SEISMIC PERFORMANCE OF ECCENTRICALLY BRACED COMPOSITE FRAME WITH BENT SHEAR PANEL DAMPERS

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Abstract

This paper investigates the seismic performance of eccentrically braced composite frame (EBCF) upgraded using bent shear panel dampers (BSPDs) in the vertical direction. Traditional shear panel dampers (SPDs) that vertically installed in EBCF can effectively increase its stiffness and strength, and dissipate input energy through their plastic deformation in seismic conditions. However, these vertically-installed dampers could also impose an additional bending moment on the composite beam in the frame, which will result in unneglectable damages on the concrete slab of the frame. To overcome these shortcomings of traditional shear panel dampers, the shear panel dampers in this paper is bent in the middle and connected to the web of the composite beam in the frame, by this mean, the resulted bending moment the shear panel dampers can be minimized and thus reducing the damage of the concrete slab. In this paper, the configuration of the bent shear panel damper in EBCF is firstly introduced. Then, key design parameters of the EBCF with bent shear panel are discussed to improve its seismic performance. Finally, a case study of a typical composite frame with different shear panel dampers is conducted, the results indicate that bent shear dampers can effectively improve the seismic performance of the composite frame and significantly reduce the damage of the concrete slab.

Keywords: seismic performance, bent shear panel damper, composite frame, eccentrically braced frame, energy dissipation

1. Introduction

Shear panel dampers (SPDs) are one of the most widely-used energy dissipation devices to improve the seismic performance of structure [1]. As shown in Fig.1, SPDs are usually used in eccentrically braced composite frame (EBCF) by connecting the steel brace and the steel beam of the composite frame, they can provide an additional stiffness and strength for the composite frame under small earthquakes, and dissipate the input seismic energy through their plastic deformation when large earthquake happens [2].

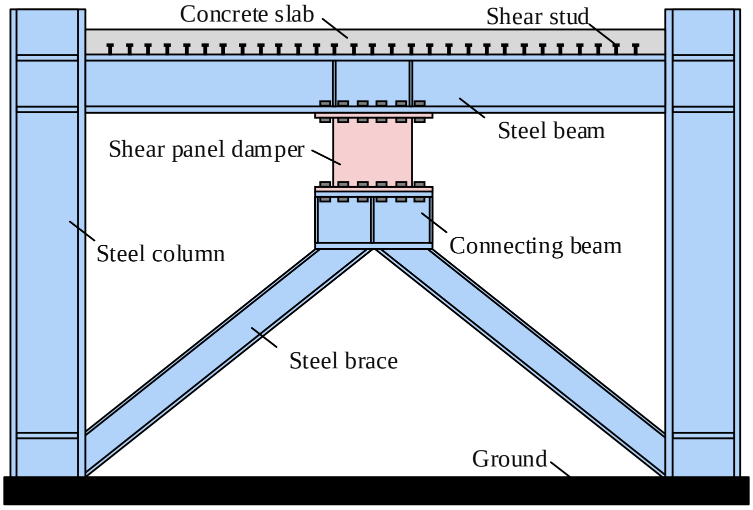


Fig. 1 – Typical configuration of eccentrically braced composite frame (EBCF)

Despite the improvement of seismic performance through the introduction of SPDs in EBCF, Fig.2 plots the moment diagram of different frames with and without the shear panel damper and steel brace. It is noticed that an unneglectable bending moment (M_B' in Fig.2) is observed in the center of the beam where the shear panel damper is installed. This bending moment M_B' may lead to the cracking of the concrete slab and thus increase the damage of the structure. Therefore, to further reduce the damage of EBCF with SPDs under earthquakes, it is urgent to modify the design of SPDs and reduce the value of M_B'.

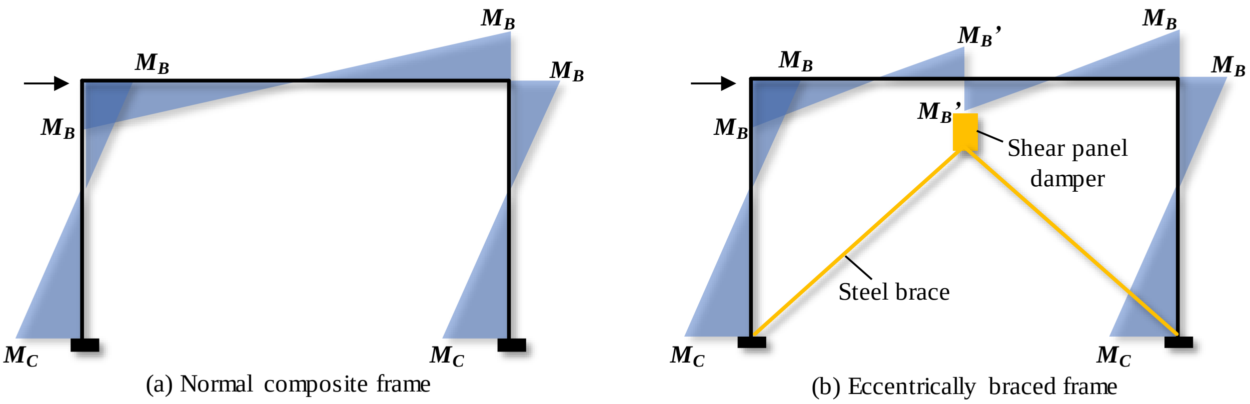


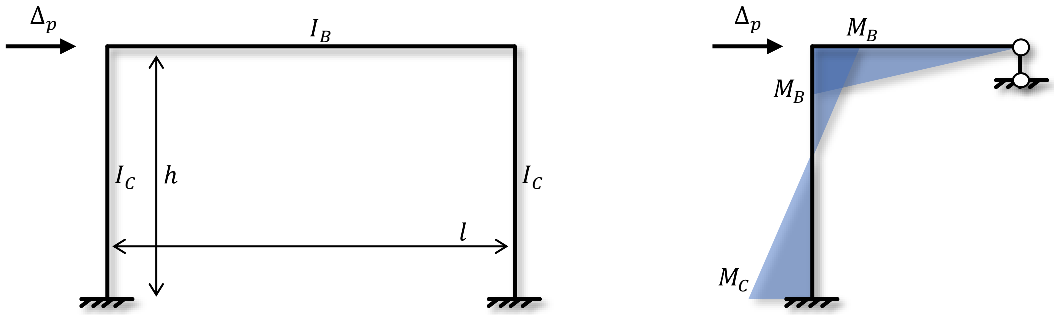
Fig. 2 – Moment diagram of different composite frame

In this paper, the bent shear panel damper (BSPD) is developed to reduce the damage of the concrete slab in EBCF. First, the damage mechanism of the concrete slab in EBCF is explained and key design parameters that influence the damage of the concrete slab are discussed. Secondly, the concept of BSPD is introduced and its working mechanism is elaborated. Thirdly, numerical simulation and experiments are conducted to verify the seismic performance of BSPD. Finally, a case study of an EBCF in actual project is carried out to evaluate the influence of BSPD on the damage of the concrete slab.

2. Damage evaluation of concrete slab in EBCF

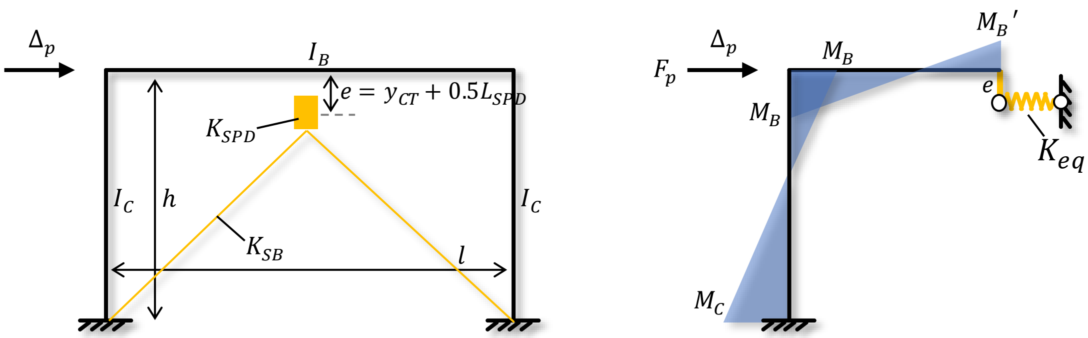
2.1 Definition of damage index of concrete slab in EBCF

Fig.3(a) and Fig.4(a) respectively shows the force analysis model of a normal composite frame (NCF) and an EBCF. The height and width of the frame are *h* and *l*, the section moment inertia of the beam and column are I_B and I_C.



(a) Frame dimension (b) Moment diagram

Fig. 3 –Force analysis of NCF under horizontal force



(a) Frame dimension (b) Moment diagram

Fig. 4 – Force analysis of EBCF under horizontal force

When a horizontal displacement Δ_p is applied to the investigated frame, Fig.3(b) and Fig.4(b) respectively plot the moment diagram of the frame (since the investigated frame is symmetrical, the moment diagram is plot on half side of the structure). The resultant moment at the end of the beam is represented by M_B. In the force analysis model of NCF, no moment is induced at the center of the beam, however, in the model of EBCF, because of the restraint provided by the SPD (the SPD mainly provide a lateral restraint to the frame, thereby this restraint is represented by an equivalent spring with an equivalent lateral stiffness of K_{eq}), an additional moment M_B' is resulted at the center of the beam.

According to the result of structure analysis, the value M_B can be expressed as Eq. (1).

$$M_B = \frac{18}{(3\alpha+2)} \frac{EI_B}{hl} \Delta_p \tag{1}$$

Where *E* is the Young's modulus of steel material, α is the linear stiffness ratio of beam and column, which is defined as $I_B h / I_C l$.

In the ECBF, the resultant M_B' can be expressed as Eq. (2).

$$M_B{}' = K_{eq}\Delta_p e \tag{2}$$

Where K_{eq} is the equivalent lateral stiffness of the steel brace and the SPD, e is the eccentric bracing distance which is defined as the length of arm of the brace, as indicated in Fig.4(a).

$$e = y_{CT} + 0.5L_{SPD} \tag{3}$$

Where y_{CT} is the distance from the neutral axis to the bottom flange of the beam, L_{SPD} is the height of the SPD.

Because the damage of concrete is mainly related to its cracking conditions, and the cracking of the concrete is determined by the applied bending moment on the beam, the degree of concrete damage can be estimated by the value of the bending moment of the beam.

In NCF, the damage of concrete slab is always concentrated at the end of the beam because of the large bending moment M_B, however, in EBCF, not only the damage of concrete slab will happen at the end of the beam, the concrete slab at the center of the beam is also damaged because of the additional moment M_B'. Therefore, to evaluate the degree of damage caused by the introduction of SPD in EBCF, a damage index is defined in Eq. (4).

$$DoC = \frac{M_B{}'}{M_B} = \frac{(3\alpha+2)hl}{18EI_B}K_{eq}e = \frac{1}{3}\frac{\beta}{\alpha}\gamma \tag{4}$$

Where β is the ratio of lateral stiffness of the brace and the frame, as shown in Eq. (5). γ is the ratio of e to the height h of the frame.

$$\beta = K_{eq}/K_F \tag{5}$$

Where K_F is the lateral stiffness of the frame, as shown in Eq. (6).

$$K_F = \frac{(3\alpha+2)h^3}{12EI_c} \tag{6}$$

According to Eq. (4), it can be seen that when the value of damage index exceeds 1.0, the bending moment at the center of the beam will be larger than that at the end of the beam, which means that the concrete slab suffers a more severe damage than the original frame without the eccentric brace. Therefore, to control the damage of concrete slab at the center of the beam, design parameters should be adjusted to reduce the value of *DoC* as lower as possible.

2.2 Influence of different design parameters on *DoC*

As shown in Eq. (4), the magnitude of *DoC* is mainly determined by the value of α, β and γ, therefore, to reduce the value of damage index *DoC*, the influence of these three parameters are discussed in this section.

α is define as the linear stiffness ratio of beam and column in the frame. In traditional design, the stiffness of the column should be larger than that of the beam, because the lateral stiffness is mainly provided by the column members of the structure and column members should not fail before the beam members when seismic conditions are considered. This design philosophy generally leads to a value of smaller than 1.0, however, as indicated by Fig.5, the value of *DoC* has exceeded 0.5 when α is smaller than 1.0 and it continues to increase sharply when α is further decreased. Since the stiffness of the column must be ensured in traditional of frame structures, reducing the value of α is not a feasible way to reduce the value of *DoC*.

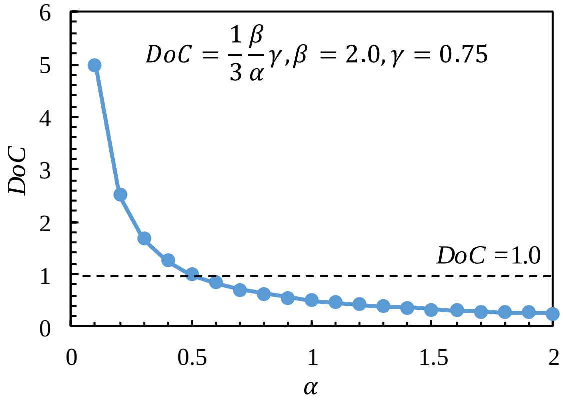


Fig. 5 –The influence of linear stiffness ratio of beam and column on *DoC*

β is define as the ratio of lateral stiffness of the brace and the frame. In the seismic design of EBCF structures, the introduction of the brace is mainly to provide additional stiffness and strength for the original frame, therefore, to effectively improve the seismic performance of the frame, the stiffness of the introduced brace should be 2.0~4.0 times large than the stiffness of frame. However, as shown in Fig.6, the value of *DoC* has exceeded 0.5 when the stiffness of the brace is twice the value of the stiffness of the frame, and *DoC* increases linearly with the increase of β. Because the stiffness of the brace should be ensured to improve the seismic performance of the frame, reducing the value of β is also not a practicable way to reduce *DoC*.

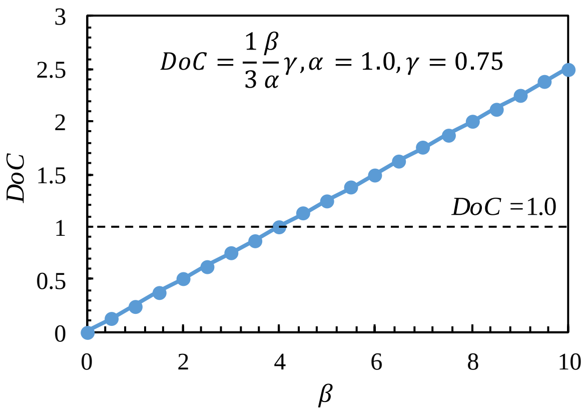


Fig. 6 –The influence of horizontal stiffness ratio of the bracing member and the frame on *DoC*

γ is define as the ratio of *e* to the height of the frame. *e* represents the distance from the neutral axis to the center of the SPD. Fig.7 indicates that, if the value of γ can be reduced, the value of *DoC* can be linearly reduced, this means that reducing the value of *e* is one of the most effectively way to reduce *DoC*. However, in traditional forms of eccentrically braced frame as shown in Fig.1, the value of *e* equals the distance between the neutral axis of the beam (y_{CT}) and its lower flange plus half the height of the SPD (L_{SPD}), this means that the influence of *e* is unneglectable because y_{CT} and L_{SPD} cannot be reduced if traditional forms of EBCF is applied.

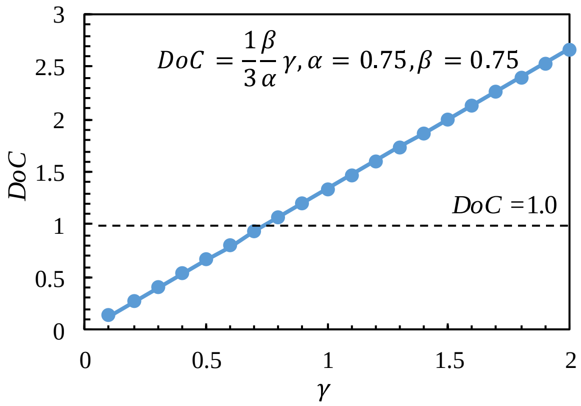


Fig. 7 –The influence of the configuration of shear panel damper on *DoC*

In conclusion, α, β and γ are the main parameters that determine the value of *DoC*, to ensure the seismic performance of EBCF, the value of α and β should be maintained. Therefore, a feasible way to reduce *DoC* is to modify the configuration of the brace and SPD in the frame, which can significantly reduce the value of γ.

3. Bent shear panel damper

According to the discussion in section 2.2, modifying the configuration of the brace and SPD in the frame is one of the most feasible way to reduce the damage of concrete slab. Therefore, bent shear panel damper (BSPD) as a modified form of SPD is proposed in this section.

3.1 Configuration

Compared with traditional SPD which usually adopts a I section composed of two end plates and one shear panel, the BSPD bends the shear panel at the middle, as shown in Fig.8. Through the bending of shear panel, the end plates become perpendicular to each other, while the deformation area of the panel remains unchanged, this ensures that the bent panel can provide similar lateral stiffness and energy dissipation capability for the frame.

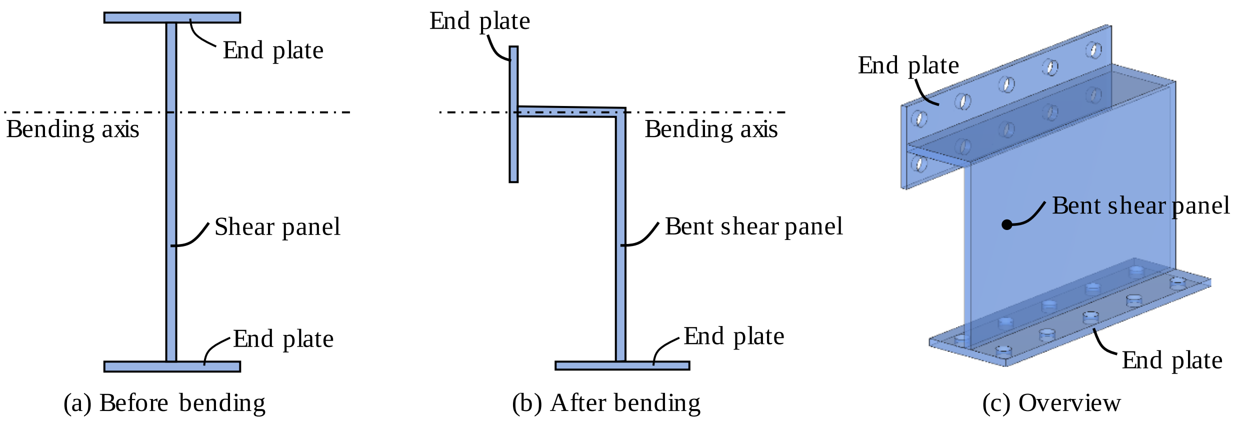


Fig. 8 – Bent shear panel damper (BSPD)

3.2 Working mechanism

Fig.9 shows the installation of BSPD in EBCF, it is noticeable that, compared with traditional SPD whose top end plate is connected the lower flange of the beam, the BSPDs in the EBCF is attached to the frame by connecting the vertical end plate of BSPD and the web of the beam, and to prevent any asymmetrical effects due to the bending of the shear panel, the BSPD is installed at each side of beam web.

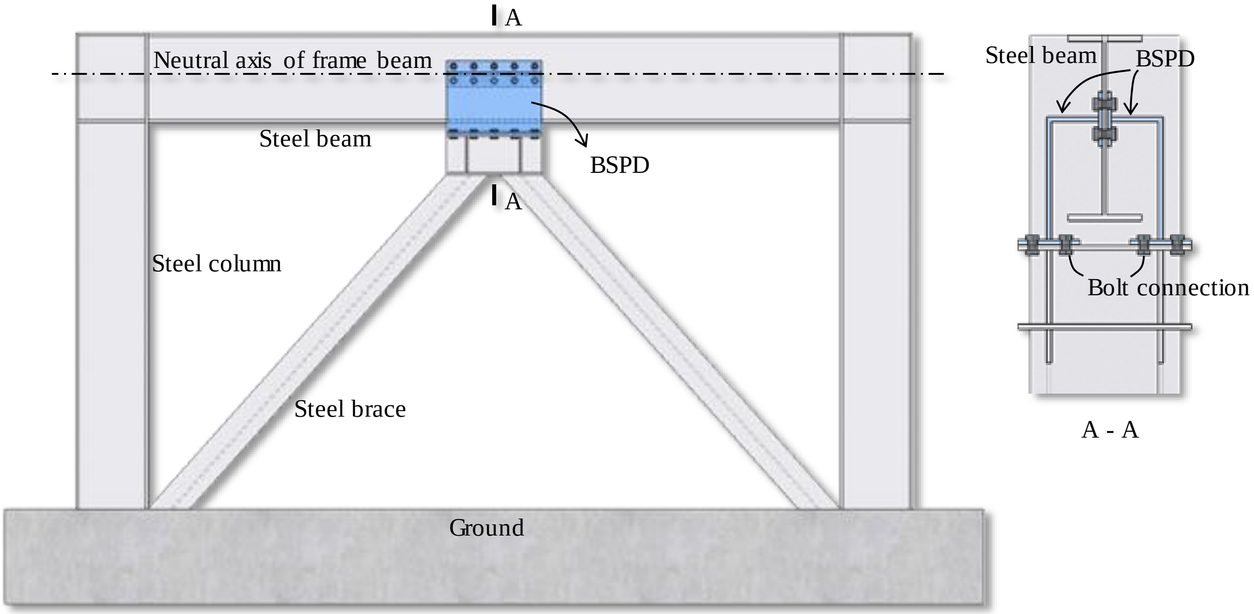


Fig. 9 – The configuration of BSPD in EBCF

As shown in Fig. 9, the vertical end plate is connected to the beam web at the neutral axis of the beam, this not only improve the height of the steel brace to provide more room space for the frame, but more importantly, the distance *e* from the neutral axis to the center of the SPD has been significantly reduced. When designed properly, the value of *e* can be reduced to 0.0 and thus the value of γ is reduced to 0.0 according to Eq. (4), which means that no damage is caused in the concrete slab at the center of the beam by the introduction of BSPD.

Numerical and experimental study are conducted in the following sections to verify its seismic performance and its influence on the damage of concrete slab at the center of the beam.

4. Numerical investigation

Numerical investigations are carried out on the general finite element analysis software Abaqus [3], The finite element model is composed of S4R shell element as shown in Fig.10(a), the dimensions of H_1, H_2 and W are respectively 400mm, 200mm and 400mm according to real practice, the thickness of the model is 16mm. LY160 steel which is usually used in steel dampers is adopt in the model, the material properties are referred to previous studies on this material [4]. To investigate the seismic performance of BSPD, hysteretic displacement load shown in Fig.10(b) is applied.

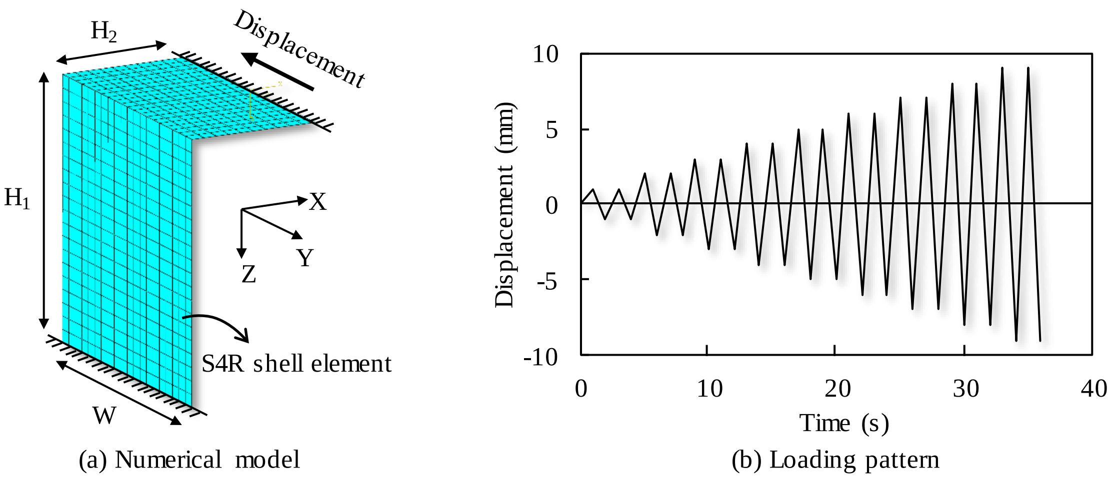


Fig. 10 – Numerical investigation

Fig.11 shows the results of the numerical investigation, it is noticed that the BSPD failed by the buckling of the panel, which is the same as traditional SPDs. The hysteretic response plotted in Fig.11(b) is plump and the maximum displacement (12mm) of the BSPD is about 6 times its yielding displacement (2mm), these phenomena indicates that the BSPD has a stable energy dissipation capacity and deformation capacity.

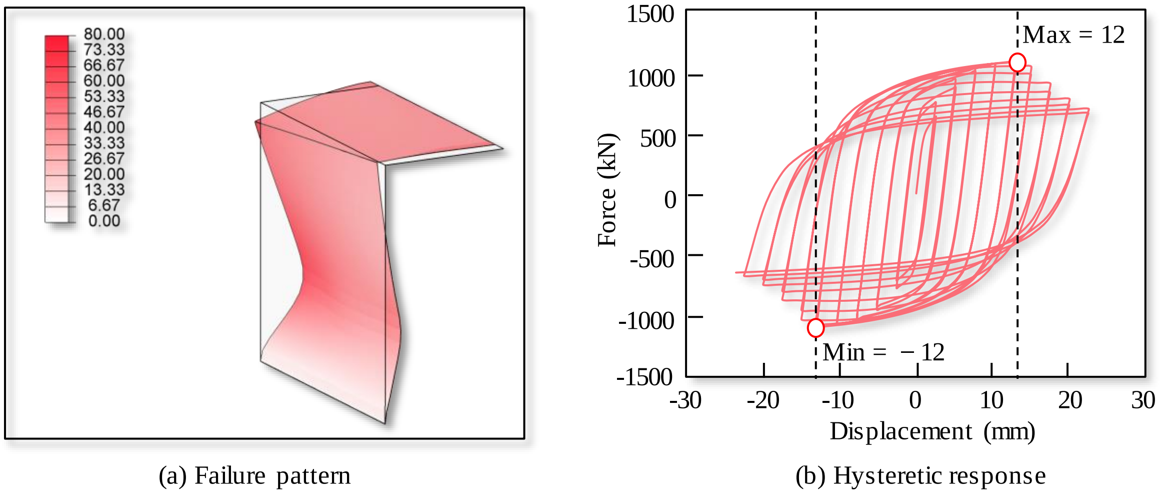
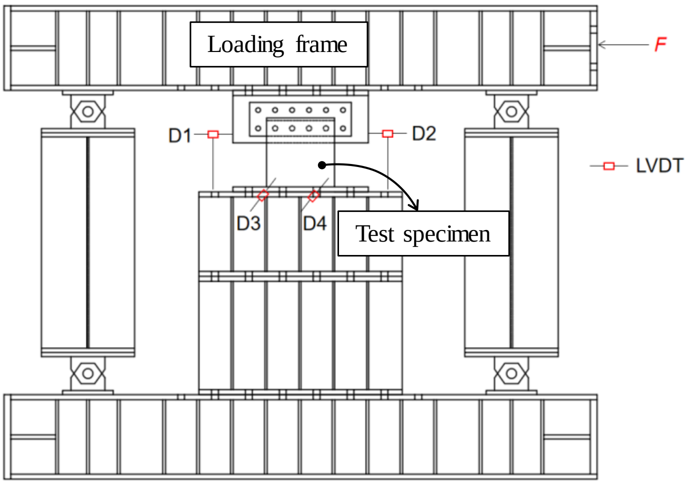


Fig. 11 – Numerical results

5. Experimental verification

The numerical investigation has proven that BSPD performs well under seismic conditions. To further verify the seismic performance of BSPD, experiments on BSPD are conducted. The design parameters of the test specimen are exactly the same as that in the numerical model, except that a transmission curve with a radius of 50mm is applied at the bending point of the shear panel due to manufacture restraints.

The test setup is shown in Fig.12, the end plates are connected to the loading frame thorough high strength bolts, a horizontal force is loaded to the loading frame which transmit the displacement load to the test specimen. Four linear variable differential transformers (LVDTs) are used to record the deformation of the BSPD, among which LVDT D1 and D2 record the horizontal displacement of BSPD, LVDT D3 and D4 record the out of plane deformation of the shear panel.

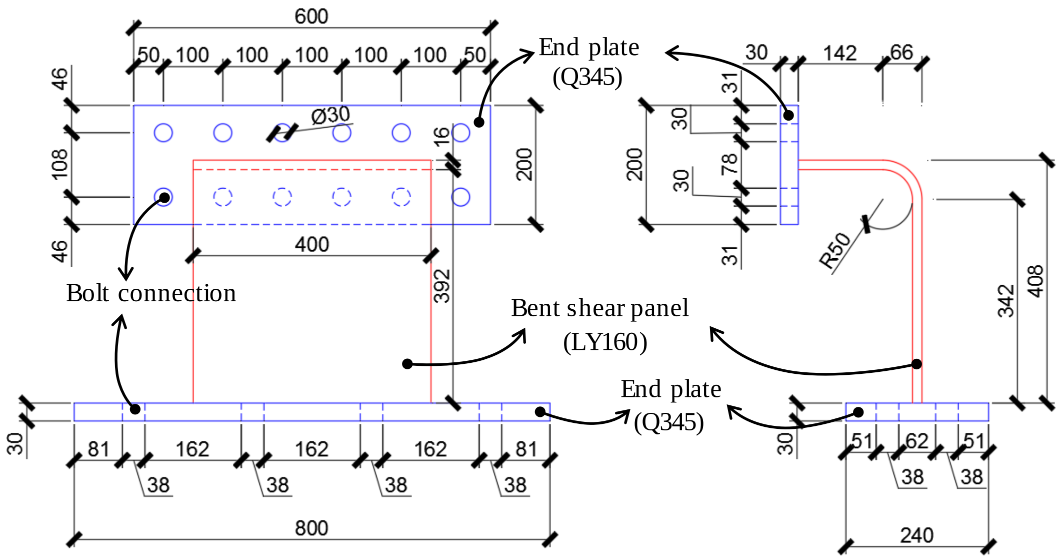


(a) Test configuration

(b) Test specimen

Fig. 12 – Test setup

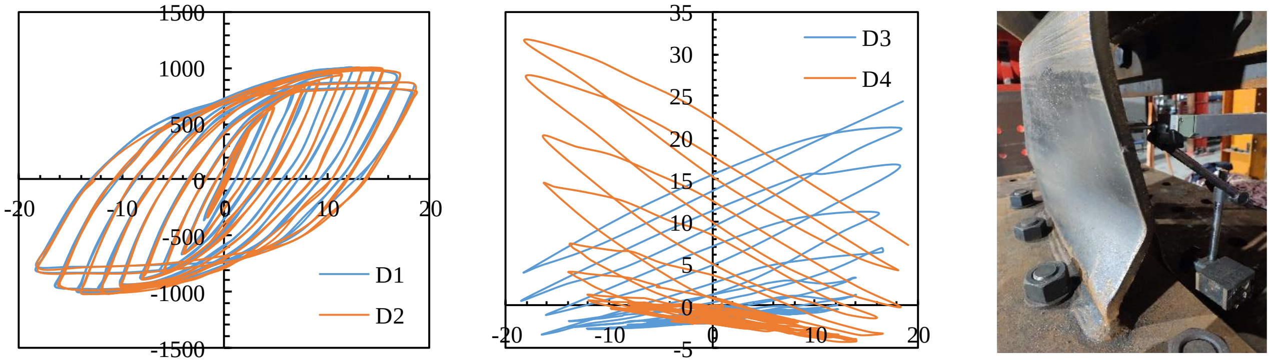
Detailed information of the dimensions of the test specimen is shown in Fig.13. Q345 steel is used as the end plate for connection and LY160 steel is applied to the bent shear panel. The loading pattern applied to the loading frame is the same as that shown in Fig.10(b).



(a) Front view (b) Side view

Fig. 13 – Dimension of test specimen

As shown in Fig.14(a), the test specimen has a stable hysteretic response and deformation capacity, verifying that BSPD has a good seismic performance. Fig.14(b) and (c) display the failure mode of the test specimen, it can be seen that, the BSPD failed by the buckling of the shear panel, which is the same as the prediction of the numerical investigation.

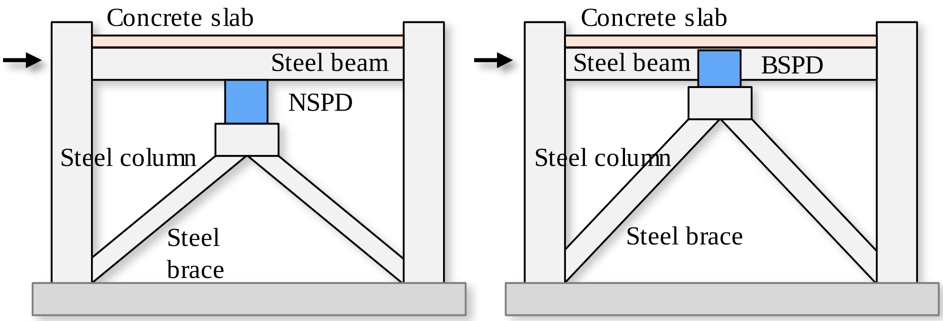


(a) Load-displacement curve (b) Out of plane deformation-displacement curve (c) Failure pattern

Fig. 14 –Test results

6. The application of BSPD in EBCF

To investigate the performance of EBCF with BSPD (model EBCF-BSPD) compared with traditional EBCF with normal shear panel damper (model EBCF-NSPD), an actual composite frame is extracted from previous study [5]. The configurations of model EBCF-NSPD and model EBCF-BSPD are shown in Fig. 15. A hysteretic displacement load with a pattern shown in Fig.10(b) is applied to the investigated model.



(a) Model EBCF-NSPD (b) Model EBCF-BSPD

Fig. 15 The invesitgated structures

Fig.16 shows the hysteretic response of the two investigated models, it is seen that EBCF-BSPD has the same stiffness and strength as EBCF-NSPD, this mean that the BSPD can improve the stiffness and strength of the composite frame as well as traditional SPD. In addition, the hysteretic curve of EBCF-BSPD is more plump than that of EBCF-NPSD, indicating that the introduction of BSPD can further improve the energy dissipation capacity of the composite frame.

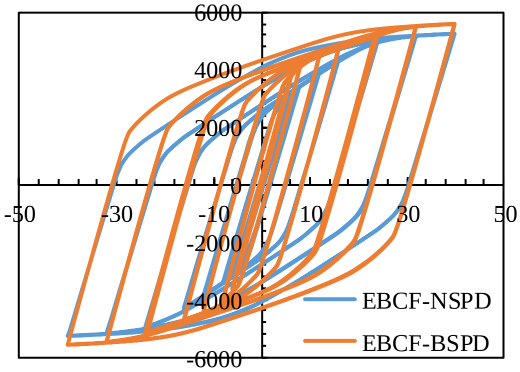


Fig. 16 Hysteretic performance

Fig.17 shows the distribution of concrete slab damage of two models, it is obvious that the concrete damage only concentrated at the end of the beam in model EBCF-BSPD, while in model EBCF-NSPD, a significant damage of concrete is also observed at the center of the beam. This comparison proves that through the introduction of BSPD, the concrete damage at the center of the beam is effectively reduced.

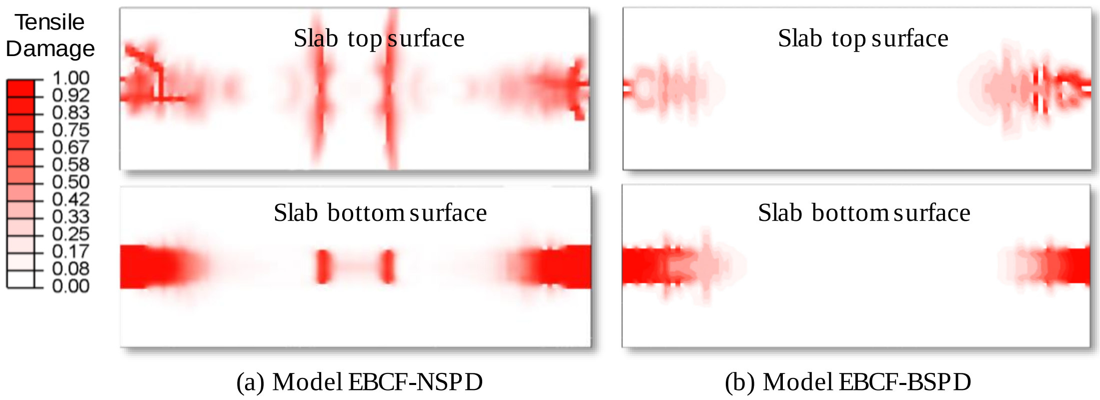


Fig. 17 Concrete slab damage distribution

6. Conclusion

To prevent the damage of concrete at the center of the beam in eccentrically braced composite frame (EBCF), bent shear panel damper (BSPD) is proposed to replace traditional shear panel damper (SPD) in the EBCF.

The numerical study and experimental verification has shown that BSPD has the same seismic performance as traditional SPD.

The case study investigated in this paper has shown that, EBCF with BSPD has a better energy dissipation capacity than traditional EBCF and the introduction of BSPD can effectively reduce the concrete damage at the center of the beam.

7. References

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