ABSTRACT

This study aims to propose an improved fabricated high-rise steel frame system with buckling restrained braces (BRBs) and pin beam-column connections, which is applicable to seismic areas. In this system, damages to the main structural members resulting from earthquake ground motions can be prevented by BRBs which are capable of resisting all the lateral seismic loads, whilst the other structural members are mainly responsible to carry the gravity loads. Having explicit load-carrying characteristics, this system is thought to have a competitive advantage of rapid construction. In this study, a 3D finite element model of a specific fin-plate connection, a typical type of pin beam-column connections, is built and its rotational stiffness is evaluated. Subsequently, a high-rise steel frame model with both BRBs and the fin-plate connections are established. The earthquake-resistant performances of the model under different levels of seismic excitation are analyzed using the nonlinear dynamic time-history method. Numerical results indicate that the proposed system performs elastically under frequent earthquakes, whereas under severe earthquakes the main structural components are well within their capacities. Furthermore, the BRBs show significant energy dissipation capacity under severe earthquakes.

KEYWORDS

Pin-connected steel frame system with BRBs; Fabricated pin connections; Earthquake resistance; Finite element analysis.

INTRODUCTION

In recent years, an increasing number of high-rise buildings are being constructed in developing nations such as China and other Asia-Pacific countries. For buildings constructed in the seismic areas, the expense of repairing or replacing the earthquake-induced damages is significant. For steel frame structures, in particular, the conventional rigid connections usually require on-field welding which lacks construction quality assurance and is prone to industrial accidents. In this proposition, it is obvious that the construction speed, precision and labor cost, are primary factors influencing the construction quality. Specifically, the developmental strategy advocated by the Chinese government indicates that a fabricated construction procedure, which emphasizes construction speed, safety, and cost effectiveness, should be highlighted to promote a new building revolution.

In the seismic design procedure of conventional high-rise steel frames, the rigid beam-column connections are considered to have relatively high ductility and energy dissipation properties, which are able to provide a certain level of lateral stiffness. However, extensive plastic deformations are likely to occur in individual structural members under a severe earthquake. In view of this drawback, rigid connections can be replaced by pin connections which only require on-site bolted assembly. The potential damage to the main structural members caused by earthquake ground motions can be effectively reduced by employing braces to withstand all the lateral seismic loads. Meanwhile, the pin-connected beams and columns are designed to carry gravity loads only. For a design-level earthquake, structural damages are reduced by the lateral-load-resisting members only when other structural members remain elastic (Kim and Seo 2004). As pin connections are normally assembled by bolts on site, the risks of low construction quality and industrial accidents would be decreased substantially. Given that the construction of the connections constitutes up to 50% of the overall cost of a steel frame structure, the application of pin connections will bring significant economic benefits (Bijlaard 2006).

It is well recognised that under earthquake loads, the energy dissipation capacity of a conventional braced frame is highly limited due to buckling of the braces. This issue has been rectified by using a novel buckling restrained braces (BRBs) which have become popular in high-rise steel building constructions in Asian countries in the past few years (Xie 2005). It has been demonstrated in many recent publications (Sabelli et al.2003, Kiggins and Uang 2006) that the BRB has similar strength and ductility behavior in both compression and tension, thereby
being able to absorb significant amount of energy during cyclic loading. As such, BRBs can be used as a replacement for conventional braces in a steel framed structure. As energy dissipation in steel braced frames mainly relies on the inelastic deformation of the diagonal members, the application of BRBs can significantly increase the energy dissipation capacity of the overall structural system. Consequently, demands for inelastic deformation of other structural members can be dramatically reduced.

In previous studies of pin-connected steel frames with BRBs, the connections have often been assumed to be ideal pins. However, in real situation, the “so-called” pin connections not only transfer end shear but also offer a limited level of rotational resistance. Indeed such idealised connections exhibit semi-rigid behaviors to some extent. As described above, this study aims to examine the performance of a pin beam-column connected structural system with BRBs, with a particular emphasis on the Chinese construction practice. In this system, the beam-column connections are considered to have certain rotational stiffness. Specifically, numerical study of a typical fin-plate beam-column connection (as shown in Figure 4) designed based on the existing code is performed using commercial finite element package ABAQUS. The resulting rotational stiffness of the connection is subsequently adopted for the analysis of a high-rise BRB steel frame (BRBF) with fin-plate connections. This is achieved by using open-source software OpenSees, through which the structural responses under earthquakes can be evaluated.

EXISTING DESIGN CODES FOR PIN BEAM-COLUMN CONNECTIONS

To date, the application scope of pin connections in high-rise buildings in earthquake-prone regions in China is still limited. As a result, the provisions of the design procedure for this type of buildings are also seldom found in the Chinese seismic design code (MOC, 2010).

In 1990, a categorisation system was proposed by Bjorhovde, et al. (1990) to classify steel beam-column connections according to their stiffness, ultimate strength, and ductility requirements. Based on their study, Eurocode3 Part1.8 (EC3) (CEN 2005) classified joints as rigid, nominally pinned or semi-rigid by their stiffness and strength. The classification boundaries in terms of the initial rotational stiffness and strength are shown in Figure 1, where $M$=actual connection moment; $M_p$=plastic moment capacity of the beam; $\theta$=actual connection rotation; $\theta_p$=plastic rotation. EC3 also recommends several common forms of simple connections such as single web-angle, double web-angle, flexible end plates and fin-plates.

![Figure 1 EC3 classification system](image)

On the other hand, studies related to EC3 steel connections (Kishi et al. 1997, Jaspart and Demonceau 2008) revealed that EC3 does not provide sufficient guidance on structural design of pin connections, especially on the behavior of joints. Therefore, it is necessary to verify the actual behavior of the connection designed following EC3 by means of finite element simulation, to facilitate safe and accurate structural designs.

NUMERICAL MODELLING AND ANALYSIS

ABAQUS, as a finite element modelling program with visualized pre- and post-processing, is very effective in conducting detailed analyses for complex assembled structural components, such as the fin-plate beam-column connection investigated in this work. It can also be used for an accurate nonlinear analysis of the seismic responses of a building. Another finite element software, the Open System for Earthquake Engineering Simulation (OpenSees), has increasingly become one of the most influential open platforms for earthquake engineering research (Lu et al. 2015). For these reasons, both ABAQUS and Opensees are adopted in this study to perform the required analyses.
In this study, a typical fin-plate beam-column connection, and a BRBF encompassing this type of connections, are designed following EC3 (CEN 2005) and Chinese design code (MOC, 2010) respectively. The outcome of the design is shown in Figure 4. Subsequently, ABAQUS is used to obtain the moment-rotation behavior of the connection, which is then used to simulate the seismic responses of the BRBF by OpenSees.

**Structural details**

A 3D model of a 9-story steel frame is considered herein. In accordance with the current Chinese seismic design provision (MOC, 2010), the model is designed for a highly seismic location where the seismic fortification intensity is 8°, and the design basis earthquake acceleration value is 0.3g (g presents the gravity acceleration). The design earthquake group is 2 and the construction field belongs to Site-class II. The structural safety is specified as the second class, and the design working life is 50 years. The plan and elevation of the model are shown in Figures 2-3. The total height of the frame is 27m with a typical 3m story height. Its plan dimension is 21.6m×21.6m comprising of 3 bays in each direction. All columns are fixed to the ground. The yield strength of the steel beams and columns is 235MPa. The cross-sectional area of the BRB is 4900mm², and its yield strength is 160MPa. Detailed dimensions of the model are listed in Table 1.

In this study, it is assumed that the BRBs are arranged symmetrically in the exterior corner bays along the X-axis and at odd stories only (Figure 3). Such an arrangement is to examine the overall structural performance under seismic load in the X-axis. The columns are continuous and connected with beams by pin connections which are in the form of a specific fin-plate connections (which will be discussed under "Rotational stiffness of fin-plate connection").

<table>
<thead>
<tr>
<th>Element</th>
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<th>Values (mm)</th>
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<td>650</td>
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<tr>
<td></td>
<td>Flange thickness</td>
<td>24</td>
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</tbody>
</table>

Figure 2 Plan view /mm

Figure 3 Elevation of Axis 1 - 4 /mm

Table 1 Detailed dimensions of the model
Rotational stiffness of fin-plate connection

The fin-plate connection (shown in Figures 4–5) considered in this study is designed following EC3 (CEN 2005). As shown in Figure 4, the configurations of the fin-plate connection consist of a rectangular fin-plate welded to the column, and bolted to the web of the beam by six bolts. The bolts are Grade 5.4 and the diameter of each bolt is 20mm. The lengths of the column and the beam are set as 1000mm and 500mm, respectively. To evaluate the rotational stiffness of this connection, a 3D model is built in ABAQUS. Solid elements are used to model the entire connection while contact pairs are created to simulate the geometrical discontinuities at the contact surfaces. The stress-strain relationship for all the components are taken as elastic-perfect plastic with a Poisson’s ratio of 0.3, and the von Mises yield criterion is used to predict the onset of yielding. The coefficient of friction for the contact surface between the fin-plate and beam web is taken as 0.44. Note that the connection behaviour is significantly influenced by the boundary conditions. In this study, a pin support is assumed to restrain the top and bottom of the column, while the beam is restrained by a vertical roller (see Figure 4). A 15mm downward prescribed displacement is applied to the restrained boundary of the beam, in order to generate a bending moment to the connection.

Figure 4 Configuration of the designed fin-plate connection/mm

Figure 5 von Mises stress distribution/MPa

Figure 6 Moment-rotation behaviour

Figure 5 shows the von-Mises stress distribution and the deformed shape of the connection under the action of the prescribed displacement. The stresses within the connection are generally low except at the region around the
top two bolts, which indicates a relatively weak moment-transfer capability of the connection. As shown in Figure 6, the analytical moment-rotation behaviour of the fin-plate connection obtained from ABAQUS is superimposed on the EC3 classification system (Figure 1). It is evident that the numerically predicted behaviour of the fin-plate connection falls within the semi-rigid area, thereby can be categorised as a pin connection in the structure design procedure.

OpenSees models

In the OpenSees model of the 9-story steel frame with BRBs (Figures 2-3), the displacement-based beam column elements with fiber sections are used to simulate the beams and columns. To take into account material nonlinearity, “steel 01” material with bilinear behaviour is applied. For geometry nonlinearity, P-δ effects are considered for the columns and BRBs. Truss elements are used to model BRBs, and “steel 02” material with hysteretic behaviour in both tension and compression (Uriz and Mahin 2008) is employed to simulate the BRBs. For the pin connections exhibiting a certain level of rotational stiffness, a pair of slave and master nodes must be defined at each beam-column connection. Specifically, these nodes are connected with a Zerolength element and share the same translational degrees of freedom. To simulate the in-plane (i.e., X-Z plane) rotation of each connection under seismic load, a multilinear material with the rotational stiffness predicted by ABAQUS (Figure 6) is assigned to the Zerolength element around the Y-axis. The out-of-plane rotations of the connections around the X- and Z- axes are replicated by assigning an elastic material property with a relatively low stiffness.

Dynamic time-history analysis method has the advantages of providing informative and accurate solutions for seismic resistance study. Therefore, this method is used herein to obtain the seismic behaviour of the structure under frequent and severe earthquakes. Two recorded earthquake ground motions, from the 1940 El-Centro Earthquake and the 1952 Taft Earthquake, are considered. The ground motions, which are scaled to a value of peak ground acceleration (PGA) of 110gal (representing frequent earthquake) and 510gal (severe earthquake), are initially used as the seismic input to the structure along the X-axis, after the static and modal analysis are conducted. Additionally, a 2% damping ratio is taken into account during the nonlinear dynamic time-history analysis.

Figure 7 shows the envelope of the inter-story drift ratios of the structure under the action of two seismic ground motions with different earthquake intensities. It can be seen that the maximum drifts occur at the 4th story when the structure suffers both frequent and severe earthquakes. Due to the various hysteretic behaviors of the seismic wave input, the response of the entire structure, especially when PGA is 510gal, is more pronounced under Taft ground motion. It can be further noticed that the predicted inter-story drifts of the structure are less than the specified upper bound values, i.e., 1/250 under frequent earthquakes and 1/50 under severe earthquakes, as specified by the Chinese code (MOC, 2010), indicating a reasonable level of lateral stiffness of the structure.

![Figure 7 Inter-story drift ratio](image)

Identical behaviour of BRBs are observed on both exterior spans due to their symmetrical arrangement (see Figure 3). The axial force-displacement relationships of the typical BRBs on the left exterior span of the 1st, 3rd, 5th and 7th stories are plotted in Figure 8. Although the seismic response of the structure is stronger under Taft ground motion, yielding of the BRBs are found under both earthquake actions for PGA=510gal. It can be seen from the figure that the BRBs on the 3rd and 5th stories exhibit excellent hysteretic and ductile behaviour, thus they play the most effective roles in dissipating seismic energy. On the contrary, the BRBs on the 1st and 7th stories demonstrate relatively smaller hysteretic energy capacity. Although not showing in the figure, the BRBs on the 9th story are found not to completely enter the plastic state. To achieve more economic design, the BRBs
on the top and bottom stories can be designed to have smaller cross section, leading to more uniform contribution from all BRBs to the overall structural performance.

(a) 1st story under El-Centro
(b) 1st story under Taft

(c) 3rd story under El-Centro
(d) 3rd story under Taft

(e) 5th story under El-Centro
(f) 5th story under Taft
CONCLUSION AND FUTURE DIRECTION

Pin connected steel frames with BRBs are able to take advantages of the BRBs in resisting earthquake loads without undergoing large plastic deformations. The finite element models are established using two software packages ABAQUS and OpenSees to study the seismic performance of such structures. The rotational property of a specific fin-plate connection and the seismic responses of the whole structure are evaluated. Simulation of the fin-plate connection demonstrates that it performs as a pin connection for the design purpose. Analysis results of the high-rise BRB steel frame (BRBF) employing this type of connections reveals that the structure performs well in energy dissipation. Most BRBs are developed into the plastic stage and exhibit excellent hysteretic and ductile behaviour in resisting the lateral forces. In other words, the BRBs play important roles in absorbing energies against seismic activities. Based on these observations, it can be initially concluded that the BRBFs can be used in the areas with a fortification intensity of 8°.

Although the seismic response of the BRBF with a typical pin connection has been preliminarily studied, more analytical data are still required to further examine this structural system. As the behaviour of connections can be significantly affected by various connection types and the number of bolts, more finite element studies will be conducted to investigate the behaviour patterns of different connections. This will facilitate further evaluation of the rotational stiffness of beam-column connections and their influences on the seismic performance of BRBF. Furthermore, different BRB arrangements and sections will be studied to optimize the performance of this type of structural system.

REFERENCES
