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Evaluation of Performance of RC Beam–Column Joint Externally Strengthened with Steel Strips

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ABSTRACT: The beam-column joints (BCJ's) are the most critical elements in reinforced concrete (RC) buildings for resisting seismic loads. Steel strips in the form of cage applied to the beams and columns results in enhancement of the capacity of the joint by an order in magnitude without compromising the ductility. Steel cage provides an economical and easy to apply strengthening technique. A 3D finite element (FE) model of the BCJ was developed which captured the experimental response of the control and steel cage strengthened specimens. Parametric studies by varying the spacing of the strips and the length of the steel cage showed that an optimum economic configuration can be reached. In comparison with steel cages, CFRP strengthening of the joint failed to achieve a significant enhancement in the capacity of the BCJ.

Keywords: Beam-column joint; Finite element model; Strengthening; Steel cages.

1 INTRODUCTION

One of the most critical components of RC structures is BCJ's, especially if the structure is subjected to seismic loads. A large number of reinforced concrete structures have been damaged in the past due to earthquakes, and some of these structures have been repaired and strengthened. There are many examples of the repair and strengthening of reinforced concrete buildings damaged by earthquakes that have been reported in earthquake-prone countries such as in the Balkan Region, Mexico and Peru. Special attention should be given to beam-column joints of a reinforced concrete structure because of their highly complex behavior under seismic loads, which is clear by a combination of large shear forces, diagonal tension and high bond stresses in the reinforcement bars, which lead to brittle mode of failure (Uma 2005,Engindeniz 2008). Jacketing of deficient BCJ was widely used in the 80's and 90's in the last century. The steel jackets due to its heavy weight and problems in its application has been to a great extent replaced by the CFRP sheets. However, the CFRP strengthening has its own shortcomings in applications, fire and is uneconomical due to its high cost (Campione et al. 2013).

A host of other techniques are being investigated to obtain a cost effective strengthening technique for deficient BCJ's. In majority of buildings, the exterior BCJ's have beams spanning from the three faces of the joint with only the back face being exposed. Strengthening of these exterior BCJ's, where the joints themselves cannot be strengthened due to lack of accessibility, is only possible by strengthening the regions of beams and columns around the joints. One such technique is proposed by Campione et al. in which steel angles and strips are used for strengthening of the joints (Campione et al 2015). The steel strip retrofitting resulted in enhancement of the load capacity of the joint in an order of magnitude.

Finite element modelling has become a powerful computational tool for nonlinear analyses of RC structures and prediction of load deflection behavior and crack patterns under applied load. FE simulation results needs to be verified by real experimental test (Alsayed et al. 2010). Load-deflection response of RC frames under the incremental loading using software ATENA (Kumari and Kwatra2013), FE modeling of reinforced concrete columns strengthened with steel cages under bending moment and axial load (Roca, et al. 2012) and evaluation of a steel-envelop approach to seismic retrofit of RC frame joints (Weng et al. 2012) demonstrates the robustness of the FE simulation. FE response of exterior BCJ strengthened with FRP and steel plates under cyclic loading was captured with a good accuracy (Sasmal et al. 2011).
Analytical equations for moment–axial force response in the presence of shear, for RC BCJ strengthened with steel angles and strips were developed (Campione et al. 2015) based on a detailed experimental program. In another study, Campione evaluated analytically the effectiveness of steel cages in strengthening columns subjected to axial loads (Campione 2013). This paper presents a nonlinear FE simulation of the experimental work (Campione et al. 2015) on exterior BCJ retrofitted with steel strips together with parametric studies to achieve an optimal configuration of spacing of the strips and the length of the steel cage.

2 DETAILS OF EXPERIMENTAL WORK (Campione et al. 2015)

Campione et al. (2015) studied experimentally and theoretically, the flexural behavior of external BCJ strengthened with steel cages. In the experimental test, the specimen of BCJ was tested under a constant vertical load and monotonically increasing lateral load acting on the tip of the beam. Beam 1.75 m in length and300 mm x 450 mm in section and column3.31 m long of cross section 300 mm x 300 mm is used for the BCJ. The column is reinforced with 4-14 mm dia. longitudinal bars and 8 mm dia. closed ties @ 200 mm c/c. The beam is reinforced with4-14 mm dia. bars (top and bottom) and 8 mm dia. stirrups @ 250 mm c/c. For joint and stump, 3-14 mm dia. bars (top and bottom)and 8 mm dia. stirrups @ 250 mm is used (See Figure 1).The BCJ was strengthened with a steel jacket shown in Figure 2. The column jacket comprises four angles 50 mm x 50 mm x 5 mm and transverse battens 40 mm x 4 mm welded to steel angle. The jacket for the beam has angles 50 mm x 50 mm x 4 mm and transverse strips welded to steel angle 12 mm x 12 mm at 120 mm c/c.

The control and strengthened BCJ's were tested under constant axial load and monotonically increasing lateral load. The load-deformation curves are shown in Figure 3. Strengthening of the BCJ using steel strips resulted in about 120% increase in the load carrying capacity of the joint. The control specimen failed by shear failure in joint but in the strengthened specimen, the failure occurred in the beam. The proposed scheme is efficient and economical for the strengthening of deficient joints.

3 FINITE ELEMENT ANALYSIS

FE simulation of the BCJ tested experimentally by Campione et al. was conducted using the commercial FE software ABAQUS. A 3D FE model of the BCJ was developed to predict the experimental response of the control and steel cage strengthened specimens using advanced damage plasticity model for concrete.

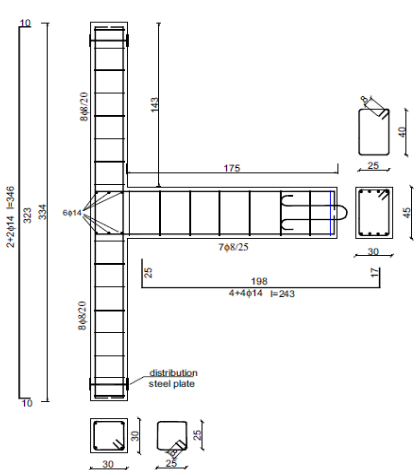


Figure 1. BCJ dimensions and reinforcement details (in cm) (Campione et al. 2015).

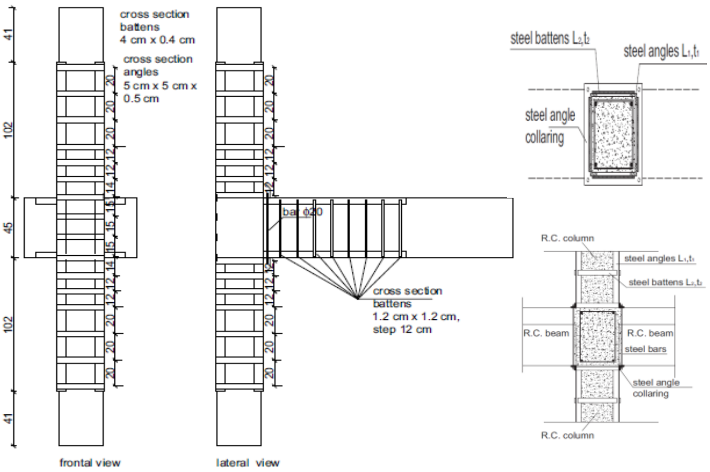


Figure 2. Dimensions and details of strengthening scheme (Campione et al. 2015).

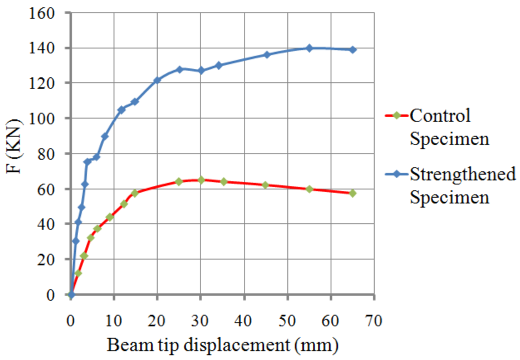


Figure 3. Load-displacement diagram for control and strengthened specimens (Campione et al. 2015).

3.1 Material models

The material parameters for concrete were found from the experimental work and some other parameters were calculated using analytical models. Table 1 shows concrete material parameters used in the FE model. For the plastic damage model, the stress-plastic strain curves of concrete for both compression and tension were estimated using Mander model. The concrete damage parameters in compression and tension are given by Eq (1) and (2). $E_C = 22704$ MPa. $b_C = b_t$ and $0 < b_C = b_t < 1$. For steel rebars, ties and stirrups, the material properties obtained from experimental work were used as shown in Table 1. Steel plates, battens and angles were defined with properties shown in Table 1.

$$d_c = 1 - \frac{\sigma_c E_c^{-1}}{\epsilon_c^{pl}\left(\frac{1}{b_c} - 1\right) + \sigma_c E_c^{-1}} \quad (1) \qquad d_t = 1 - \frac{\sigma_t E_c^{-1}}{\epsilon_t^{pl}\left(\frac{1}{b_t} - 1\right) + \sigma_t E_c^{-1}} \quad (2)$$

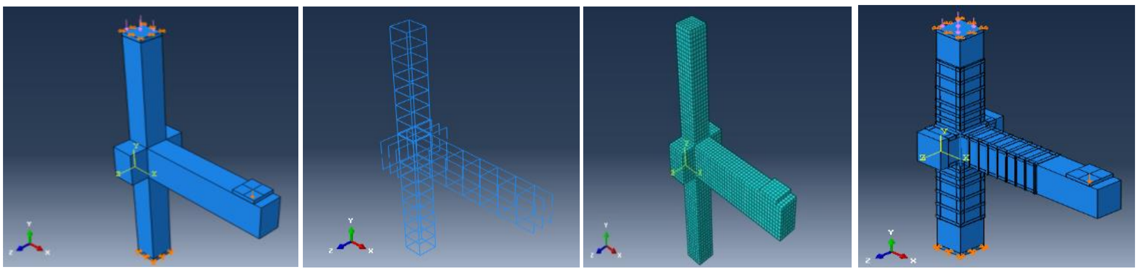
3.2 Element type, meshing and boundary conditions

Dynamic explicit analysis that is available in ABAQUS was used. The steel reinforcement was modeled as a 3D truss element model and embedded region in concrete. Tie contact between steel plates and angles with concrete was considered as epoxy was used between them in experimental work. Figure 4(a) shows boundary conditions of BCJ model. The top end of the column surface is constrained in x and z-direction and the bottom end of the column is constrained in x, y, and z-direction. The tip of the beam is constrained in y-direction for application of experimental displacement of 65 mm. A constant axial load of 200 kN is applied to the column. The BCJ model was meshed with a size of 50 mm for all parts and steel reinforcement was modeled as truss element as shown in Figure 4(b). The 3-D Model of BCJ strengthened specimen is shown in Figure 4(d). Dimensions of steel plates, steel angles used for strengthening and properties in the experimental work were replicated in the model.

Table 1. Model parameters

Concrete			**Reinforcing Steel**		
Parameter	Value	Unit	Parameter	Value	Unit
f'_c	23	MPa	f_y	450	MPa
E_c	22704	MPa	E_s	200000	MPa
Mass Density	2.5 E-9	Ton/mm^3	*Mass Density*	7.8 E-9	Ton/mm^3
Poisson Ratio	0.2	-	*Poisson Ratio*	0.3	-
Dilation Angel	36	º	**Steel Plates and Angles**		
Eccentricity	0.1	-	Parameter	Value	Unit
f_{bo}/ f_{co}	1.16	-	f_y	275	MPa
k	0.67	-	E_s	200000	MPa
			Mass Density	7.8 E-9	Ton/mm^3
			Poisson Ratio	0.3	-

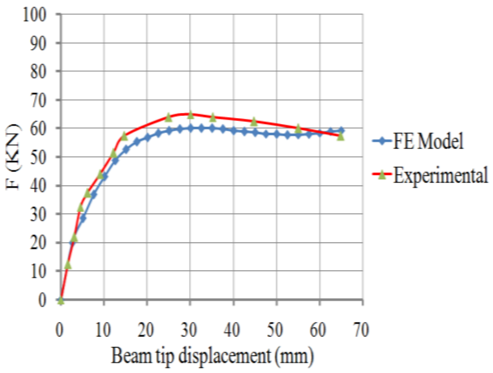
where:
f_{bo}/ f_{co}: "Ratio of initial biaxial compressive yield stress to initial uniaxial compressive yield stress; K:"is the ratio of the second stress invariant on the tensile meridian (TM) to that on the compressive meridian (CM).



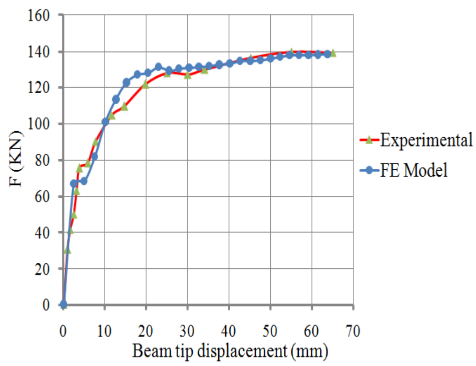
(a) Boundary conditions (b) Steel reinforcement (c) Meshing (d)Strengthened specimen
Figure 4. Modeling of the BCJ specimen.

3.3 Validation of the Finite Element Model

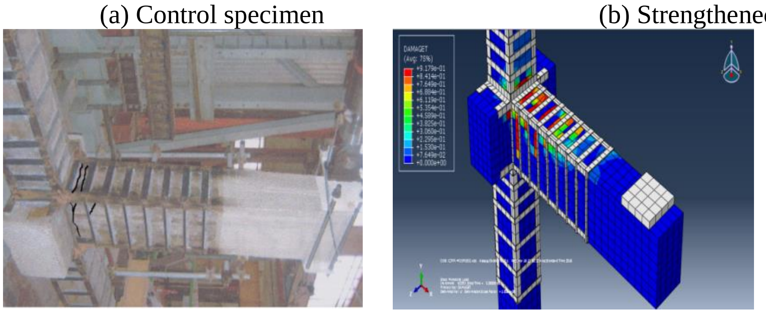
The results of FE analysis were compared with experimental results in terms of load-deflection response for both the control and the strengthened specimens. Figure 5(a) shows the FE and experimental curves for the control specimen. The value of maximum load at a displacement of 30 mm from FE model was only 6% higher with 65 KN from experiment and FE model predicted a load of 61 KN. The FE model captured the experimental results with great accuracy. Figure 5(b) shows the results for steel strip strengthened specimen. The maximum load from experimental and FE model was 140 KN. The FE generated curve follows closely the experimental curve during the loading history. Damage pattern obtained from FE simulation and the experimental result as shown in Figure 5(c). The fist cracks due to flexure in the strengthened specimen from experimental test and FE model were almost same. The first crack appears at the BCJ interface. Multiple cracks occur in the beam.



(a) Control specimen



(b) Strengthened specimen



Experimental FE model

(c) Damage pattern in strengthened specimen

Figure 5. Results of specimens from experimental test and FE model.

4 OPTIMIZATION OF STRENGTHENING USING STEEL STRIPS

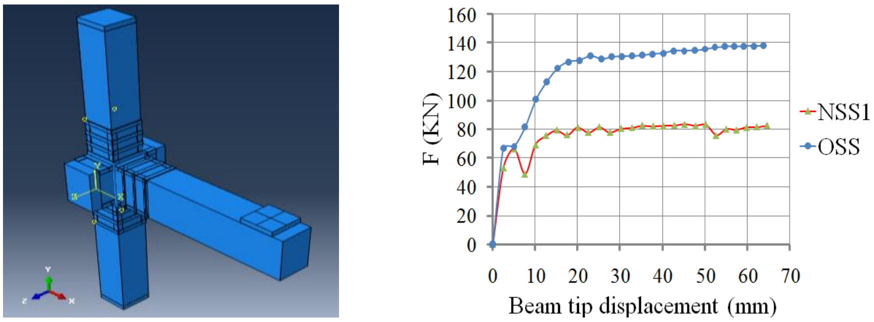
It was shown in the previous section that the FE model of the steel-strip strengthened specimens captured the experimental results with high accuracy. The maximum tensile stress in steel strips occurs in the beam near the joint. The stresses in steel plates and angles in the column did not reach the yield stress. Therefore, the length of strips and number of plates used in beam and column could be varied to optimize their sizes. Parametric studies were conducted to evaluate the behavior of BCJ by varying the lengths and spacing of the angles and the steel plates.

4.1 Decreasing the length of angles and the number of battens used in column and beam.

The length of angles and the number of battens used in column and beam was changed to evaluate the behavior of BCJ with the new strengthening system. The length of angles in column from each side was decreased from 1020 mm to 405 mm and number of battens was decreased from 6 to 3 battens. In the beam, the length was decreased from 920 mm to 405 mm and number of battens was decreased from 8 to 3 battens. Figure 6(a) shows the FE model and 6(b) shows the load-displacement response of new strengthening system, scheme-1 (NSS1) and the original strengthening system (OSS). Reduction in length is not an effective scheme to resist seismic loads as the load capacity decreases from 140 kN to 84 kN, the latter being slightly higher than the control specimen (60 kN).

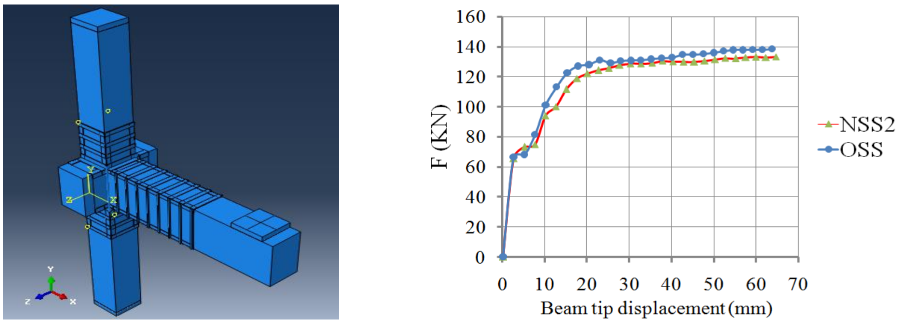
4.2 Decreasing the length of angles and the number of battens used in the column only.

In this model, the length of angles and the number of battens were minimized in the column only because tensile stresses in the beam were higher than in the column. The length of angles in column from each side was decreased to 405 mm and number of battens to 3. Figure 7(a) shows the FE model of strengthening system, scheme-2 (NSS2). Decreasing the length of angles and the number of battens did not decrease the load capacity of the BCJ as in the previous case. The load-deflection response for this case follows closely the original strengthening scheme (OSS) and is an economical option (Figure 7(b)). The maximum load capacity for the BCJ with Scheme-2 strengthening, decreased by only 4% to 134 kN.



(a) (b)

Figure 6. (a) BCJ model Scheme-1 (NSS1). (b) Load-Beam tip displacement diagram for NSS1 and OSS.



(a) (b)

Figure 7. (a) BCJ model Scheme-2 (NSS2). (b) Load-beam tip displacement diagram for OSS and NSS2.

4.3 Increasing the distance between battens used in column and beam.

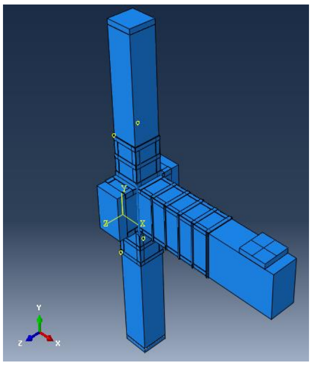
In Scheme-3, the distance between battens used in column and beam was increased. The length of angles remained constant and the distance between battens in the column was changed to 178 mm instead of 120 mm and distance between battens in the beam was kept at 184mm. Figure 8(a) shows new strengthening system Scheme-3 (NSS3) and Figure 8(b) shows the load-deflection curve for OSS and NSS3. It can be observed that increasing the distance between battens did not affect the capacity of BCJ. The angles predominated on the capacity of BCJ. The maximum load from OSS and NSS3 was almost the same 140 kN.

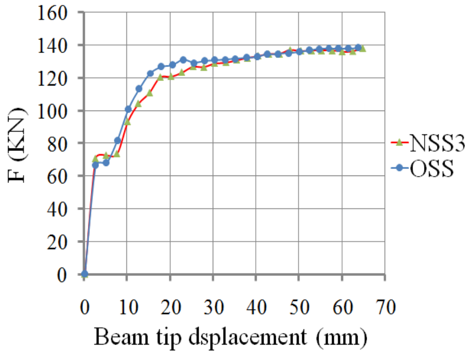
4.4 Decreasing the thickness of angles used in the beam.

In this scheme, the thickness of angles used in the beam was decreased from 4 mm to 3 mm. The results of the load-deflection curve as shown in Figure 9 indicate that the capacity of the BCJ model to carry loads decreased to 127 kN for the Scheme-4 (NSS4). The stiffness of angles in beam controls the capacity of steel plate strengthening system.

4.5 Using CFRP sheets instead of steel plates and angles.

In this model, the steel battens and angles were replaced by one layer CFRP sheet. The CFRP properties are shown in Table 2. CFRP sheets of 0.167 mm thickness was applied to the column and beam in same way as the steel cages in NSS2 (Figure 10).





(a) (b)

Figure 8. (a) BCJ model for Scheme-3 NSS3 (b) Load-beam tip displacement diagram for OSS and NSS3.

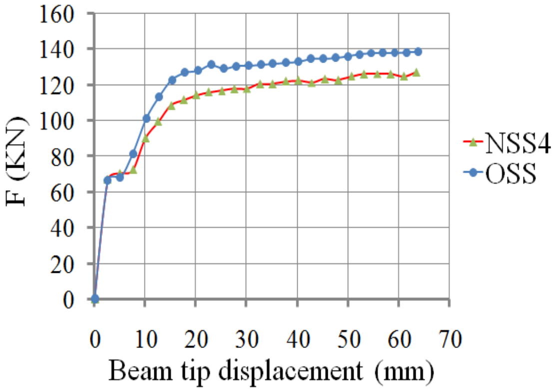
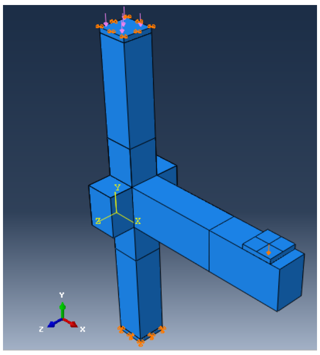


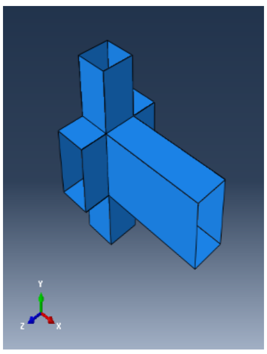
Figure 9. Load-beam tip displacement diagram for OSS and NSS4.

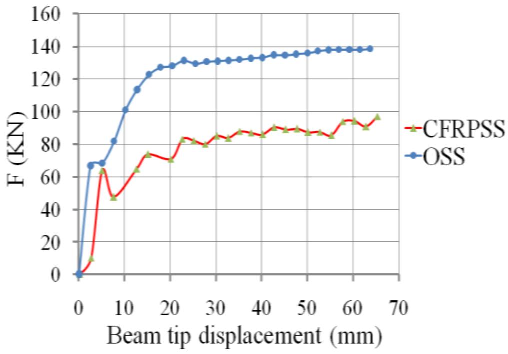
Figure 11 shows the load-deflection curve for OSS and CFRP strengthening system (CFRPSS). It can be noticed that 1-layer CFRP sheet decreases the load capacity by 44% to 97 kN as compared to 140 kN for steel plates and angles. Therefore, the strengthening of BCJ with steel battens and angles is more effective than one layer of CFRP sheets.

Table 2. Properties of CFRP sheets

Mass density (Ton/mm^3)	E_1 (MPa)	E_2 (MPa)	U1N2	G_{12} (MPa)	G_{13} (MPa)	G_{23} (MPa)
1E-9	226000	96500	0.3	5200	5200	3400







(a) BCJ strengthening with CFRP (b) CFRP sheets.

Figure 10. BCJ model with CFRP Sheets.

Figure 11. Load-beam tip displacement diagram for OSS and CFRPSS.

5 CONCLUSIONS

The use of steel-strips for strengthening of the exterior BCJ's is an effective way for enhancing the shear capacity of deficient joints, particularly in cases where the faces of joints have beams attached to it. The FE modeling using the Damage Plasticity Model in ABAQUS environment was noted to yield reasonably accurate results for the steel strip retrofitted BCJ specimens. The damage in the joint and the c crack patterns were captured. Parametric studies indicated that the length of angles and numbers of battens used in the column could be decreased without decreasing the shear capacity of the joint and this will be more economical. The stiffness of angles used in beam controls the response of the retrofitted specimen. The study also shows that the strengthening of BCJ with steel battens and angles is more effective and economical compared to one layer of CFRP sheets.

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