Role of few BRB settings in seismic performance of reinforced concrete frame bent structure

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Abstract. Reinforced concrete frame bent structure (RCFBS) is a popular structural pattern in industrial power plant, while it behaves poor seismic performance in several previous earthquake accidents. This study adds buckling restrained brace (BRB) in the experiment model to improve the seismic performance of main structure. However, for such structures few BRBs just are permitted to set into its body due to the limits of process layout. To reinforced concrete power plant, the work aims to how to set BRB in reinforced concrete frame bent structures and to examine the role of BRB in the seismic performance of main structure.

1. Introduction
BRB is a novel brace and consists of outside restraint cell and internal core cell [1], which are separated by unbonded coating and gap. As it is stressed, BRB is able to yield so that its hysteresis loop is full and energy dissipation is better than that of ordinary brace, because internal cell is confined by outside element. It can improve the ductility and seismic performance of main structure and has extensive scope of application. Hence, it is of good potential for development in structural seismic engineering.

RCFBS, as frequently-used structure system, were damaged severely in previous earthquakes [2-3], which caused highly attentions to be paid. Some studies[4-6] have added BRB to steel frame bent structure, and found that BRB can improve the vibration mode of original structure and reduce the displacement of each layer, leading to the enhancement of seismic performance of main buildings of thermal power plant. Consequently, it is worth rendering it popularization and application. Although the improvement of BRB to the seismic performance of steel FBS has been identified, studies on the effect of BRB in RCFBS still are insufficient. For some industrial buildings, few BRBs just are permitted to set in main structure due to the limit of process condition. In the cases, how to layout BRB and set its parameters containing mainly stiffness and yield force are important for the applications of BRB in RCFBS. If the yield bearing capacity of BRB is too high, the design of embedded parts becomes difficult and the accommodation capacity of concrete component is prone to be finite. Hence, how to realize a match of BRB with main structure is worth studying deeply.

To reinforced concrete structure of main building in a certain thermal power plant at 8 intensity site, one RCFBS-BRB structure is designed to conduct static tests and to study failure mechanism, hysteresis hoop and energy dissipation capacity, and the match of BRB with main structure. This can provides experimental basis for the application of BRB in large-scale structure of RC frame bent in highly seismic region.
2. Background and design of brace system

2.1. Engineering background
The main structure of a certain thermal power plant with unit capacity 660MW is selected, with transversal frame bent-brace and longitudinal frame brace structures. The main workshop is arranged in four columns: steam engine room, deaeration room and coal bunker room. Total length, width and height of the structure are 90m, 54.1m and 60.1m, respectively; the concrete is C40 and the longitudinal bearing force rebar is HRB400; stirrup is HPB235 and steel brace is Q235B. Seismic fortification intensity is 8 degree; site classification is II categories, and the characteristic period is 0.35s. Fig. 1 shows the horizontal layout for first floor structure.

2.2. Preliminary design of brace system

To this engineering, the design scheme of BRB is as following: 1) The slenderness ratio of brace in original FB-steel brace structure are calculated, and then the smaller and larger are selected; and the steel brace for which slenderness ratio is larger should be replaced first by BRB; 2) When the original structure undergoes plastic deformation, its displacements are calculated and then the BRB is set up in the floors with large displacement, while it is not installed in floors with small displacement; 3) According to performance objectives of structure, BRB is designed to match with main structure; otherwise, it need to be designed repeatedly; 4) The effect of BRB on vibration reduction needs be checked. If the effect is not good, one goes back to the third step for redesign. The process is iterative until BRB is able to match well main structure so that a good seismic performance is obtained. Fig. 2 is the preliminary design of brace system of this project.

3. Pseudo static test of RCFBS-BRB system

3.1. Design of test model
Considering model manufacturing accuracy and experimental condition, one typical and transversal frame bent structure is selected as object, and then the model according to 1:10 reduced scale design is made to conduct static test. Model size and main parameters of components are seen in Figs.2 and 3 respectively (Only the embedded parts and the joint plate of BRB2 and BRB3 are listed in the figure3).
3.2. Test method
The experimental model is an unequal-height structure with staggered layers. In order to be easy to load, two distribution beams with vertical loading are designed to assign the axial force for four columns. Vertical axial force is applied according to the same axial compression ratio as the original structure. The original structure concentrates a lot of loads at the heights of 17.5 m, 30.05 m and 42.53 m. After calculation, the three-point loading ratio is 0.47:1:0.35 from the top to the bottom. Due to the limitation of loading conditions, a horizontal distribution beam is designed to realize three-point loading. In order to obtain the displacement and strain of the control part, the measuring points are arranged at the end of the beam, the foot of the column and the brace. Figure 4 shows the detailed arrangement of loading equipment and measuring points. Considering the small out-of-plane stiffness of the specimens, two anti-lateral devices (see Figure 5) are installed at the heights of 3.625 m and 2.0 m to prevent the out-of-plane instability of the main structure.

3.3. Layouts of monitoring point of BRB
Strain gauges are glued at the connecting segment of BRB to obtain the stress of BRB; see Fig.4. Generally, after steel core of BRB yields, the connecting segment still is elastic. The average value of four strain gauges can offset the effect of bent strain and give axial strain of BRB; axial stress of BRB is obtained by the formula of $F_{BRB} = E_{con} A_{con}$ and then axial force-axial displacement hysteresis curve of BRB is calculated, combined with the measured axial displacement of BRB. In addition, bending strain is obtained by subtracting two adjacent strain gauges and calculating half of the mean value.
Then the bending moment is obtained by $M_{BRB} = \epsilon_w E I / y$; further bending moment-axial displacement hysteresis curve is given. Note that, the strains by above formula should be lower than that corresponding to yield stress of the materials; otherwise, axial force and moment should be determined by that calculated by the strain from the strain-stress curve of the material.

4. Results and Discussions

4.1. Development of cracks and damage of structure

As the vertex displacement of KZ4 reaches 83.26mm (H/50), the structure is damaged and loading stops. Figure 6 shows cracks in local model structure as final damage forms. It is seen that cracks mainly concentrate on the bottom of column, the end of beam and joints. For KZ1 (not given in Fig. 6), horizontal cracks is dominant, and is mainly in the segment below 1.1m; and they are globally few and slight. For KZ2, the concrete on KZ2 root cracks along oblique direction, and the lower oblique cracks penetrate. For KZ3, the concrete at its root segment is crushed and the stirrup is exposed outside, with severe damage. For KZ4, the concrete at its bottom is crushed and cracks. The concrete at the bottom of both ends of KL1-1sheds partially, and the damage on the east side is more serious than that on the west side. For KL2-1, oblique cracks cover fully the beam and the cracks extending to KZ2 at the west end of the beam are larger. For KL1-2, the cross crack forms in the westside. Lots of cracks appear on JD4 and JD5. Bulk concrete falls from the bottom of embedded parts on the east and west sides of KL5.BRB begins to yield when the vertex displacement of KZ4 is H/350, shown in Fig.10, and dissipate constantly energy until the main structure is damaged. The steel core of BRB is not pulled off and the connecting segment becomes not unstable. In entire process, the gusset plates and embedded parts which are connected to BRB are not buckling and welds-opened and pulled out. The entire structure eventually is damaged by stress and bending. After the experiment, the steel core of BRB is taken out. It is found that high-order buckling occurs on steel core of BRB, as shown in Fig.7.

4.2. Hysteresis curve and story drift ratio of structure
Figure 8 shows hysteretic behaviors of the main structure. It is seen that in the elastic stage the force increases linearly with the change of displacement, with a constant slope and small hysteresis loop area. As loading increases, the displacement increases nonlinearly and the hysteresis loop gradually opens. When the BRB core yields (that is $\Delta = H/350$), the hysteresis loop area rises. In the second cycle, loading and stiffness of the main structure slightly lower due to the accumulation of damage of the main structure, but total loading still increases constantly, showing that BRB dissipates energy ahead of time and prevents the main structure from damage. Eventually, the hysteresis loop is shuttle-shaped, indicating that the BRB improves the seismic performance of RCFBS. The stiffness degradation law and the equivalent damping ratio of the structure can be deduced from the hysteretic curve. It is found that the residual stiffness of the model is 13.08% initial stiffness, and the maximum equivalent damping ratio reaches 28.9% (much larger than 0.145 in [7]), by means of calculation. This indicates that the ductility and energy dissipation capacity of RCFBS have increased due to BRB.

Figure 9 shows story drift ratio (SDR) of the model structure. It is seen that the change trend of story drift ratio is basically the same under each loading condition. For the layers below 1.75m, the SDR is larger; As the vertex displacement is $H/100$, the SDR for the second layer is over 1/50. When the leading is $H/50$, the positive and negative SDRs are respectively 1/25.1 and 1/23.5 at $H=1.37m$, which is over the limit of 1/50, which is required for the concrete structure in [8]. This indicates that BRB can improve the anti-collapse capacity of concrete frame bent structure and strengthens the deformation ability of the main structure.

4.3. Performance of BRB

Figure 10 shows axial force-axial displacement hysteresis curve for B1 (BRB in the first layer). It is seen that BRB starts to yield and dissipate energy as the vertex displacement is $H/350$; With the continuous increase of loading, the hysteretic loop area increases. The hysteresis loop looks like shuttle-shaped plump, indicating that BRBs have good effect of energy dissipation. The maximum deformation is 23.4$D_y$ (yield displacement of BRB) for BRB, while the cumulated plastic deformation is 389$D_y$ and is over the minimum limit $D_{cp}=200$ ($D_{cp}$ represents the ratio of cumulated plastic deformation to yield displacement) in [9], demonstrating that BRB has good capacity of energy dissipation. Figure11 shows the moment-axial deformation hysteresis curve of B1. We observe that the bending moment increases with the increase of the axial displacement. The hysteresis loop opens slowly and its area increases gradually. The slope of vertex of hysteresis loop in each stage decreases gradually, showing that the steel core of BRB absorbs seismic energy through its own plastic deformation.
5. Conclusions
To a certain main building structure of RC power plant, the study conducts scaling experiments and adds the BRB in the experiment model to enhance the seismic performance of the structure. By above discussions, some conclusions are draw, as following:

(1) In pseudo-static tests, yield sequence for the model: BRB to beam ends to the bottom of column, and eventual ductile failure. In the entire experiment, BRB is not pulled off nor buckling, and the gusset plate and the embedded parts connecting with BRB do not buckle and crack at welding point and be pulled out, demonstrating that the design of the model is reasonable and the parameters of BRB and embedded parts is matched with reinforced concrete structure.

(2) From the overall performance of the main structure, the bearing force is high and the hysteresis loop is full; the effect of energy consumption is better and the structure occur ductile failure. BRB can significantly improve the seismic performance of RCFBS.

(3) The measurement method using strain gauge to BRB axial force and bending moment is simple and effective. It is significant for such experiments. The hysteresis loop of BRB is full and the energy dissipation is stable, indicating that it is feasible to extend application in the RCFBS.

(4) The design of BRB in RCFBS needs to study further for systematic design method being proposed. The quantitative index of matching of BRB parameters and embedded parts parameters with reinforced concrete structure merits problem in future work.

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