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Research Note

Numerical modelling of the mechanical behaviour of steel brace modified by CFRP sheet

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Abstract. One of the deficiencies of diagonal (X) bracing is buckling under compressive load, hence not reaching the yielding threshold and being unstable. In this numerical study, the behavior of X-shape brace was investigated, which was modified by Carbon Fiber Reinforced Polymer (CFRP) plates that could absorb compressive force and make it stable. This innovative brace consisted of two separate steel plates connected by CFRP sheets to each other in the middle of the compressive element. Thus, these two parts were connected by epoxy resin and bolts. In this study, Finite Element Method (F.E.M.) was used to simulate the elements of steel and fiber polymers by Abaqus software under cycle loading after designing of fiber layers and connection type. Also, the numerical result was compared with the normal steel brace. The result showed that the innovative brace had more efficiency under seismic response. According to this output, ductility and energy absorption increased in the innovative model (CFRP-BR), but stiffness decreased as compared with the normal steel brace.

1. Introduction

The first (and older) method for steel structures is the Allowable Strength Design (ASD) method. But, in the recent two decades, another newer method, called Load and Resistance Factor Design (LRFD) method, has been used.

One of the new systems opposite to seismic loading is Buckling Restrained Braces (BRBs) that includes a slender steel core continuously supported by a concrete layer, in order to avoid buckling under axial compression. The core and casing are decoupled to prevent interaction between them. The concept of BRBs was developed in Japan at the end of the 1980s. It appeared in the United States after the Northridge earthquake in 1994 and is now accepted with its design regulated in current standards, as a displacement dependent lateral load resisting solution. As earthquake awareness among engineers has been enhanced by evolving European standards, the need for economical solutions providing adequate resistance for new structures is now increasing in Europe and has precipitated the use of BRBs there [1].

From the beginning of the 1990s, assessment studies have started to evaluate the possibilities of utilizing extra-structural damping in order to reduce seismic demand in asymmetric-plan systems [2].

Takewaki and Yoshitomi in 1998 [3] presented how the optimal dampers distribution and the lowest mode damping ratio were affected by the variations of support member stiffness of dampers. Takewaki presented new approaches to displacement-acceleration simultaneous control with stiffness-damping simultane-

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ous optimization in 1999 and 2000 [4-6]. Takewaki [7] presented an optimization procedure to compute the optimal size and place of dampers for planar building frame using minimum transfer function. Aydin et al. [8] proposed a procedure based on the base shear force to find optimal damper distribution using the transfer functions in 2007 [7].

The effect of installing buckling-restrained braces in CBFs on the seismic response of such frames has been studied [9]. It has been found that buckling-restrained braces provide an effective means for overcoming many of the potential problems associated with special CBFs. Passive energy dissipation devices include hysteretic [10], friction, [11] and Viscous Fluid Dampers (VFDs) presented in 1992 and 1993 [12,13].

Converging braces as a common lateral load system have accurate geometry, providing rigidity and lateral desirable function against earthquake. Another advantage of converging brace system is reparability. Based on seismic design methods, it is desirable that converging brace systems in severe earthquakes may have stable and steady inelastic responses. The strategy of the design method is that the plastic deflection only occurs at braces and other parts of the structure such as columns, beams, and junctions. According to the past studies about earthquakes engineering, diagonal X bracings was not suitable against the lateral loads, because of low ductility. The Hastert curve of diagonal X bracing does not have symmetric shape and the compression strength is less than the extensional strength in total. One of the disadvantages of diagonal X bracings is its collapse before yield stress when compressive load is exerted. Moreover, these braces have a capacity of energy wasting, constrained flexibility, and high elastic stiffness. If buckling of braces is prevented until the final yield limit is reached, it is expected that an economic and resistible lateral strength system with high capacity of energy will be achieved. The method to achieve this purpose is using materials which can enhance tensile strength, cause high absorbing energy, and prevent buckling. Application of bonded Carbon Fiber Reinforced Plastic (CFRP) materials to strengthen steel structures has drawn the attention of many researchers and for more than a decade, several experimental and numerical investigations have been conducted to explore the behavior of externally bonded steel-CFRP lap connections [14,15].

A major disadvantage of bonding the FRP sheets to structural elements via epoxy resin is the effort and time consumed in surface preparation and requiring a sufficient time, in days, to achieve the desired bonding strength of the system. On the contrary, the procedure of preparing mechanically anchored systems is quiet simple and requires basic labor skills to connect the FRP laminates to the steel brace. Moreover, the strengthened section can be exposed to loads immediately once all bolts are properly tightened. The idea of strengthening steel elements using mechanically anchored FRP laminates emerged as a consequence of the successful application of this technique to FRP-BR connections. The favorable ductile behavior and significant increase in the load-carrying capacity of the strengthened concrete sections opened the doors for researchers to conduct further investigations in this field [16].

In a common system, decreasing the ductility occurred versus increasing the stiffness against lateral load. The function of this model is similar to that of spring as it eliminates compressive force and enhances tensile force, leading to more energy absorption. Considering the P-Δ (BEHAVIOR CURVE) in the desired Δ gives the energy absorption of the structure system; thus, when Δ increases, the structure saves more energy. In this research, the energy absorption of the diagonal X bracing is compared with that of the innovated model.

The innovative model is named (CFRP-Br) that is a combination of steel plates and CFRP sheets. CFRP-Br prevents total buckling of brace. Therefore, the new brace does not absorb pressing load but absorbs tensile load. According to the description, the idea of using brace, which is improved by CFRP sheets, is reconsidered.

2. Composites of improved brace by CFRP sheets

As shown in Figure 1, brace is a composite of two steel arms connected together by CFRPs, which are jointed to the plate by screw.

This brace is divided into two parts of functional and behavioral:

- Part number 1: Steal arms which yield in tension;
- Part number 2: CFRP part, screws, and rigid connection pare brace that do not yield.

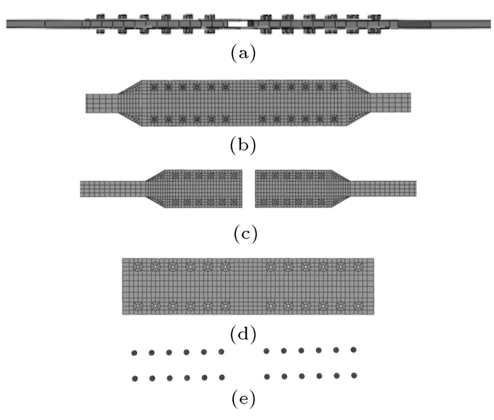

Figure 1. Members of the CFRP brace: (a) Side view of the brace, (b) plan view of the brace, (c) steel arms of the brace, and (d) CFRP sheet, and (e) high-strength screw.

3. Design of the model

This brace has been designed using SAP2000 [17] and the behavior of the structure against lateral load is simulated by Abaqus [18]. The model is designed for a region with medium risk of hazard and soil type III; thus, the reflection coefficient diagram of the structure is achieved based on IBC2006 [19] and loading is assigned using FEMA356 [20].

4. Project model and numerical simulation

This model is designed by considering 30 kN/m approximate load in horizontal direction on 3*5 m frame to avoid the eccentricity of brace. One arm is a single plate while the other is a double plate and each of them has been designed for half of the applied load; the arms have alike distance from the middle (Figure 2). Dimensions of the single plate and the double plate are shown in Figures 3 and 4.

In this case, safety factor is half (1/2) to prevent tearing in appearance of tension in CFRP and hole. The critical range should be in arms; hence, the width of the plate has been enhanced in the junction zone of CFRP and the distance between screws is $6d$ (d = Diameter) based on the previous experiments [21]. The distance between the two plates is at least 2% the height of the frame, according to IBC2006 [19]; therefore, in this case, it is 10 cm. The junction between the two plates has been made by CFRB and screw. This structure prevents torsion of the frame when the earthquake load is exerted because of the gap between the two arms: While the frame is under pressure, the two opposite arms get closed together, but do not make contact, and the arm on the other side gets stretched. The reverse action occurs when the direction of the earthquake changes.

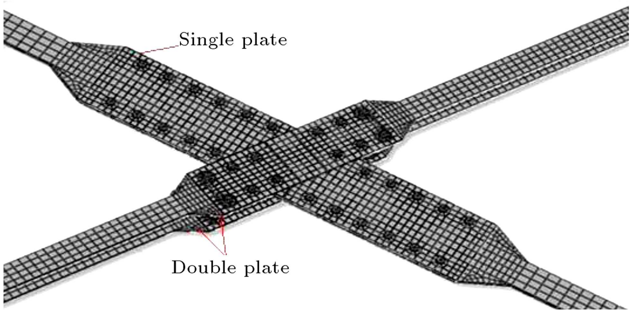

Figure 2. Position of each member of brace.

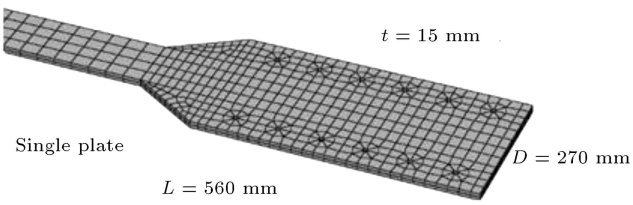

Figure 3. Dimension of the single plate.

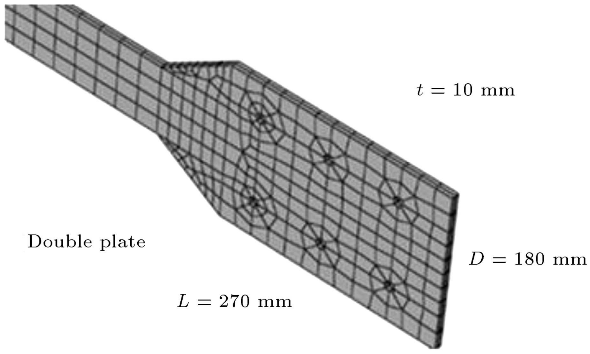

Figure 4. Dimension of the double plate.

5. Model calibration and results

To calibrate the Abaqus, the Abaqus EBF modeling has been compared with the closed EBF modeling. Therefore, 80 kN/m loads, which have been exerted horizontally on a 3*5 frame, are applied. To evaluate the accuracy of the results in the Abaqus, envelop diagram and a comparison between failures in threshold value software and closed form are utilized (Figure 5).

5.1. Results of calibration

Amounts of failure load of brace are achieved based on the closed form:

$$\text{Pcr} = 205.4 * 2200 = 451880 \text{ N} = 452 \text{ kN},$$

$$\lambda = 55.3 \Longrightarrow \text{Fa} = 1202; \ \text{Pa} = 1202 * 22 = 26444 \text{ N} \Longrightarrow$$

$$\text{Pa} = 26.4 \text{ kN},$$

$$\text{Pcr} = 71.6 \text{ kN}.$$

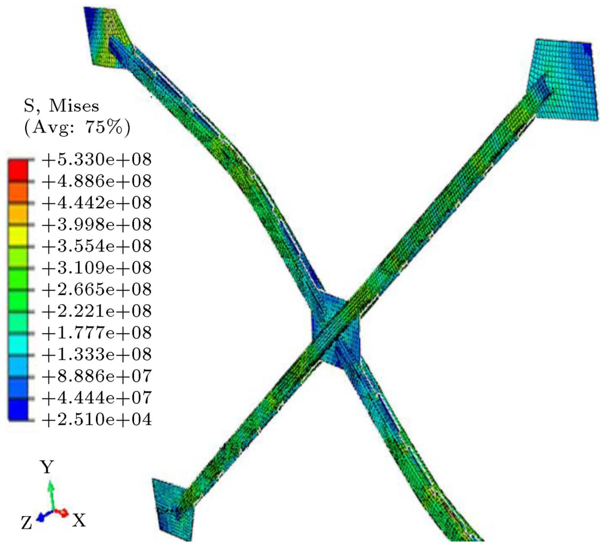

Figure 5. Three-dimensional deformation diagram of the EBF modeling in Abaqus, showing the buckling of EBF.

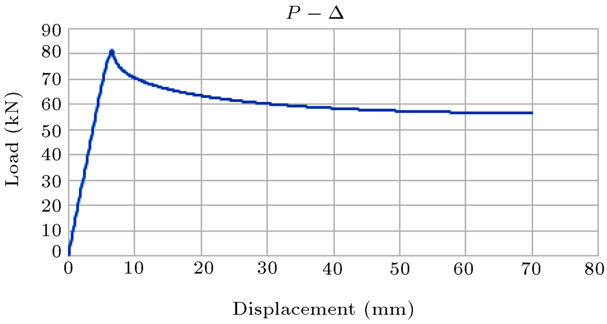

Figure 6. Envelop diagram of EBF.

According to the above formula, the load (71.6 kg/m^2) is equal to the force in the rupture point of the envelop diagram. It indicates the accuracy of results, which are modeled by Abaqus. The area under the force diagram against displacement is energy absorption (Figure 6).

6. Simulation in Abaqus

Envelop diagrams in Abaqus are evaluated by simulating the brace member and performing mesh. Arms of the brace at the bottom are defined as fixed junction. In three directions of X, Y, and Z, displacement is zero; but at the top, first, the left part (single plate) is fixed and, then, for the right part, 0.07 m of the displacement is exerted. As the same for the other arm, the right part (double plate) is fixed and the single plate gets displaced (Figure 7).

The force-displacement diagram was shown for the innovative's brace behavior. Considering that the X-shape steel brace (with UNP section) is designed for 80 kN load and CFRP BR is designed for 30 kN load, energy absorption increases by 3%, according to CFRP-BR and X-shape steel brace force-displacement diagrams.

As slope of the force-displacement curve in linear area indicates, CFRP-BR rigidity coefficient decreases by 35% as compared with the X-shape steel brace.

Delineation of ductility of the braces requires the maximum amount of displacements. In this modeling, the displacement is considered up to 0.07 m ($U_{\max}$ = 0.07 m); thus, ductility (ductility $= \frac{U_{\max}}{U_y}$) ratio of CFRP-BR to X-shape steel brace has increased by 6%.

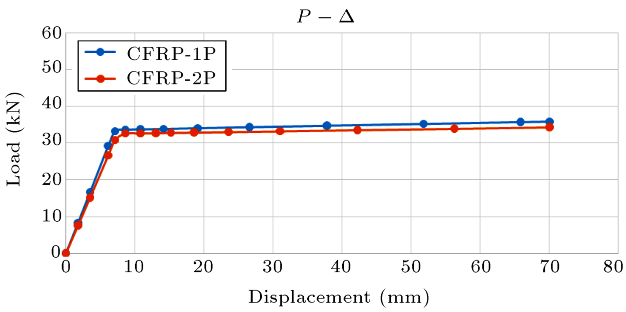

Figure 7. Envelop curve of single plate (blue), and envelop curve of double plate (red).

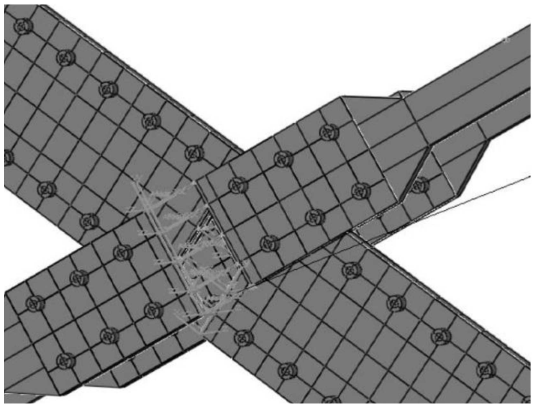

Figure 8. Schematic illustration of compressive force elimination by Abaqus.

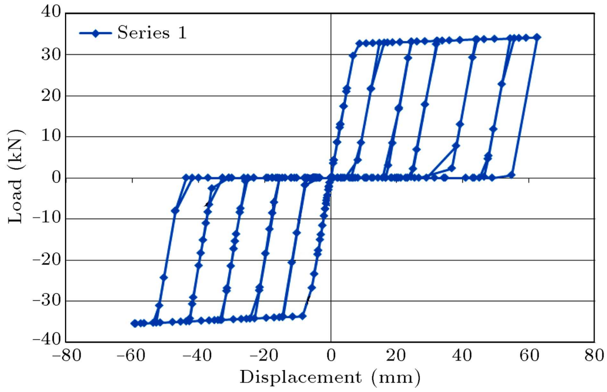

Figure 9. An illustration of hysteresis diagram.

The ascending diagram of CFRP-Br in comparison with the descending diagram of EBF indicates more energy absorption. Considering that the compressive force has been eliminated, the system lacks local bulking, which is the main defect of the normal brace (Figures 8 and 9).

7. Conclusion and results

In this research, innovative braces were studied, which were made of a composite element including two steel arms connected together by CFRPs and jointed to the plate by screw. The results showed that the innovative brace had more efficiently under seismic response. According to these numerical outputs, the area under load-displacement curve in the innovative model indicated up to 3% increase in energy absorbing compared with normal X-shape steel brace.

In the common system, decreasing the ductility occurred versus increasing the stiffness against lateral load. The functional of this model is similar to that of spring as it eliminates compressive force and enhances tensile force, leading to more energy absorption. Thus, in the CFRP-BR sample, stiffness was reduced up to 35% and ductility increased up to 6% as compared with the X-shape steel brace.

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Biographies

Farzad Hatami was born in Tabriz, Iran, in 1977. He received the BS degree in Civil Engineering from Tabriz University, Tabriz, Iran, in 2000, and the MSc and PhD degrees in Civil Engineering with specialty in the structural branch from Khaje Nasir University (KNTU) and Amirkabir University of Technology (AUT), Tehran, Iran, in 2002 and 2007, respectively.

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Dr. Hatami is a fellow of the Iranian Society of Civil Engineering (ISCE), head of the Educational Department; Iranian Society of Steel Structures (ISSS); and Iran Color Society (IRCS). He is a Committee to develop a charter member of the "Design and Construction of Concrete" (Iran's National Building Regulations Chapter 9), a team member of elevated train railway (LRT) project, a team member of the shaking table design and construction project, a team member of seismic Bridges studies of Tehran-Organization and Civil Engineering, and Editorial Board of the ASAS research journal in Persian Language. He was the vice president of the 4IBC International Conference on Bridge Engineering (4BC2015) held in Tehran, Iran. He obtained the Best Paper Prize of the Universal Researchers in Civil and Architecture Engineering (URCAE2014), Awards for his contributions to the field of Concrete Engineering in December 2014, the Best Oral Presentation Award of the International Academy of Computer Technology (IACT), Paris Area, France (ICCEM2015) for his contributions to the field of tall building anti-seismic behavior in August 2015, Best Researcher Awards from Research Institute of Petroleum Industry (RIPI) in 2010 and Best Iranian Research Awards by Institute of Standard and Industrial Research of Iran (ISIRI) in 2008.

Zahra Baheri was born in Tehran, Iran, in 1983. She received the BS degree in Civil Engineering from Allameh Mohaddes Nouri University, South of Iran, Iran, in 2010, and the MSc degree in Civil Engineering with specialty in the structural branch from Amirkabir University if Technology (AUT) Tehran, Iran, in 2013 under the supervision of Professor Hatami. The title of her MSc thesis is "Innovative Model of Brace Frame Using CFRP (Carbon Fiber Reinforced Polymer)." Her current research includes utilizing Fiber Reinforce polymer (FRP) sheets in repairing of concrete in Metro (Line 4) of Tehran's underground. She was project manager assistant in 2012 underground Tehran subway projects (Lines 5 & 7) with the expertise to choose the best executive methods according to the tender's documents; set meetings with management, engineers, and field operations staff; and commissioning, reviewing, and approving project reports.

Ghazaleh Oshagh was born in Tehran, Iran, in 1985. She received the BS degree in Civil Engineering from Semnan University, Iran, in 2010, and the MSc degree in Civil Engineering with specialty in the structural branch from Amirkabir University of Technology (AUT), Tehran, Iran, in 2013 under the supervision of Professor Hatami. Her current research includes utilizing Fiber Reinforce polymer (FRP) sheets in repairing of concrete in Metro (Line 4) of Tehran's underground. She was project manager assistant in 2012 underground Tehran subway projects (Lines 5 and 7) with the expertise to choose the best executive methods according to the tender's documents; set meetings with management, engineers, and field operations staff; and commissioning, reviewing, and approving project reports.