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Comparative Response Assessment of Steel Frames With Different Bracing Systems Under Seismic Effect

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ABSTRACT

The field of earthquake engineering and seismology is of a great importance to structural engineers around the world. Choosing an appropriate lateral force resisting system has a significant effect on performance of the steel structure. The paper presents 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 are modeled and analyzed in four different height levels. Nonlinear static and dynamic analyses were performed. The frames consist of three bays and steel braces were inserted in the middle bay of each frame. The structural responses of frames are studied in terms of capacity curve, drift ratio, global damage index, base shear, storey displacements, roof displacement time history and plastification. The results showed a good improvement in the seismic resistance of frames with the incorporation of bracing. The results revealed that the bracing elements were very effective in diminishing drifts since the reduction of inter-storey drifts with respect to unbraced frames were on the average 58%. Also steel braces considerably reduced the global damage index.

1. Introduction

Steel structures are obviously one of the most common choices for residential building constructions in the world. Different types of bracing systems are used in these structures [1–6]. Braced frames categorize into two different types, concentric and eccentric, which have specific characteristics and design requirements.

In seismically active zones, structures are subjected to lateral earthquake forces in addition to bearing the primary gravity load. The performance of a structure during an earthquake depends on the intensity of the earthquake and the properties of the structure.

In case of high rise buildings, stiffness is more important than strength. Moment resisting frames and braced frames have been commonly used as lateral load resisting structural elements in steel buildings. Moment resisting frames provide ductility through yielding, but due to their flexibility, they do not satisfy stiffness criteria [7]. There are several ways of providing braces to increase the seismic resistance of buildings. The different bracing systems include typical diagonal bracing, X-bracing, chevron bracing and V-bracing configurations, which connect the brace concentric to beam-column joint. Roeder & Popov [8] and Hjelmstad & Popov [9] proposed another bracing system, named eccentric bracing, combining good features of both moment resisting frame and concentric braced frame. In eccentric braced frames, energy dissipation capacity in a seismic excitation is provided by shear links that are an integral part of a beam. However, after a severe earthquake, replacing a damaged shear link can be time consuming and expensive as it is a primary structural component. Recently, Ochoa [10] has proposed an alternative system, named knee braced frame. In this system, the ductile fuse element is used to prevent collapse of the structure by dissipating energy through flexural yielding of the knee element. Subsequently, Balendra et al. [11,12,13] re-examined the knee braced frame and proposed some modifications and the results indicated that the knee braced frame is an attractive alternative system for earthquake resistant steel buildings. It has a clear advantage of greatly reduced floor damage.

The seismic performance of non-ductile chevron braced frames can be improved by delaying the fracture of braces. This can be achieved in chevron by redesigning the brace and floor beams to a weak brace and the strong beam system. This upgraded chevron braced frame results in an excellent hysteretic response, where in ductile braces provide a reasonable distribution of damage over the height of building [14]. Tremblay et al. studied seismic performance of concentrically braced steel frames i.e. diagonal braced frame and X-braced frame, under cyclic loading [15]. In addition, the maximum ductility was achieved

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by rectangular hollow bracing members [16]. Yang et al. proposed a design methodology for zipper-braced frames aimed at achieving a good ductile behavior [17]. The zipper elements demonstrated their ability to activate buckling in all storeys except the top one, by redistributing the loads in the structure [18]. Similarly, Nouri et al. investigated the limitations of concentric braced frames subjected to seismic loading and proposed zipper braced configuration to mitigate the vertical unbalanced force in case of chevron braced frame [19].

Many experimental and analytical studies have been conducted on the hysteretic behavior of steel braces under severe cyclic load provided useful information on the effect of several properties of the braces on their cyclic inelastic response. Inelastic modelling of steel braces can be classified into three broad categories: phenomenological, continuum finite element, and physical theory models. Phenomenological models are based on simplified hysteretic rules simulating the experimental cyclic axial force–deformation relationship of braces, whereas finite element models subdivide the brace longitudinally into a number of elements where the geometry and material properties of each element are defined. Such finite element models provide the most accurate approach to simulate the brace behavior [20]. On the other hand, D'Aniello et al. [21] discussed the physical theory model approach in which the brace hysteretic behavior is usually modeled with two elements connected by a generalized plastic hinge for braces simply pinned. Physical theory models of braces have been implemented using force-based finite elements with fibre discretization of the cross-section [21]. Moreover, the accuracy and the suitability of the existing formulations of the initial camber width were verified in the physical theory model [22]. Besides, it should be noted that some parameters such as the plastic local buckling, the low-cycle fatigue effects were not considered in physical theory models. It is interesting to note that the analyses performed with different plasticity models showed that the elapsed time for the analysis with concentrated plasticity elements is lower than in the analysis with distributed plasticity. In this study, analyses have been performed by the concentrated (lumped) plasticity model.

Shen et al. [23] carried out a numerical study on similar buildings and they concluded that brace-intercepted beams designed with the minimum possible required strength permitted by the current US design provisions could undergo significant vertical inelastic deformations for interstorey drift ratios ranging within 0.02–0.04. In addition, they observed that the inelastic deformations in the middle spans of brace-intercepted beams considerably increase ductility demands on both braces and beam-to-column connections. In line with those results, D'Aniello et al. [24] highlighted that the relative beam-to-brace stiffness is the key parameter characterizing the performance of chevron braced frames. In particular, they showed the relationship between ductility demand of braces and the flexural stiffness of braced-intercepted beam. Experimental tests carried out for classic eccentric bracing of steel buildings have consistently shown that peak inelastic shear forces up to 1.4–1.5 times the plastic shear strength can develop at plastic link rotations of about 0.08–0.1 rad (plastic overstrength). However, more recent tests have shown that larger forces could be developed. Three basic parameters are devised as influencing shear overstrength: (i) axial forces acting on the link, (ii) the ratio of link flange over web area and (iii) the ratio between link length and cross section depth [25].

New Zealand design procedures stated that if eccentrically braced frame structures were pushed into the inelastic range, necessitating replacement of active links in some buildings, the design procedures have been adapted to accommodate the replaceable link concept. This concept will allow for rapid inspection and replacement of yielded and damaged links following a major earthquake, thereby permitting the structure to be economically brought back to its original safety level.

In this study, an attempt is made to assess the seismic behavior of different braced and unbraced systems in steel frames by using six structural configurations: moment resisting frames (MRFs), X-braced frames (XBFs), V braced frames (VBFs), inverted V braced frames (IVFs), Knee braced frames (KBFs) and zipper braced frames (ZBFs). The structural response of each bracing system and its effect on the behavior of steel frames under seismic loading has been evaluated. The steel frames are modeled and analyzed in four different height levels of 4, 8, 12 and 18. Nonlinear static and dynamic analyses were performed. The frames are dual-steel system which consists of a moment-resisting frame which resists the gravity load and partially seismic load. These frames equipped with braces which resist the seismic load.

2. Description of the analytical models

The structures studied in this research were unbraced and braced buildings with 4, 8, 12, and 16 storeys. The different bracing systems are XBFs, VBFs, IVFs, KBFs and ZBFs along with MRF systems. The buildings consist of three bays in each direction as shown in Fig. 1 and steel braces were inserted in the middle bay. Frame selected for analysis is shown in plan of the buildings Fig. 1. Santa-Ana and Miranda [26] studied first the unbraced MRF frames. The elevation views of unbraced frames, the storeys height, beams and columns section are shown in Fig. 2. The buildings were designed as strong column–weak beam as reported by Santa-Ana and Miranda [26], so that the sum of plastic section modulus of the columns connecting into each connection was greater than that of the beams connecting into the same connection.

The sizes of beams and columns of different bracing patterns are the same as that of MRF. Different braces are added in such a way that the total steel required is the same for all the braces except for ZBF. The same sizes of braces are assigned to different bracings VBF, IVF and KBF; however, XBF is assigned a different size of brace with nearly equal amount of steel as that of VBF, IVF and KBF. For the X braced system, the two braces are in the same plane and their intersection point is modeled as pinned. In case of ZBF, the same brace sizes of IVF pattern are used in addition to zipper struts. Zipper struts shall be designed to resist the vertical unbalanced forces generated by the IVF braces [17,18,19].

The frames were designed according to the lateral load distribution specified in International Building Code (IBC 2012) [27]. These frames satisfy the maximum inter-storey drift limitation given in the code [27]. Consequently, these frames practically characterize the wide variety of frames that can result from the design according to IBC 2012. The

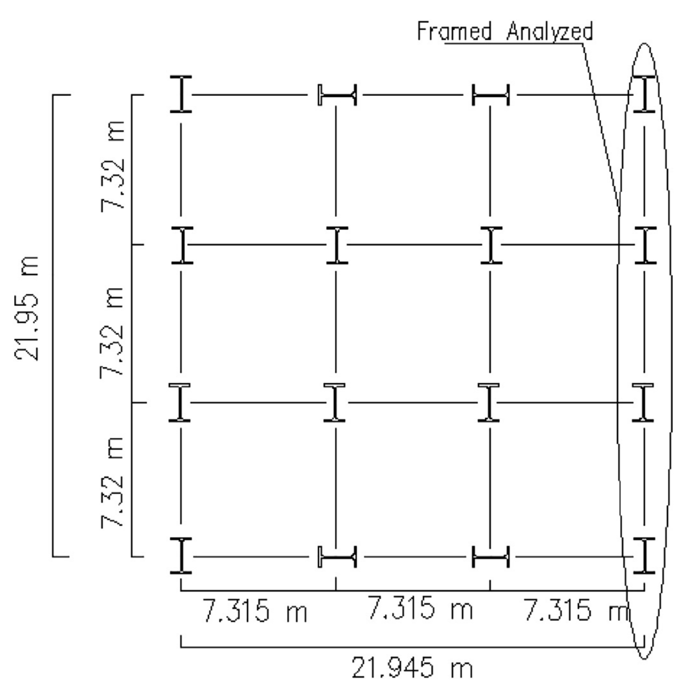

Fig. 1. Typical floor plan of the buildings [26].