I, as 1, soil type as Z2 and seismic load reduction factor, R_x, as 7 for braced direction, R_y, as 8 for the moment-resisting frame direction. The equivalent seismic load method was utilized to design the steel structure. A strong column-weak beam assumption was performed to design the moment steel frame. Steel material was assumed as S355 with F_y=355 N/mm², and F_u=510 N/mm². Fig. 1 shows the plan view of the steel office structure.

Figure 1. Plain view of the steel office structure

In this study, a moment-resisting frame and four different braced configurations of a steel structure were considered. The braced configuration was applied to “A” axle, and the moment frame configuration is applied to the fifth axle shown in Fig. 1. The most used brace systems, XBF, IVF, EIVF, and KBF, in steel structure, were analyzed. It is known that the XBF structure is able to carry the biggest percentage of the lateral loads by brace element, and the braced are expected to reach the nonlinear capacity. Compressions braced are immediately failed after buckling means that it reaches compression capacity, and tension brace continue to carry the lateral load until the system becomes unstable. Because of the performance characteristics of the XBF, these systems have extensive deformation capacity in the nonlinear part. In IVF and EIVF braced, systems are connected to the middle of the beam with a contribution of the lateral load. Thus, large moment and plastic deformations are exposed in the middle of the beam, and the structure were subjected to important plastic deformations. In the KBF frame system, lateral force's transfer from compression braces to tension braces and after compression braces reach its buckling capacity, the lateral forces start to transfer from braces to the adjunctive columns, and nonlinear deformations may be observed in these columns. The nonlinear behavior of the column allows the structure to have more displacement capacities after exceed its elastic part. Fig. 2 shows the investigated steel structural configurations.

Figure 2. Structural configurations

(a) moment-resisting frame, (b) IVF, (c) EIVF, (d) KBF, (e) XBF

The finite-element (FE) model of structures was created by using SeismoStruct [19]. Bilinear steel material model was used in the FE model that allowed us to consider linear kinematic strain hardening of the steel material. Columns and beams were modeled as inelastic

displacement-based frame elements that ensured to consider geometric and material nonlinearities. Also, inelastic truss elements were employed to define braced members. Dead load and thirty percentage of live load were applied to beam element and lateral load

calculated according to equivalent distribution method were applied to each story node in the lateral direction.

4. Results

The modal parameter is an important issue to understand the behavior of steel structures. The increase in lateral rigidity decreases the modal period of the structure. Table 1 shows the obtained first three modal periods and Fig. 3 represent the identified first three mod shapes of the moment-resisting and four braced steel frame structures. The smallest periods were found in the XBF and IVBF structure, and the largest period existed in the moment-resisting frame. The modal parameter showed that the biggest lateral rigidity was expected to be in the XBF and IVBF structure, and the smallest lateral rigidity was supposed to be in the moment-resisting frame structure.

Table 1 Fundamental period vibration(s) by modal analysis.

Type of buildings	Periods (s)		
	1st	2nd	3rd
EIVBF	0.1207	0.0424	0.0240
XBF	0.0994	0.0323	0.0213
KBF	0.1162	0.0392	0.0229
IVBF	0.0976	0.0344	0.0203
Moment Frame	0.2595	0.0836	0.0458

the gravity load and lateral displacements due to the second-order effect. These second-order effects were also considered in the FE analysis. Lateral seismic loads applied to the nodes of the structures were increased to target displacement. The maximum lateral displacements expected as %4 of the total height of the structure offered in ATC-40 [20] was calculated as $18500 \times 0.04 = 740 \text{ mm}$. Capacity curves of the steel frame structures were illustrated in Fig. 4.

Capacity curves of structures were illustrated that moment-resisting frame had the smallest base shear capacity, however, it demonstrated more nonlinear displacement capacity than the other structural systems. EIVBF and KBF showed similar initial rigidity, but the maximum top displacement was calculated as 0,27 meters in EIVBF, “because of the second-order effects and losing rigidity due to the plastic deformation” failure of the structure was visualized after reaching these displacements. The buckling of the compression frames was a critical issue for KBF. After one compression braces failed, tension braces continued carrying the load, and the structural system could reach more lateral displacement without fail. XBF and IVBF appeared to have the largest initial rigidity. The failure occurred in the IVBF steel structure after the maximum top displacement reached 0,38 meters. The buckling of the compression part of the IVBF frame decreased the lateral rigidity of the structure. failure in compression braces resulted in a redistribution of the lateral load from braced elements to the main beam, therefore, significant nonlinear deformations initiated on the main beam. As a result of these deformations, the structural system became unstable, and failure of the structural system visualized.

Pushover analyses are conducted by considering large displacement and material nonlinearity. With the increase of the lateral displacement, the moment acting on the systems increased related to

Figure 3. First three mod shapes of steel structures
(a) moment-resisting frame, (b) IVF, (c) EIVF, (d) KBF, (e) XBF

Figure 4. Pushover curve of the steel structures

It was understood from the analysis results that the XBF structure had the biggest initial rigidity and more nonlinear displacement capacity than the other braced structures. In addition, the XBF structure carried the largest base shear force. After the buckling of the compression brace in the XBF system, the structure started to lose some lateral rigidity, but the tension braced elements continued to contribute lateral resistance capacity of the structure. After the structure reached its maximum nonlinear displacement capacity, failure of the structure took place. Fig. 5 shows the deformed shape of the building at maximum top displacement condition.

Figure 4. Deformed shape of the building model under maximum top displacement condition
(a) moment-resisting frame, (b) IVBF, (c) EIVBF, (d) KBF, (e) XBF

Different brace condition resulted in the different nonlinear deformation target. In the IVBF structure, the braces and main beam reached its plastic capacity and the plastic deformations were concentrated on the first three floors. In the EIVBF structure, the nonlinear deformations concentrated in the middle of the main beam. The gaps between the two braces were exposed to extensive nonlinear deformations and consumed large seismic energy. Similar to the IVBF structure, the nonlinear deformation concentrated on the first three floors in the EIVBF structure. In the KBF structure, the buckling braces were seemed to be critical to lateral rigidity and nonlinear deformation concentrates on the first two floors. In XBF structure, buckling of compression braces was crucial and nonlinear deformations were visualized on the first two floors. In the MRF structure, both the main beam and column on the first four floors were exposed to extensive nonlinear deformation. Fig. 6 shows initial rigidity and maximum base shear of the building.

Figure 6. Initial rigidity and Maximum base shear of the building.

Initial rigidity of structures had a strong correlation with the maximum base shear of building. Also, the frequency of the first mode of the structures had a strong correlation with initial rigidity and maximum base shear acting on the structure.

Conclusion

This study aimed to perform a nonlinear pushover analysis on a moment-resisting frame and four braced steel office structure. Bilinear material model was used to represent nonlinear steel material behavior and inelastic displacement-based frame element were employed to describe column and beam element mechanical behavior. Brace member was defined using an inelastic truss element. Both material and geometric nonlinearity were considered in pushover analysis and capacity curves for each structure were examined. The main conclusions of this study are the following.

- XBF had the biggest initial lateral rigidity and exposed to the largest base shear force. Large nonlinear deformation visualized, and the structural system demonstrated significantly positive behavior considering the other system.
- EIVBF and IVBF system could not reach the target displacement of 0,74 meter and failure of the structures was occurred at 0,38 meter and 0,27 meter, respectively. These structural systems caused large nonlinear deformation on the main beam.
- Moment-resisting frame had the smallest initial rigidity and exposed to the smallest base shear force but had the largest nonlinear deformation capacity. The plastic deformations were distributed to the first four floors on both columns and beam. Therefore, the moment-resisting frame had a large energy consumption capacity.

Symbols

X Relative displacement vector

x_t Roof displacement

M Mass matrices

C Damping Matrices

Q Story force vector

$\ddot{x}_g$ Ground acceleration

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest.

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