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# Torsional Behaviour of RCC Beam-Column Joints Strengthened Using Different Composite Materials.

Anil Varghese[1], Dr. Sheela S[2]

[1]*Assistant Engineer-Greater Cochin Development Authority (GCDA), Govt. of Kerala, India*
[2]*Principal (Former), College of Engineering Trivandrum, Thiruvananthapuram, Kerala, India*

***Abstract*— Generally in any reinforced concrete structures stress resultants such as axial forces, shear forces, bending moments, torsion or a combination of these, may be generated due to external loading. Bending moments and shear forces are the primary criteria for most design situations and usually torsion is either neglected or under estimated. As a result the RC structures could become deficient against the torsion created due to loading eccentricities or due to earthquakes or due to unbalanced loading etc. and hence needs strengthening. An experimental study has been conducted to study the behaviour of RCC beam column joint specimens strengthened with Ferrocement, Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) under torsion. From the study it was observed that GFRP is effective as compared to Ferrocement and CFRP for strengthening the beam column joint against torsion.**

***Keywords*—Strengthening, Ferrocement, CFRP, GFRP, Torsion .**

## I. INTRODUCTION

Most of the structures we lay our eyes on are invariably made of Reinforced Cement Concrete or RCC. Even though RCC is a wonderful construction material, it is very difficult to increase its strength once it hardened. Another major drawback with RCC is its workmanship. In most of the places it is largely constructed by unskilled workers, and hence leads to produce RCC of reduced strength or poor quality. Other issues are due to increase in water cement ratio, improper curing and improper shuttering etc. Strengthening the reinforced concrete members become essential due to number of reasons such as substandard detailing of the steel reinforcement and deterioration of the concrete under severe environmental conditions etc.

Failure of RC member is mainly due to the diagonal tension and compression developed under torsion. Brittle failure of elements is undesirable as it could lead to an inductile behaviour of structures during earthquakes. During the past decade strengthening and rehabilitation of structures has been an important research topic worldwide. Strengthening of concrete structures could be an optimum solution in many cases such as change in the usage of the building or change in the design codal provisions [1].

This paper discusses the experimental study conducted on RCC beam column joint specimens strengthened with Ferrocement, CFRP and GFRP under torsion. A cost comparison was also done to find out the economic feasibility of strengthening of the specimens.

## II. PRELIMINARY INVESTIGATIONS

A preliminary investigation was carried out to determine the properties of the constituent materials for arriving the optimum proportion for the $M_{20}$ concrete.

### *A. Properties of Constituent Materials*

Properties determined for the constituent materials used for the study are as follows.

*1. Cement:* 53 grade Ordinary Portland Cement was used for the study. Specific gravity of cement was found as 3.15. The properties of cement conform to IS 12269:1987 [2]

*2. Sand:* Locally available good quality river sand was used. Sand belongs to zone I as per IS 383-1970. The optimum moisture content was found as 6% with a maximum bulking of 37.82% and Fineness modulus of sand was 3.41.The properties of sand conform to IS 383-1970 [3].

*3. Coarse aggregate:* Crushed aggregate with a maximum size of 20mm was used. The fineness modulus of aggregate was 7.08 and the specific gravity was 2.86. The properties of coarse aggregate conform to IS specifications, (IS 2386 Part III -1963) [4].

*4. Steel:* High yield strength deformable bars of 6mm and 8mm diameter were used. The properties of steel bars determined are shown in Table I.

**TABLE I**
**PROPERTIES OF STEEL BARS**

| Particulars | 6mm dia. | 8mm dia. |
|---|---|---|
| Yield Stress ( $N/mm^2$) | 468.39 | 440.85 |
| Ultimate Stress ( $N/mm^2$) | 555.13 | 608.91 |
| Modulus of Elasticity ($N/mm^2$) | $2.0 \times 10^5$ | $2.1 \times 10^5$ |

*5. Welded Wire Mesh:* 1.5 mm x 1.5 mm square welded wire mesh in ferrocement was used for strengthening beam-column joints. The wire mesh has an ultimate strength of 828.48 N/mm$^2$ and its percentage elongation was found as 35%.

*6. Carbon Fiber Reinforced Polymer (CFRP):* Nitowrap EP (CF), a carbon fiber composite wrapping system is used for strengthening in conjunction with an epoxy sealer cum primer (Nitowrap 30) and a high build epoxy saturant (Nitowrap 410) was used. The properties of CFRP, which is given by Fosroc Chemicals Ltd., are given in Table II

**TABLE II**
**PROPERTIES OF CFRP**

| Particulars | Properties |
|---|---|
| Fiber Orientation | Unidirectional |
| Fiber Thickness | 0.30 mm |
| Ultimate elongation | 1.5 % |
| Tensile Strength | 3,500 N/mm$^2$ |

*7. Glass Fiber Reinforced Polymer (GFRP):* Nitowrap EP (GF), a glass fiber composite wrapping system is used for strengthening in conjunction with an epoxy sealer cum primer (Nitowrap 30) and a high build epoxy saturant (Nitowrap 410) was used. The properties of GFRP, which is given by Fosroc Chemicals Ltd., are given in Table III.

**TABLE III**
**PROPERTIES OF GFRP**

| Particulars | Properties |
|---|---|
| Fiber Orientation | Unidirectional |
| Fiber Thickness | 0.90 mm |
| Ultimate elongation | 1.5 % |
| Tensile Strength | 3,400 N/mm$^2$ |

### *B. Concrete Mix design*

As the study was focusing on strengthening of RC structures the $M_{20}$ concrete mix was prepared as per IS 10262-1982 [5] recommendations was used for the study.

The design mix proportion obtained as per IS code guidelines was 1: 1.617: 3.40: 0.5. By varying the cement content several trial mixes were prepared to determine the suitable mix proportion, with optimum cement content, satisfying the workability criteria.

From the trial mixes, a mix with cement content 355 kg/m$^3$ was chosen for the further study which satisfies the required workability and strength. Optimum mix proportion for $M_{20}$ concrete was found out as **1: 1.708: 3.591: 0.50**.

## III. EXPERIMENTAL INVESTIGATION ON BEAM-COLUMN JOINT SPECIMENS

Six sets of beam column joint specimens were prepared. The size of beam for the beam column joint specimen was selected as 100 mm x 150 mm having 600 mm length and the column portion was 100 mm x 150 mm with 1000 mm length. The sizes of the specimens were arrived based on the literature [6] and the fabrication and testing facilities available in the laboratory was used. The designation of the beam column joint specimen prepared is given in Table IV.

**TABLE IV**
**DESIGNATION OF BEAM COLUMN JOINT SPECIMEN**

| Beam Designation | Description |
|---|---|
| BCJ | Beam column joint----Control Specimen |
| BCJ FC | BCJ strengthened with Ferrocement |
| BCJ CF-01 | BCJ strengthened with one layer of CFRP |
| BCJ CF-02 | BCJ strengthened with two layer of CFRP |
| BCJ GF-01 | BCJ strengthened with one layer of GFRP |
| BCJ GF-02 | BCJ strengthened with two layer of GFRP |

For better comparison of the results, the experiment is limited to the beam column joint specimens strengthened with ferrocement and one and two layers of FRP composites only.

*A. Reinforcement details of beam-column joint*

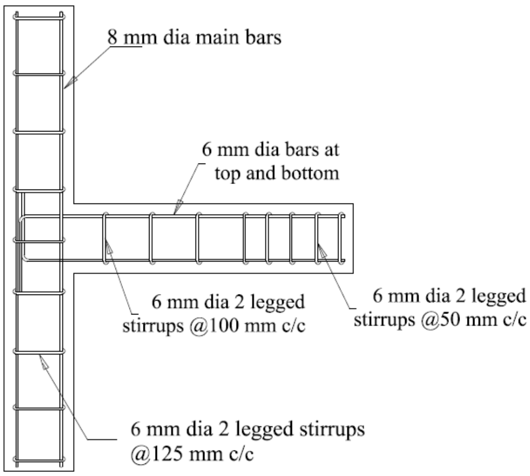


**Fig. 1. Reinforcement detailing of beam column joint**

*B. Preparation of strengthened Specimens*

The composite materials used for strengthening were applied to a distance of 150 mm (depth of beam) towards top and bottom from the mid height of the column. Similarly on the beam portion 150 mm (depth of column) towards left and right from the beam column interface. The strengthening scheme for beam column joint is given in Fig.2.

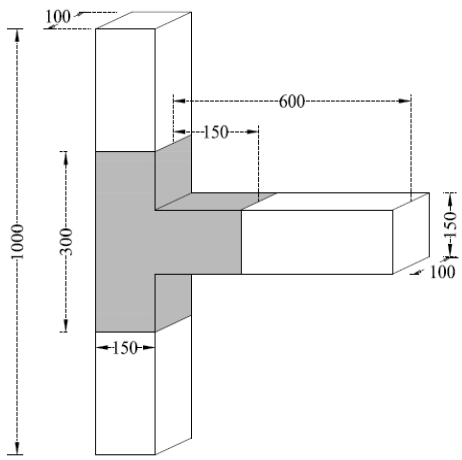


**Fig. 2. Strengthening Scheme ( All dimensions in mm)**

Strengthening using ferrocement was done using welded wire mesh oriented at 45$^{o}$. Fiber reinforced Polymer (FRP) composite was applied in one and two layers. FRP sheets were fixed to the concrete surface by using an epoxy sealer cum primer (Nitowrap 30) and a high build epoxy saturant (Nitowrap 410).

*C. Experimental Set Up*

All the beam column joint specimens prepared were tested in a loading frame shown in Fig.4. The column portions of the specimen were fixed at the ends and beam end was set free. An eccentric load was applied at the beam end to induce torsion. Figure 3 shows the schematic diagram of introducing torsion in the specimen.

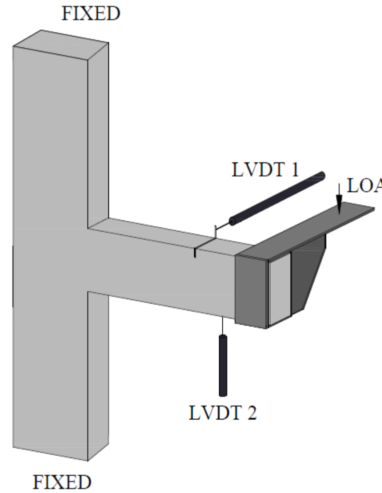


**Fig. 3. Schematic diagram of Test Setup**

Two Linear Variable Differential Transformer (LVDT) were used to measure the deformations. LVDT 1 was placed horizontally to measure the beam rotation and the other LVDT 2 was placed vertically to measure the deflection at the beam end. Loading was applied by using a hydraulic jack and a load cell of capacity 50 T was used to measure the load.

For introducing torsion in the specimen an eccentric loading was applied as shown in the Fig. 3. LVDT 1 will capture the deflection of the beam in horizontal direction due to twisting. LVDT 2 will capture the vertical deflection of the beam portion. During testing observations were taken and recorded. Test setup with specimen is shown in Fig.4.

**Fig. 4. Test setup with beam column joint specimen**

*D. Test Results*

The discussion on the test results of specimens tested under static loading is shown under different heads.

*1. First Crack Load and Ultimate Torque:* From the observations taken the first cracking load and ultimate torque of the different beam-column joint specimens are given in the Table V.

**TABLE V**
**FIRST CRACK LOAD AND ULTIMATE TORQUE OF SPECIMENS**

| Specimen Designation | First Crack Load | | Ultimate Torque | |
|---|---|---|---|---|
| | kN | % increase | kNm | % increase |
| BCJ | 6 | -- | 3.6 | -- |
| BCJ FC | 8 | 33.33 | 4.2 | 16.67 |
| BCJ CF-01 | 8 | 33.33 | 4.5 | 25.00 |
| BCJ CF-02 | 9 | 50.00 | 4.8 | 33.33 |
| BCJ GF-01 | 10 | 66.67 | 5.7 | 58.33 |
| BCJ GF-02 | 11 | 83.33 | 6.3 | 75.00 |

From the Table V, it is evident that the first crack load and ultimate torsional capacity of specimens were improved due to strengthening of specimens. The first crack load and ultimate torsional capacity of the specimen strengthened with two layers of GFRP was increased by 83.33 % and 75% respectively as compared with the control specimen.

*2. Load Deflection Characteristics:* The deflections at free end of the beams were plotted against the loads at an interval of 1 kN. The load-deflection behaviour for each category of beam column joint specimens was compared and is given in Fig.5.

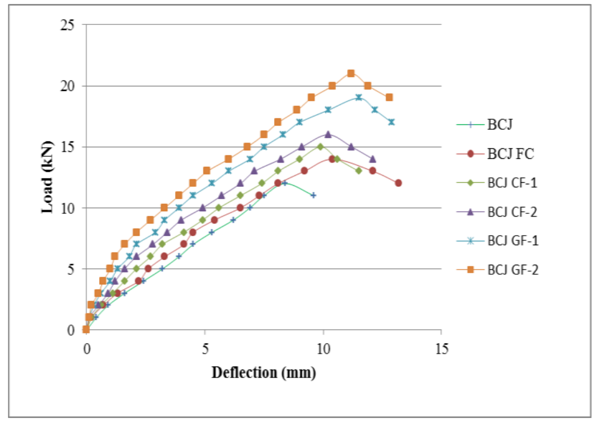


**Fig. 5. Load Deflection Behaviour of Specimen**

It may be observed from the Fig.5 that, for a particular load, the deflection of all the strengthened beam-column joints specimens were found to be lesser than that of the control specimen in the pre-cracking stage but a greater deflection at ultimate load was observed when compared to that of the control specimen. Behaviour of specimen BCJ GF-02 was better as compared with all other specimens.

*3. Torque Twist Characteristics:* The angle of twist at the beam was plotted against the torque at an interval of 1 kN-m. The torque twist behaviour for each category of specimens were compared and given in Fig.6.

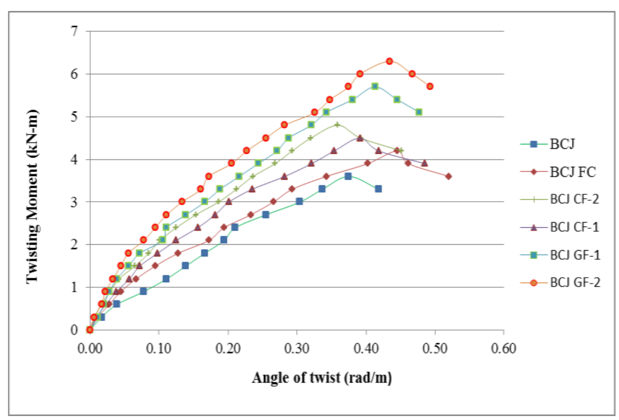


**Fig. 6. Torque Twist Characteristics of Specimen**

A similar behavior as the load deflection was obtained for the torque twist plot. From the Fig.6 it may be observed that, for a particular torque, the twist of the strengthened beam-column joints were found to be lesser than that of the control specimen in the pre-cracking stage but a greater twist at ultimate torque was observed when compared to that of the control specimen.

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The specimen BCJ GF-02 showed superior behaviour as compared with all other specimens.

*4. Energy Absorption Capacity:* Energy absorption capacity of the structural member plays an important role in the behaviour of structures against earthquake. Energy absorption capacity of a member is derived from the load-deflection curve. The area under the load-deflection curve gives the energy absorption capacity, for all the specimens and it is tabulated in Table VI.

TABLE VI
ENERGY ABSORPTION CAPACITY OF SPECIMENS

| Beam Designation | Energy Absorption Capacity (kN-m) x $10^{-3}$ | % Increase in Energy Absorption |
|---|---|---|
| BCJ | 68.80 | -- |
| BCJ FC | 127.35 | 85.10 |
| BCJ CF-01 | 113.65 | 65.19 |
| BCJ CF-02 | 136.90 | 98.98 |
| BCJ GF-01 | 179.45 | 160.80 |
| BCJ GF-02 | 199.40 | 189.80 |

The Table VI shows that the maximum energy absorption capacity is for the beam column joint specimens strengthened with 2 layers of GFRP.

*5. Deflection Ductility Ratio:* Earthquake imposes displacement in the structural members. So the members should allow the greatest possible ultimate displacement. Ductility refers to the capacity of the member to yield without breaking and is calculated in terms of ductility ratio. It is the ratio of the deformation (deflection) at ultimate load to that at yield load.

Deflection Ductility factor

$$= \frac{\text{Deflection at ultimate load } (P_u)}{\text{Deflection at yield load } (P_y)} = \frac{\delta_u}{\delta_y}$$

The deflection at yield load was determined by using method as described in literature (Shannag et.al.). The yield load for all specimens were calculated from the load deflection plot shown in Fig.5, based on the literature [8].The ductility ratio for each specimen was calculated and is shown in Table VII.

TABLE VII
DEFLECTION DUCTILITY RATIO

| Specimen Designation | Deflection (mm) at | | Deflection Ductility Ratio | Increase in Ductility Ratio (%) |
|---|---|---|---|---|
| | Yield Load | Ultimate Load | | |
| BCJ | 4.00 | 8.40 | 2.10 | -- |
| BCJ FC | 4.20 | 10.40 | 2.47 | 17.62 |
| BCJ CF-01 | 4.10 | 9.90 | 2.41 | 14.76 |
| BCJ CF-02 | 4.00 | 10.20 | 2.55 | 21.42 |
| BCJ GF-01 | 4.10 | 11.50 | 2.81 | 33.80 |
| BCJ GF-02 | 3.90 | 11.20 | 2.87 | 36.67 |

From the Table VII it is clear that, the specimens strengthened with composites showed large deflection at ultimate load, thus there was a significant increase in the ductility ratio. The specimens strengthened with two layers of GFRP showed the maximum increase of 36.67% in deflection ductility ratio as compared with control specimen.

*6. Torsional Ductility Index:* Torsional ductility of a member refers to the capacity of the member to yield without breaking. It is the ratio of the angle of twist at ultimate torque to that at yielding torque. The ductility ratio for each specimen in different category was calculated and is given in Table VIII.

TABLE VIII
TORSIONAL DUCTILITY INDEX

| Specimen Designation | Angle of Twist (rad/m) at | | Torsional Ductility Index | Increase in Ductility Index (%) |
|---|---|---|---|---|
| | Yield Torque | Ultimate Torque | | |
| BCJ | 0.166 | 0.375 | 2.26 | -- |
| BCJ FC | 0.176 | 0.445 | 2.53 | 11.95 |
| BCJ CF-01 | 0.156 | 0.389 | 2.49 | 10.17 |
| BCJ CF-02 | 0.153 | 0.359 | 2.35 | 3.98 |
| BCJ GF-01 | 0.165 | 0.413 | 2.50 | 10.62 |
| BCJ GF-02 | 0.161 | 0.434 | 2.66 | 17.70 |

From the Table VIII it can be observed that strengthened specimens showed large twist at the ultimate load, thus there was an increase in the torsional ductility ratio.

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The specimen BCJ GF-02 showed the highest torsional ductility index of 2.66 with an increase of 17.70% when compared with the control specimens.

*7. Crack behavior and crack pattern:* During testing crack initiation and development of cracks were recorded. Control specimens and strengthened specimens were exhibited a typical torsional failure mode with spiral diagonal cracks. As the beam portion is loaded eccentrically, inclined cracks were developed which propagates towards the support and form a complete loop. Crack patterns at failure of specimens are shown from Fig.7 to Fig.12.

**Fig. 7. Crack Pattern of BCJ**

**Fig. 8. Crack Pattern of BCJ FC**

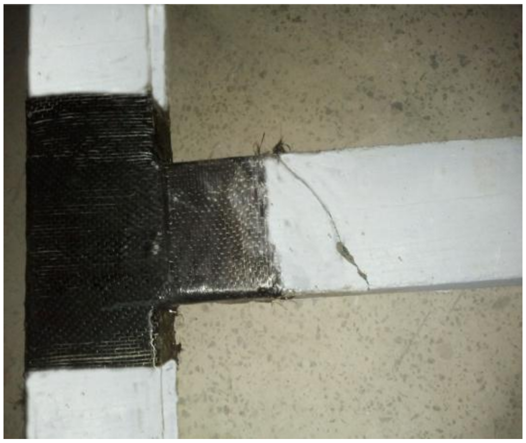

**Fig. 9. Crack Pattern of BCJ CF-01**

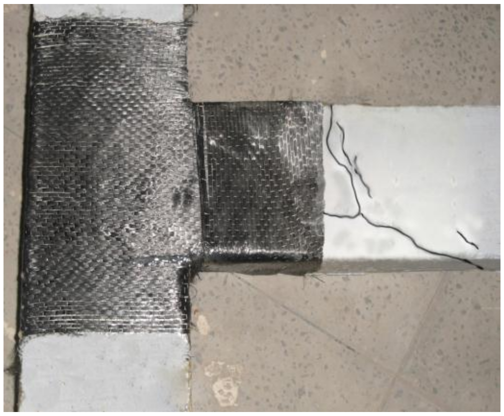

**Fig. 10. Crack Pattern of BCJ CF-02**

**Fig. 11. Crack Pattern of BCJ GF-01**

**Fig. 12. Crack Pattern of BCJ GF-02**

From the Fig.7 to Fig.12, it is evident that the failure of the strengthened specimens were partially delayed in respect of the failure of the control specimens, but eventually diagonal torsional cracks occurred and widened in the unwrapped concrete part. From Fig.8 to Fig. 12 it may be observed that, failure of strengthened specimens were characterized by the formation of inclined cracks beyond the strengthened portion of the beam without any crack at the joint. Hence strengthening enhances the torsional behaviour of beam column joint and also it satisfies the strong column weak beam concept. Control specimens failed due to the advancement of crack width at beam-column interface.

*8. Cost Assessment:* A detailed cost analysis to check the economic feasibility of different strengthening techniques was conducted by evaluating the cost to strength ratio. The cost to strength ratio for different strengthened specimen was compared with the control specimen. The increase in ultimate torsion is considered for the strength ratio. The comparison of cost to strength ratio is given in Table IX.

**TABLE IX**
**COST TO STRENGTH RATIO OF SPECIMENS**

| Specimen | Cost (Rs.) | Cost Ratio | Strength (kN-m) | Strength Ratio | Cost/ Strength Ratio |
|---|---|---|---|---|---|
| BCJ | 614.8 | -- | 3.6 | -- | -- |
| BCJ FC | 992.8 | 1.61 | 4.2 | 1.16 | 1.39 |
| BCJ CF-01 | 1404.8 | 2.28 | 4.5 | 1.25 | 1.82 |
| BCJ CF-02 | 1790.8 | 2.91 | 4.8 | 1.33 | 2.19 |
| BCJ GF-01 | 1087.3 | 1.77 | 5.7 | 1.58 | 1.12 |
| BCJ GF-02 | 1191.8 | 1.94 | 6.3 | 1.75 | 1.10 |

From the Table IX ,It is noted that beam column joint specimens strengthened with two layers of GFRP composite are the most efficient as its cost to strength ratio is the lowest at 1.10 when compared to the other strengthening techniques used in this study.

## IV. CONCLUSIONS

The following conclusions were drawn based on the experimental investigation conducted.

- Strengthening techniques can be adopted as a feasible solution for enhancing the torsional capacity of concrete members
- Confinement was achieved by wrapping the specimen with the ferrocement and FRP composites and proved that the torsional and flexural behaviour were enhanced due the confinement pressure exerted by the strengthening material.
- The cracking characteristics of the specimens were enhanced due the presence of strengthening materials, which delayed the crack initiation and inhibited the propagation of crack because of its high tensile capacity.
- First crack load and Ultimate torsional capacity were increased for the strengthened specimens and it was observed that by 83% and 75% respectively for the specimen strengthened with two layers of GFRP.
- Strengthened specimens showed large deflection at the ultimate load, thus there was a significant increase in the ductility ratio. The specimen BCJ GF-02 showed the highest deflection ductility ratio of 2.87 with an increase of 37% and torsional ductility ratio of 2.66 with an increase of 18% as compared with the control specimen.
- All strengthened specimens showed considerable increase in the energy absorption capacity. The specimen BCJ GF-02 recorded the maximum energy absorption capacity which was increased by 190 % than the control specimen.
- Control specimens failed due to the advancement of crack width at beam-column interface whereas no cracks were observed at beam column interface for strengthened specimens.
- Failure of strengthened specimens were characterized by the formation of torsional cracks occurred beyond the strengthened portion of the beam.
- Beam column joints strengthened using two layers of GFRP were the most cost effective with a minimum cost to strength ratio of 1.10.

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- Considering all the results obtained from this experimental study, the beam column joint specimens strengthened using two layers of GFRP were found out as the most efficient and cost effective method for strengthening.

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