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A study into effects of plate stiffeners on the retrofitted deep RC coupling beams

B. Cheng [1], C.T. Yang [2], C.H. Shi [2], M.J. Zhou[2]

[1] *Associate Professor, Department of Civil & Transportation Engineering, Beijing University of Civil Engineering and Architecture, China, chengbei@bucea.edu.cn*

[2] *Master Candidate, Department of Civil & Transportation Engineering, Beijing University of Civil Engineering and Architecture, China*

Abstract

Existing deep reinforced concrete (RC) coupling beams with low shear span ratios and conventionally reinforced shear stirrups tend to fail in a brittle manner with limited ductility and deformability under reversed cyclic loading. Previous studies have developed a new retrofitting method with stiffened laterally restrained steel plate (LRSP) for existing deep RC coupling beams. The additional stiffeners can prevent plate buckling and ensure that the steel plate has a wider yield area and hence the retrofitted coupling beams could achieve a higher energy dissipation capability. However, according to experimental study, it can be found that too much stiffening would lead to a loss of deformability of the retrofitted coupling beams.

In this paper, by using finite element analysis program MSC.Marc, plate stiffeners with different arrangement were adopted in order to study the effect of stiffeners on the performances of the retrofitted coupling beams. The numerical results revealed that by adding more stiffeners on steel plate, the shear capacity of the retrofitted coupling beam could be increased slightly. And the stiffeners set passing the center point of steel plate could effectively restrain plate buckling. Moreover, stiffeners set passing the plate center point of steel plate and diagonally stiffeners could better control the cracking of concrete and the failure modes are more ductile. These two kinds of arrangement are more preferable for enhancing the seismic performances of the retrofitted deep coupling beams.

Keywords: Deep coupling beams, Seismic retrofitting, plates buckling, Plate stiffeners, Finite element analysis.

1. Introduction

Reinforced-concrete (RC) shear walls and core walls are widely used in high building structures as a lateral load-resisting system. Individual wall piers are coupled together by coupling beams thus forces could be transferred between them. Hence, the lateral strength, stiffness and ductility of the lateral load-resisting system have strong relationship with those of coupling beams. Local failure of coupling beams may lead to an overall failure of the whole system. Most coupling beams with a small span-to-depth ratio are known as deep coupling beams. Their behavior is normally controlled by shear forces, especially for deep RC coupling beams with span-to-depth ratios less than 1.5. They tend to fail in a brittle manner with shear failure, and their deformability capacity are usually insufficient, which is not desirable for seismic resistant design. For many current coupling beams in the old reinforced concrete buildings built in the last few decades, due to the reasons such as the aging of construction material or changing of building function, the updated design requirements of new codes, they may be deficient in shear reinforcement. Hence, to ensure the sufficient strength, stiffness and deformability capacity of the old buildings, a large number of RC coupling beams may require seismic retrofitting.

Many studies have focused on retrofitting of normal RC beams, however, only a few methods are applicable for RC coupling beams, especially for deep RC coupling beams. Harries et al. [1] conducted an investigation on retrofitting coupling beams with different attachment methods to fix the steel plate to one side of the coupling beams. Specimens in their experiments have the same span-to-depth ratios of 3.0. Their studies illustrated that the hybrid method of bolting and epoxy bonding to attach the steel plates both in the span and at the ends is more desirable. Su and Zhu [2] presented a set of tests for RC coupling beams with span-to-depth ratios of 2.5, which were retrofitted by means of bolting the steel plate to both ends of the wall panels without adhesive bonding. They found that this retrofitting method could enhance the strength and deformation capacity of medium length coupling beams under cyclic loadings. Minor plate buckling all occurred in their experiments. Su and Cheng [3, 4] focused on the coupling beams with span-to-depth ratios smaller than 2.0 and they proposed the method of bolted laterally restrained steel plate (LRSP) without stiffeners to retrofit deep RC coupling beam. They experimentally studied several deep coupling beams with span-to-depth ratios of 1.1. The experimental results revealed that the post-peak behavior, deformability and energy dissipation of LRSP retrofitted coupling were all improved while the stiffness did not increase. Obvious plate buckling occurred in their experiments. Then Cheng and Su [5] conducted a numerical study to investigate the influence of plate buckling on the behaviors of LRSP retrofitted coupling beams. The effects of plate buckling, plate thickness and the bolt stiffness were investigated in their study. Serious plate buckling could result in the significant pinching and stiffness degradation in the hysteresis response of the coupling beam. Cheng and Su [6] added some appropriate stiffeners on the steel plate to avoid plate bucking. It can be found that the LPSP retrofitted coupling beams with stiffeners can achieve higher and more stable energy dissipation ability. The effects of the plate's stiffeners on the performances of LRSP retrofitted coupling beams was investigated.

In this study, a nonlinear finite element analysis (NLFEA) by using the software MSC.Marc (2014) was conducted to predict the performances of LRSP retrofitted coupling beams with stiffeners. The NLFEA model was validated by the previous experimental results. The stress distribution of the steel plate with different stiffeners was studied. The numerical results revealed that by adding more stiffeners on the steel plate, the shear load carrying capacity of retrofitted coupling beam could be increased slightly. And the stiffeners set passing the center point of steel plate could effectively restrain plate buckling. Moreover, stiffeners set passing the plate center point of steel plate or diagonally stiffeners could better control the cracking of concrete and the failure modes of the retrofitted coupling beams are more ductile. These two kinds of arrangement are more preferable for enhancing the seismic performances of the retrofitted coupling beams.

2. Previous Experimental Studies

In order to control the plate buckling, Cheng and Su [3] proposed a buckling restrained device, which is composed of four steel angles and installed at the beam span by bolts connections (as shown in Fig.1). Slotted holes were used at the four joints between the steel angles, and then the two lateral steel angles were allowed to freely rotate and move in the longitudinal direction. Therefore, the stiffness of the coupling beams would not be increased after being retrofitted. Because the increment in the stiffness of the beam could induce more seismic loading in the system which is not desired.

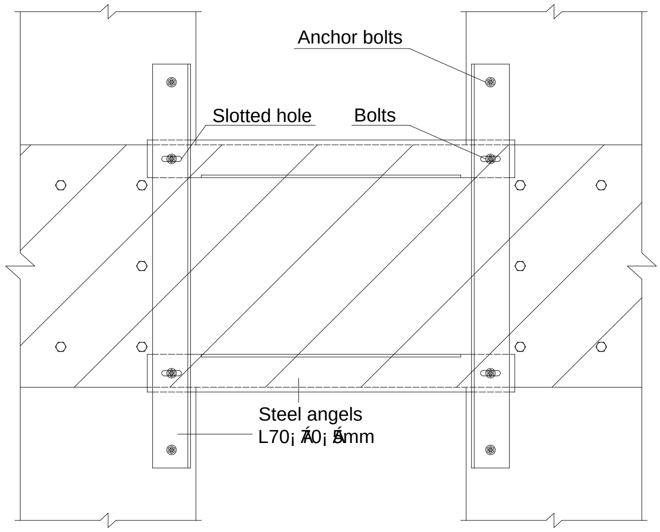

Fig. 1 Buckling-controlled device

Cheng and Su [6] conducted a set of tests for deep coupling beams with small span-to-depth ratios of 1.1. All specimens have the same dimensions and reinforcement arrangement but different retrofitting schemes (Fig. 1). The size of the coupling beams was 450 mm deep by 120 mm wide with a clear span of 500 mm. Specimen DCB8 is the original deep RC coupling beam without retrofitting for control purpose. Another three specimens (DCB10, DCB11 and DCB12) were retrofitted by the method of LRSP but with different arrangements of plate stiffeners (Fig.2). Two kinds of stiffeners arrangements were investigated in tests. Rectangular steel plates with a width and a thickness of 20 mm and 9 mm, respectively, are selected as horizontal stiffeners and steel rebars with a diameter of 10 mm are used as diagonal stiffeners. The stiffeners are placed symmetrically along the span of the steel plate.

Summary of the experimental results are showed in Table.1, which demonstrated that, by using laterally restrained steel plate with stiffeners, the strength, deformability and energy dissipation ability of the retrofitted deep RC coupling beam could be increased effectively. The failure mode of the retrofitted coupling beams became more ductile. And the shear strength and energy dissipation capacity could be increased by adding properly arranged stiffeners. However, too much stiffening would lead to a loss of structural deformability. Hence, it is of significant importance to study the role of stiffeners by numerical studies.

3. Numerical Studies

3.1 Finite element model

Nonlinear finite element analysis (NLFEA) was conducted by utilizing the MSC.Marc (2014) program [7]. The nonlinearities of materials were properly modeled in the finite element model. And the “Large Strain” option was activated to consider the geometric nonlinearity. Furthermore, the buckling of steel plate was modeled by incorporating the initial geometric imperfections. The slipping effects of bolts were also considered in proposed model.

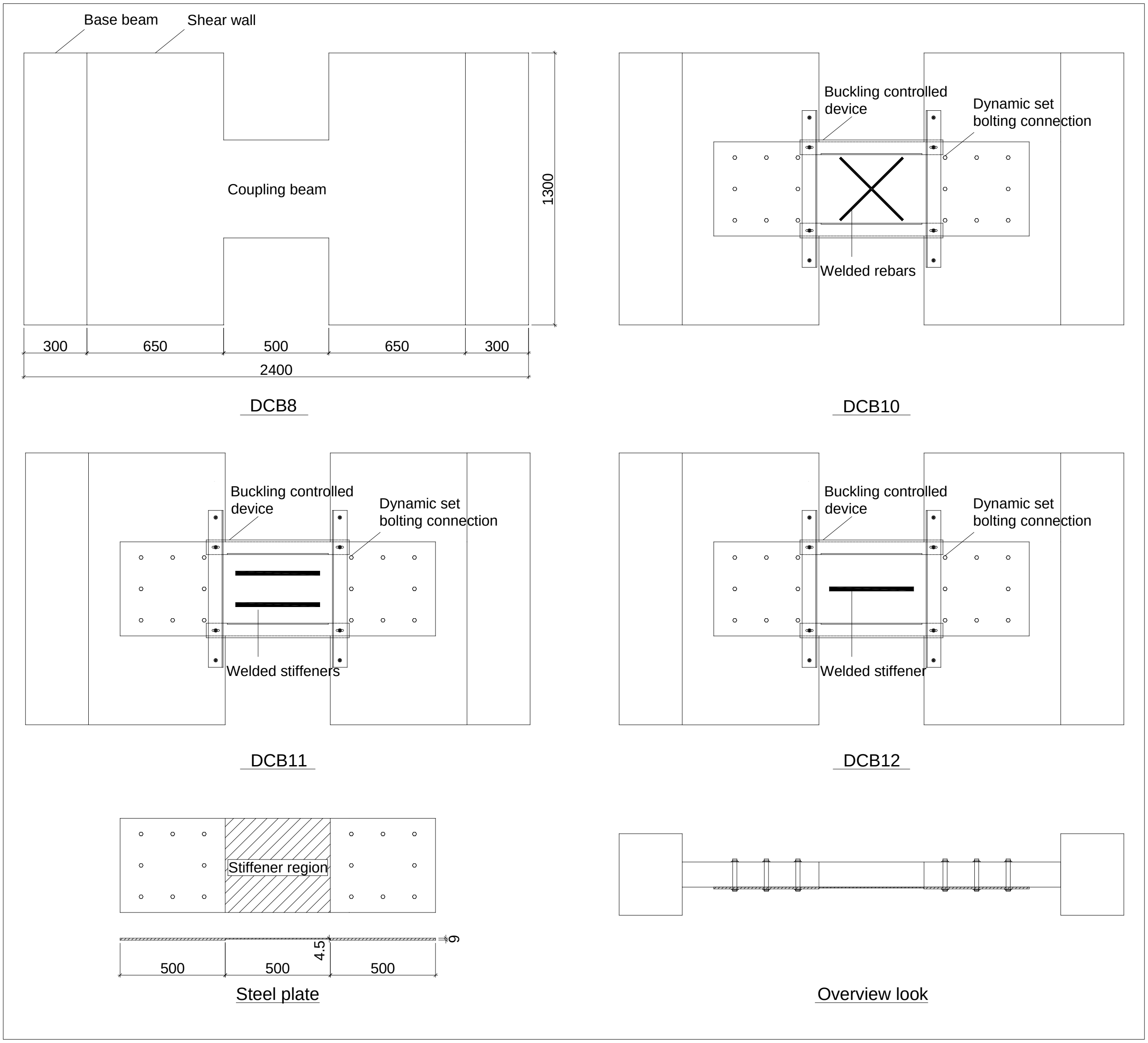

Fig. 2 Details of test specimens

Table 1 – Summary of experimental results

Specimen	Failure Mode	V^*_u kN	V_u kN	V_u increased%	v_{max} MPa	θ_y rad	θ_u rad	θ_u increased%	μ	μ increased%	K_o 10^6kN/mm
DCB8	brittle	242	246	N/A	4.6	0.0055	0.0186	N/A	3.4	N/A	27
DCB10	ductile	460	411	67	7.6	0.0092	0.0403	116	4.4	29	27
DCB11	brittle	460	400	63	7.4	0.0083	0.0287	54	3.5	3	29
DCB12	ductile	460	366	49	6.8	0.0076	0.0374	101	4.9	44	29

3.1.1 Element types and boundary conditions

Multilayer shell element [8] was utilized in the proposed NLFEA model. Based on the principles of composite material mechanics, this kind of element is composed of certain number of layers with different thickness and material properties, representing concrete layers and smeared rebar layers respectively. Depending on the reinforcement ratio, the rebars can be smeared into one or more layers with isotropic or orthotropic materials.

Considering the complexity of reinforcement arrangement and uniformity of reinforcement ratio, rebars can be modeled in two ways: smeared rebar layer model and embedded discrete rebar model. In this study, stirrups in the coupling beam and transverse rebars in the shear walls were modeled with the smeared rebar layer model, and all longitudinal rebars were modeled with the embedded rebar model. Truss 9 elements were selected to simulate longitudinal rebars. Steel plate and stiffeners were molded with Shell 75 elements. The boundary conditions were modeled based on the real test situations. The meshes of specimen DCB 10 and the boundary conditions are shown in Fig. 3.

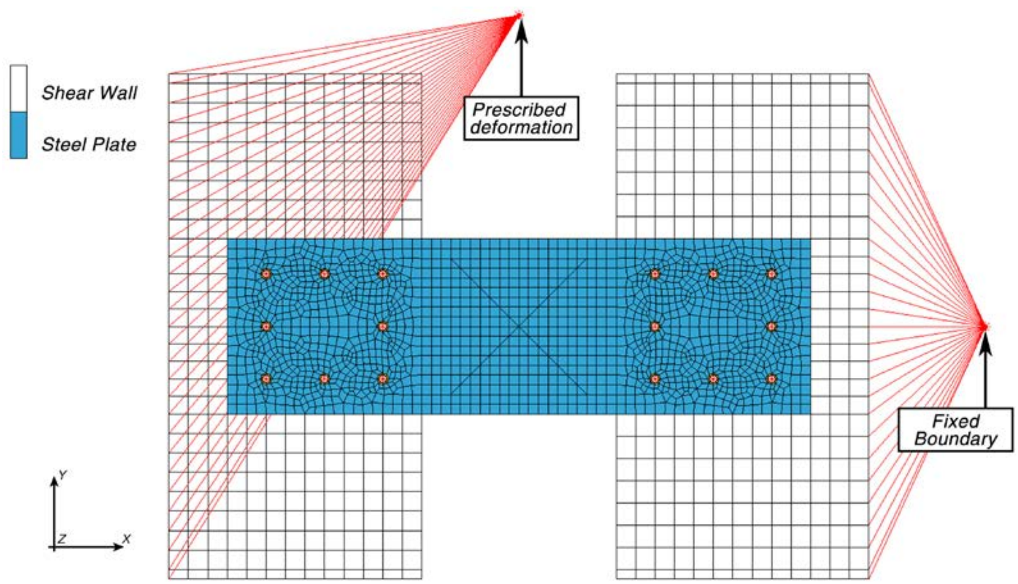

Fig. 3 Finite element model of a LRSP coupling beam

3.1.2 Modeling of materials

The nonlinear properties of concrete and steel materials were simulated using the elastic-plastic constitutive models based on the experimental tests results.

For concrete material, the equivalent yield stress vs. equivalent plastic strain relationship was determined by the uniaxial compressive stress–strain relationship of concrete. To consider the confinement effect of concrete, the ascending branch of the uniaxial compressive stress-strain relationship was determined by Mander et. al [9]. The descending branch of the uniaxial compressive stress-strain relationship was described with a linear relationship. To ensure the computational stability, a residual strength was incorporated. The yield criterion was based on the Buyukozturk model.

Smeared crack model with fixed crack angles, packaged in MSC.Marc, was selected for simulating the cracking damage behavior of concrete. The critical cracking stress was taken as the tensile strength of concrete.

3.1.3 Initial geometric imperfections of steel plate

According to experimental studies, the local buckling effect of steel plate could significantly affect the overall behavior of the retrofitted RC coupling beams [3]. Ignoring the effects of local buckling in NLFEA model may lead to overestimates of the ultimate load of the retrofitted coupling beam. Hence, buckling effects of steel plate was considered in this study by means of incorporating initial geometric imperfections of steel plate.

An elastic buckling analysis (i.e. eigenvalue analysis) was conducted to obtain the buckling modes of steel plate. The numerical model of steel plate was a part of the corresponding numerical models of the retrofitted coupling beam (as showed in Fig. 4). With the lowest buckling mode, the initial geometric imperfections of steel plates could be determined. The maximum magnitude of the initial geometric imperfections at the plate was taken as 0.003 h_p (h_p = the height of the steel plate) [10].

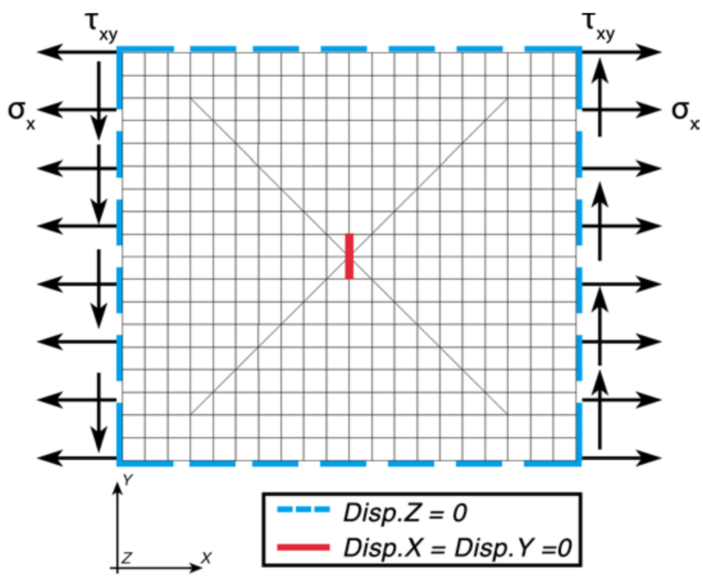

Fig. 4 Finite element model of the steel plate

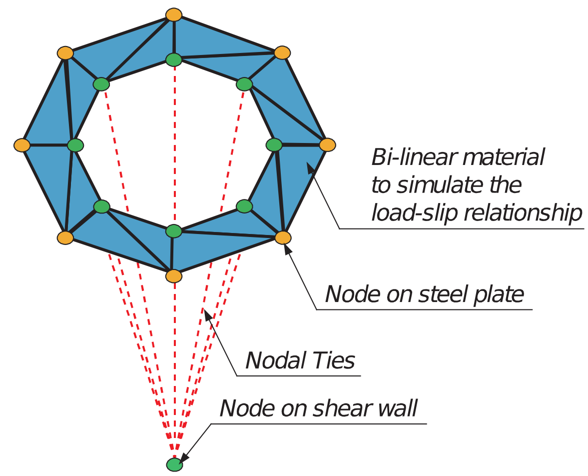

Fig. 5 Finite element model of the bolt connection

3.1.4 Modeling of bolt slipping effect

Previous investigations revealed that, to accurately simulate the behavior of retrofitted coupling beam, the slipping effects of bolts have to be considered. In this study, a numerical model of bolt connection was incorporated as shown in Fig.5. A ring region consisting triangular elements was used to simulate the interactions between the bolt shank, the steel plate and the surrounding concrete. The material of triangular elements was modeled with a bi-linear model to simulate the load-slip relationship. Nodal ties were created between the nodes on the shear wall and the nodes of inner ring.

3.2 Verification of the finite element model

Finite element model should be validated by the previous experimental results. Fig. 6 shows the comparison of load-rotation curves of DCB10 obtained from NLFEA and experiment. It can be found that numerical results have good agreement with experimental results, especially for the ascending branch. The initial stiffness and the yield strength of retrofitted specimen can be accurately predicted within an acceptable error range. Moreover, the prediction of hysteretic behavior and energy dissipation capability are instructive for further research.

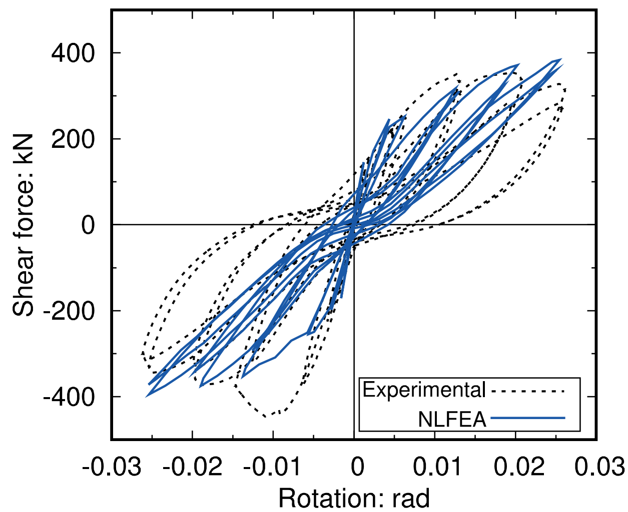

Fig. 6 Experimental and numerical load-rotation curves of DCB 10

3.3 Arrangement of plate stiffeners

The arrangement of plate's stiffeners, which may affect the performances of the retrofitted coupling beam, is a key concern in this study. Case studies for the retrofitted coupling beam were carried out by using NLFEA. Apart from the different arrangements of stiffeners, the other properties are as same as those of Case 1. The stiffeners arrangements of each case are presented in Table 2. Case 1 was the original one without stiffeners added.

Table 2 – Detail of numerical study model

Case	Stiffener Arrangement		Stiffener size
Case1	N/A		N/A
Case 2 (DCB 12)	One horizontal		□ 20mm*9mm*400mm
Case 3 (DCB 11)	Two horizontal		□ 20mm*9mm*400mm
Case 4	Three horizontal		□ 20mm*9mm*400mm
Case 5	One Vertical		□ 20mm*9mm*400mm
Case 6 (DCB 10)	Two diagonal		Rebar diameter = 10mm

3.4 Effects of plate stiffeners on the crack patterns in concrete

The crack patterns at the peak load of experimental results and numerical results are showed in Fig. 7. Comparing of the crack patterns obtained from the NFLEA results with the experimental results, it can be found that the NLFEA model could correctly predict the crack patterns of deep RC coupling beams. The extensive diagonal crack at the peak load indicates that the shear capacity of the beams was insufficient. The extent of concrete cracking could be reflected by calculating the maximum cracking strain which is shown in Figure 8. By comparing the cracking strain of DCB 8 with that of the other cased, it is obvious that adding plate stiffeners could alleviate the concrete cracking. Moreover, using two diagonal stiffeners (DCB10) and one horizontal stiffener passing through the center of plate (DCB12) are more preferable to control concrete cracking. However, using vertical stiffener (Case 5) and without stiffeners passing through the center of plate (DCB11) are not effective to control concrete cracking.

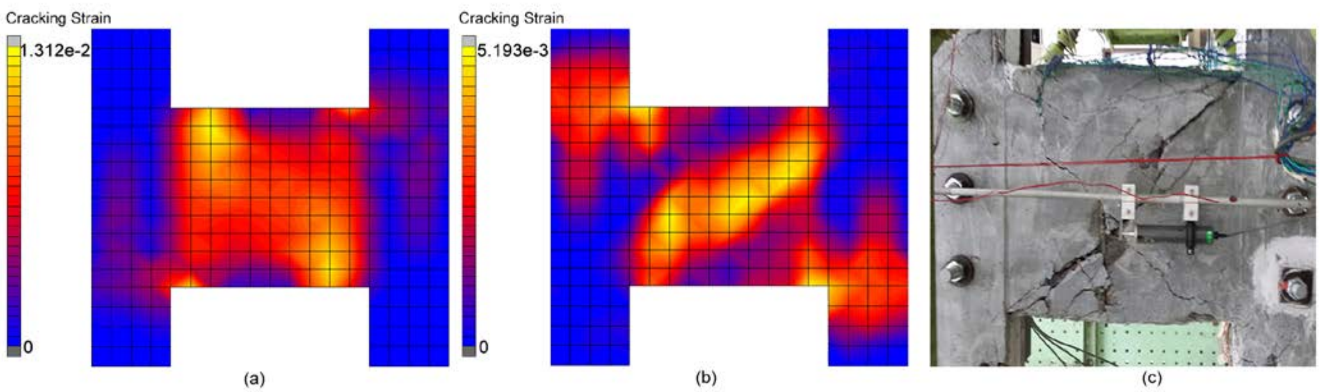

Fig. 7 Crack patterns at the peak load of (a) DCB8, (b) Case 2 (DCB 12), (c) DCB12 (Experimental)

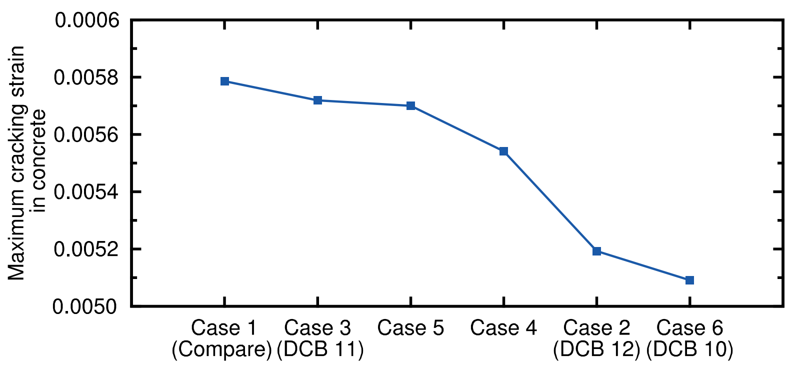

Fig. 8 Maximum cracking strain of concrete

3.5 Effect of plate stiffeners on the shear capacity of retrofitted beams

Fig. 9 shows the peak strengths of the simulated specimens by comparing the results of the original coupling beam DCB8 with the other retrofitted coupling beams (Case1-Case6). It is obvious that LRSP retrofitting method with stiffeners could effectively enhance the shear capacity of RC coupling beams.

By comparing the results of Case 1 to Case 6, it can be found that adding more stiffeners could slightly enhance the shear capacity. It can be concluded that the optimization for increasing the shear capacity of the retrofitted coupling beam is the minimum amount of stiffeners which can control the overall buckling of the steel plate.

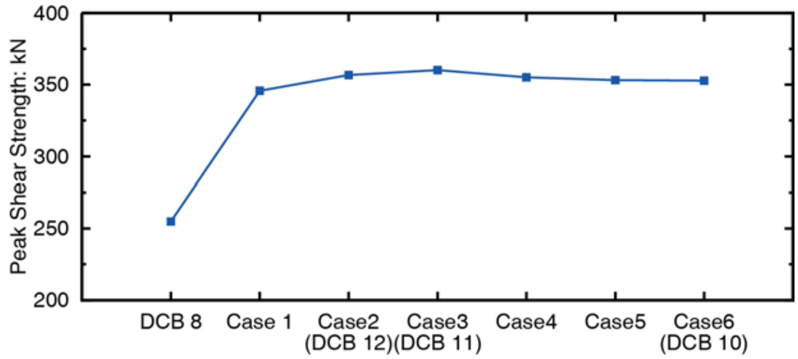

Fig. 9 Effect of plate stiffeners on the peak shear capacity

3.6 Effect of plate stiffeners on the buckling deflection

The maximum deflection δ of steel plates can be calculated through numerical analysis. The ratios of δ to δ_0 (δ_0 = the maximum out-of-plane deflection of Case 1 without stiffeners) are showed in Fig. 10. The effect of plate stiffeners on the buckling deflection of the steel plates can be revealed. It is obvious that adding stiffeners could remarkably alleviate the out-of-plane deflection of steel plate. With more stiffeners added, more decrement of deflection could be achieved. However, for Case 3 (DCB 11) with two horizontal stiffeners, the deflection was larger than that of Case 2 (DCB 12) with only one horizontal stiffener. This may due to the arrangement of stiffeners. The single stiffener of DCB 12 was set horizontally passing the center point of steel plate while the two stiffeners of Case 3 (DCB 11) was set horizontally and symmetrically, not passing the center point of steel plate. According to the distribution of minimum principal stress of steel plate of Case 1 at the peak load, the compression region of steel plate was right around the plate center, where local buckling tends to occur. Hence, stiffeners set passing the center point of steel plate could better control the buckling deflection of steel plate.

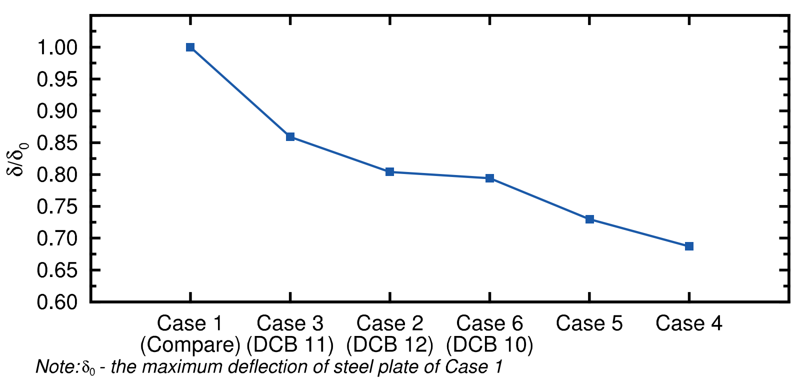

Fig. 10 Maximum deflection of steel plates in numerical analysis

3.7 Effect of plate stiffeners on the stress distribution of steel plate

The shear stress distribution of steel plate and stiffeners at the peak load are showed in Fig. 11. It is clearly observed that by adding stiffeners or changing the arrangement of stiffeners, the distribution of shear stress was changed slightly although adding stiffeners may result in some high stress concentration regions. While for DCB10 with two diagonal stiffeners, it can be found that diagonal stiffeners can help to resist more shear force than the other kinds of stiffeners.

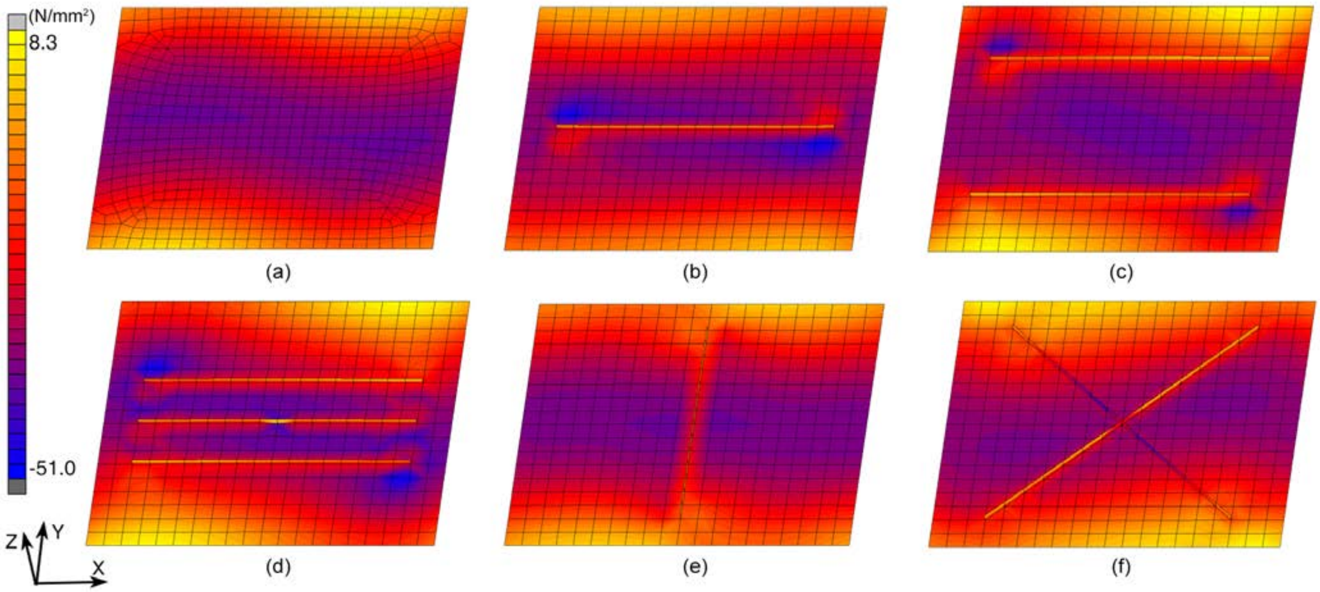

Fig. 11 Shear stress of steel plates and stiffeners at the peak load

(a) Case 1 (b) Case 2 (DCB 12) (c) Case 3 (DCB 11) (d) Case 4 (e) Case 5 (f) Case 6 (DCB 10)

The minimum principal stresses of steel plates at the peak load are shown in Fig. 12. It can be found that the arrangement of plate stiffeners have great effects on the distribution of the compression region in the steel plates. It should be noted that great compression force in the steel plate is not preferred because this may due to much tension force in the RC coupling beam, which may accelerate the cracking of concrete. For Case 3 with two horizontal stiffeners, the compression region of steel plate was larger than that of Case 2 with only one single stiffener. And for Case 6 with two diagonal stiffeners, the compression region of steel plate is less than that of other five cases. Much plate stiffeners may result in large compression region and high stress concentration. Hence the plate-center-passed stiffeners and diagonal stiffeners are more desirable. This can also explain why the failure modes of these two cases are more ductile as was discussed in part 3.4.

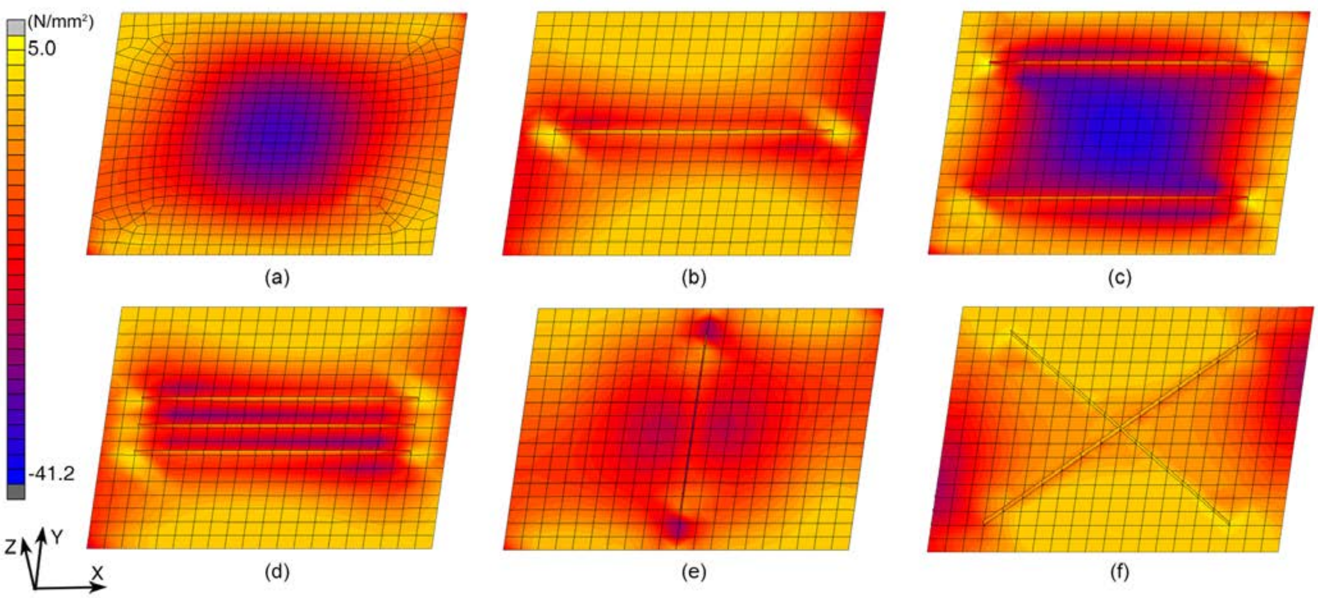

Fig. 12 Minimum principal stress of steel plates and stiffeners at the peak load

(a) Case 1 (b) Case 2 (DCB 12) (c) Case 3 (DCB 11) (d) Case 4 (e) Case 5 (f) Case 6 (DCB 10)

4. Conclusions

This paper presents experimental and numerical investigation of deep RC coupling beams retrofitted with a laterally restrained steel plate (LRSP) with stiffeners. The key findings of this study are summarized as follows.

(1) The retrofitting method of laterally restrained steel plate with stiffeners is effective for strengthening deep RC coupling beam. The strength, deformability, ductility and energy dissipation capability could be greatly increased while the stiffness of the coupling beam will not be increased.

(2) The proposed finite element model based on MSC.Marc program for the retrofitted coupling beams could accurately simulate the behaviors of the retrofitted beams. The local buckling effect of steel plate and load-slip behavior of bolts was properly incorporated in proposed model. Using this model, the shear capacity of coupling beam and the internal forces in the steel plate could be correctly predicted.

(3) The effects of stiffeners on the performances of retrofitted coupling beam was investigated by using NLFEA model. By adding stiffeners on steel plate, the shear capacity of retrofitted coupling beam could be slightly increased. Stiffeners set passing the center point of steel plate could effectively restrain local buckling of steel plate and control the cracking of concrete. It is concluded that an optimum amount of diagonal stiffeners or horizontal stiffeners set passing the center point of steel plate should be used to achieve desirable behaviors.

(4) The proposed NLFEA model for the retrofitted coupling beam is instructive for further research. A more simplified macro model of the retrofitted coupling beams should be studied and incorporated into the numerical mode of coupled shear wall systems for further investigation the performances of the whole shear wall buildings after retrofitting.

5. Acknowledgements

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