# Retrofitting of Non-Ductile Exterior Beam-Column Joints by RC Jackets with U-Bars and Collar Bars

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*Abstract*—**In a RC framed structure, beam-column joints are highly susceptible to failure when subjected to large lateral loads, especially during earthquakes. In this study, six scaled down models of the beam-column joint of a non-seismically designed structure were prepared. Retrofit in the form of reinforced concrete (RC) jackets were provided on the control specimens. Three types of RC jacketing schemes were used, first one is the conventional RC jacketing having longitudinal and transverse reinforcements, the second is the non-conventional jacketing scheme in which the joint region of the jacket was provided with diagonal ties, and the third is the non-conventional jacketing scheme in which the stirrups of the RC jackets were tied together by U shaped bars. All the specimens were subjected to quasi static reverse cyclic loading. The experimental results showed an improvement in ultimate load carrying capacity, stiffness, energy dissipation capacity, toughness index and displacement ductility for jacketed specimens compared to that of control specimens. The non-conventional RC jacketing techniques were found to have better performance compared to the conventional scheme.**

## I. INTRODUCTION

The performance of beam-column joints is a prominent factor that affects the behaviour of RC framed structures subjected to large seismic loads. The joint is defined as that portion of the column within the depth of the deepest beam that frames into the column. They are crucial zones for effective transfer of loads between connecting elements in a structure. Unsafe design and detailing within the joint region jeopardizes the entire structure, even if other structural members conform to the design requirements [1]. The first design guidelines for reinforced concrete beam-column joints were published in 1976 in the U.S. (ACI 352R-76) and in 1982 in New Zealand (NZS 3101:1982). So the buildings constructed before 1976 may have significant deficiencies in the joint regions [4].

Considering normal practice in analysis of a structure, the beam-column joints are assumed to be rigid. For structural integrity the beam-column joint must be provided with stiffness and strength sufficient to resist and sustain the loads transmitted from beams and columns. The plastic hinges are expected locations where the structural damage can be allowed to occur due to inelastic actions involving large deformations. Hence, in seismic design, the damages in the form of plastic hinges are expected to be formed in beams rather than in columns [2]. Mechanism with beam yielding is characteristic of strong-column/weak-beam behavior in which the imposed inelastic rotational demands can be achieved reasonably well through proper detailing practice in beam-column joints. Therefore, in this mode of behaviour, it is possible for the structure to attain the desired inelastic response and ductility. For a beam hinging mechanism to occur in the frame, a number of jacketing schemes have been adopted. The most common ones are RC jacketing, steel jacketing, fibre reinforced polymeric composite (FRPC) jacketing, ferrocement jacketing and shotcrete jacketing [5]–[7]. RC jacketing is the most commonly used method. It improves the strength, stiffness and energy dissipation capacity of the joint by a considerable margin. It also shifts the location of plastic hinge in the beam. The disadvantages include labour intensiveness and increase in dead weight of the structure as a whole, thereby altering the dynamics of the same. Studies have shown that RC jackets with conventional detailing pattern have highly unpredictable behaviour when subjected to lateral loads and exhibits excessive cracking in the jacket as well as joint region which is highly undesirable. Due to the absence of any tying mechanism, the stirrups in these jackets act independently during the action of lateral loads resulting in highly unpredictable responses.

## II. EXPERIMENTAL PROGRAMME

The multistoreyed structure chosen for the study was assumed to be non-ductile in nature, hence the exterior beam-column joint was designed strictly in accordance to IS 456:2000. The details of the scaled down control specimen (CS) is shown in Fig.1. The detailing of the conventional jacketing scheme with longitudinal and shear reinforcement alone was done and was designated as R-CJ. Non-conventional reinforcement in the form of diagonal ties or collar bars in the joint region of the jacket was incorporated with an aim to avoid the diagonal shear crack formation in the joint. They were designated as R-NCJ 1 and details are shown in Fig.2. A second detailing scheme with U-bars tying together all the stirrups in the beam jacket region were provided, with an aim to improve the hysteretic behaviour of the joint under lateral loads. They were designated as R-NCJ 2 and details are shown in Fig.3.

### A. Material Properties

Portland Pozzolana Cement (PPC) was used for making concrete for both control as well as jacketed specimens. Crushed granite stone of maximum size 12.5mm with a specific gravity of 2.74 was used as coarse aggregate.

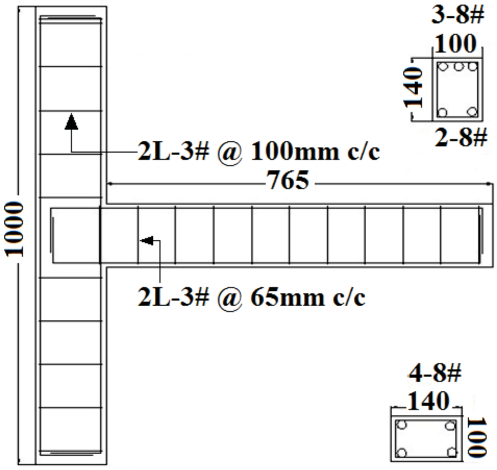


Fig. 1. Reinforcement detailing of control specimens

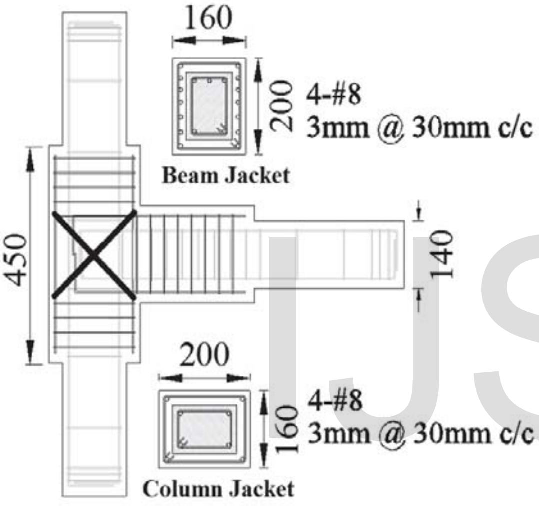


Fig. 2. Reinforcement detailing of R-NCJ 1

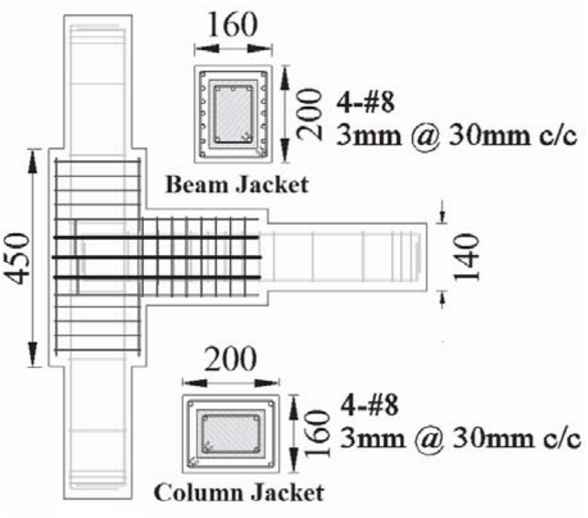


Fig. 3. Reinforcement detailing of R-NCJ 2

M-sand with fineness modulus 2.9 and specific gravity 2.46 was used as fine aggregate. The concrete mix proportion for control specimens was 1:1.41:2.65 with 0.44 w/c ratio. The concrete mix achieved a compressive strength of 42 N/mm$^2$ after 28 days. The mix proportion for RC jacketing was 1:1.38:2.6 with a w/c ratio of 0.44 and maximum aggregate size of 10 mm. It yielded a 28 day compressive strength of 45 N/mm$^2$. TMT steel rods of diameter 8 mm with a yield stress of 423 N/mm$^2$ were used as longitudinal reinforcement. Galvanized Iron (GI) wire of diameter 3 mm with a yield stress of 610 N/mm$^2$ was used as transverse reinforcement.

### B. *Casting of Specimens*

*1) Control specimens:* The longitudinal as well as transverse reinforcement were prepared as per the dimensions and the reinforcement cage was placed in the steel mould after oiling the surface of the mould. A cover of 10mm was provided. Concrete was poured into the mould and thoroughly vibrated so that complete compaction was achieved. A total of eight specimens were cast, out of which six were retrofitted. Specimens were demoulded after 24 hours and then cured in water tanks for 28 days after which the jacketing was done.

*2) Retrofitted specimens:* Dirt and grit was removed from the control specimens using a wire brush and markings were scribed on the specimens to demarcate the portions up to which the jacketing was required. The cover concrete was chipped off this portion using a pointed chisel and hammer. Reinforcements including longitudinal and transverse bars were tied to form a cage around these specimens. 8mm diameter bars were used in the beam jacket region as U-bars, to tie together all the stirrups. 6mm bars were used as diagonal collar bars. Bars of 12 mm diameter were cut into small pieces and inserted between the reinforcement cage and the control specimen so that proper cover was maintained. The portions consisting of the reinforcement cage was properly brushed with cement grout so as to ensure good bond between the new and existing concrete. The steel mould was thoroughly oiled and the reinforcement cage was then inserted into the mould and concrete was poured into the same with simultaneous vibration. The surface was finished off properly. Specimens were demoulded after 24 hours and cured in water tanks for 28 days.

### C. *Test Setup*

The control specimens as well as retrofitted specimens were subjected to quasi static reverse cyclic loading conditions. One end of the column was given an external hinge support, which was fastened to the strong reaction floor, and the other end was laterally restrained by another hinge support to allow moment-free rotation at both ends. A schematic diagram of the setup is shown in Fig.4. Cyclic load was applied at 50 mm from the free end of the beam with the help of two hydraulic jacks of 20T capacity. The test was load controlled. The load increment chosen was 2 kN/cycle. To record loads precisely, load cells with least count 1 kN were used. The specimens were instrumented with Linear Variable Differential Transformer (LVDT) having least count 0.1 mm to measure the deflection at the loading point.

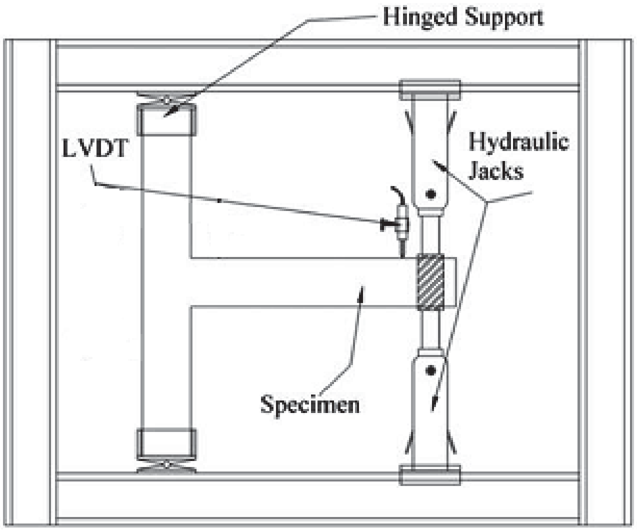


Fig. 4. Experimental setup

## III. RESULTS AND DISCUSSIONS

The test results of control specimens as well as jacketed specimens are presented and compared in terms of load-displacement hysteretic curves, load displacement envelope, energy dissipation capacity, displacement ductility, toughness index and cracking patterns. Table I summarises the results of the tested specimens.

### A. *Hysteresis curves*

The force-displacement hysteresis loops for the specimens are shown in Fig.6 Hysteretic loops show the performance of beam column joint under cyclic loading. The wider the loops, the larger will be the energy dissipation capacity. From the hysteresis curves it can be clearly seen that the area enclosed by the hysteresis curve of control specimens are very small compared to that of the jacketed specimens. So all the jacketing schemes improved the seismic performance of the non-ductile control specimen. But the loops of R-CJ showed high irregularities both on positive as well as negative cycles. This can be attributed to the fact that the stirrups in the beam jacket of these specimens behaved as independent units when it came to lateral load resistance and after a certain number of loading cycles, they started to disorient due to the lack of any unifying agent, resulting in unpredictable and non-linear hysteretic behaviour. In R-NCJ 1, the provision of collar bars at the joint prevented the excessive load transfer from the joint to the beam jacket region and hence the stirrups experienced much lesser magnitudes of load. Hence these specimens exhibited predictable and fairly linear hysteretic behaviour. The provision of U-bars in R-NCJ 2, tied together the stirrups in beam jacket so that during lateral load resistance, all these stirrups acted as a combined unit and showed higher degree of stiffness. Since the stirrups acted as a single unit, the hysteretic behaviour followed a definite pattern in all cycles and their behavior was predictable until failure occurred. So it can be seen that provision of non-conventional reinforcement in the form of U-bars and collar bars visibly improved the hysteretic response of the retrofitted specimens.

### B. *Ultimate load response*

From the hysteresis curves it can be seen that the jacketed specimens R-CJ, R-NCJ 1 and R-NCJ 2 had better load carrying capacities compared to the non-ductile control specimen. This is due to the high strength offered by the RC jackets which strengthened the joint region thereby improving the load carrying capacity of the specimens as a whole. It was also observed that the provision of non-conventional reinforcement did not show any significant improvement in ultimate load carrying capacity over conventional jacketing scheme. This is owing to the fact that the failure of all the jacketed specimens occurred due to breaking of the beam portion beyond the jacketed region.

### C. *Load-displacement envelope*

The maximum loads and displacements obtained in each half cycle were used for plotting the load displacement envelopes for the tested specimens. The envelope shown in Fig.5 enables the comparison of relative performance of the different specimens. The large area enclosed by the wider load displacements envelopes of R-CJ, R-NCJ 1 and R-NCJ 2 specimens signifies that their energy absorption capacity is much better than that of the non-ductile control specimens. It was also seen that the ultimate load as well as ultimate deflection of proposed jacketing schemes is slightly better compared to R-CJ. The increase in ultimate deflection is an important factor which determines the displacement ductility of the specimens. The most important feature that can be noticed in the load-displacement envelope is that the stiffness (obtained as the slope of the load-deflection curve) of the jacketed specimens were very high compared to the control specimens. It was also seen that the stiffnesses of R-NCJ 1 and R-NCJ 2 were significantly higher when compared to R-CJ owing to the fact that provision of collar bars and U-bars as a unifying reinforcement improved the stiffness of the joint. As mentioned earlier, the increase in stiffness of the improved jacketing schemes played a major role in reducing the displacement at yield, directly improving the displacement ductility. In actual structures this improvement in stiffness is highly desirable as it considerably reduces the excessive deformations (before yielding) in the structures on application of lateral loads and thereby improving the ductile nature of the same.

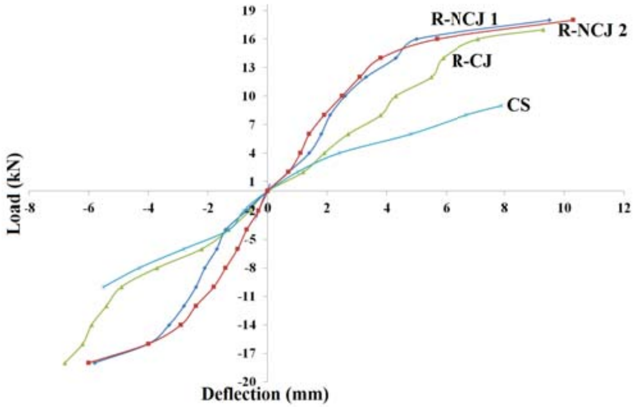
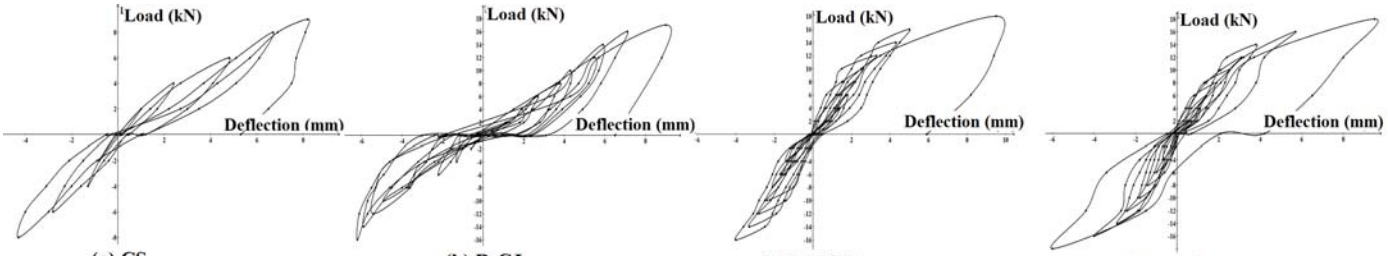


Fig. 5. Load-displacement envelopes for tested specimens

TABLE I. TEST RESULTS OF CONTROL AND JACKETED SPECIMENS

| Specimen | Ultimate load | | Displacement ductility | | Energy dissipation capacity | | Toughness index | |
|---|---|---|---|---|---|---|---|---|
| | (kN) | % Increase | - | % Increase | (kN-mm) | % Increase | - | % Increase |
| CS | 9 | - | 1.65 | - | 172.8 | - | 2.60 | - |
| R-CJ | 17 | 89 | 2.16 | 31 | 549.9 | 218 | 2.77 | 7 |
| R-NCJ 1 | 18 | 100 | 2.32 | 41 | 600.6 | 247 | 3.75 | 44 |
| R-NCJ 2 | 18 | 100 | 2.76 | 68 | 699 | 304 | 4.11 | 58 |



(a) CS (b) R-CJ (c) R-NCJ 1 (d) R-NCJ 2

Fig. 6. Hysteresis curves for tested specimens

### D. Displacement ductility

In addition to adequate strength, all structural members should exhibit sufficient ductility under overload conditions. Ductility refers to the ability of the structural members to undergo very large deformations after yielding of tensile reinforcement without much reduction in load carrying capacity. Displacement ductilty factor is a crucial parameter which defines the ductile nature of the members. It is defined as the ratio between the ultimate displacement ($\delta_u$) and yield displacement ($\delta_y$). Table I shows a relative comparison of the displacement ductility values of the tested specimens. It was seen that the provision of collar bars and U-bars decreased the displacement at yield load and increased the displacement at failure load simultaneously which resulted in significant increase of displacement ductility of R-NCJ 1 and R-NCJ 2 compared to R-CJ. This clearly signifies the fact that the addition of non-conventional reinforcement to the jacket reinforcement plays a major role in increasing the ductile response of the beam-column joint.

### E. Energy dissipation capacity

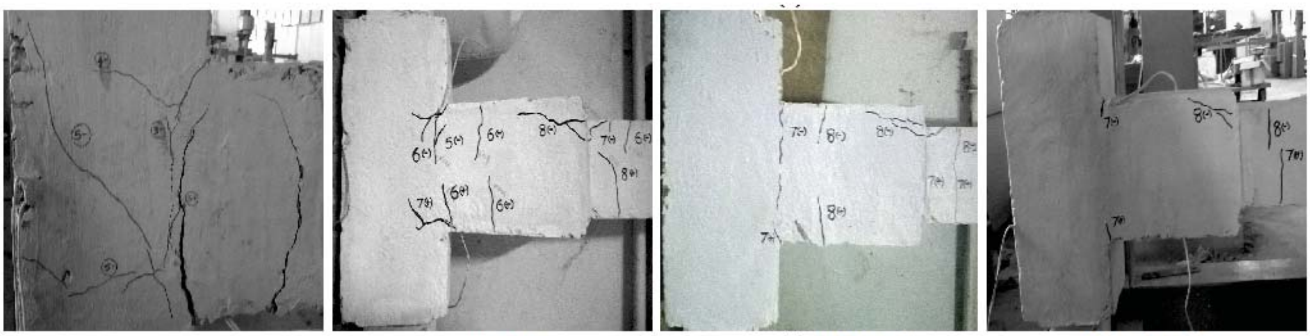
As a measure of the dissipated energy of the specimens, the area enclosed by the hysteresis loops were computed and defined as the energy that could be dissipated by the specimens before the system lost its stability. As it was already seen that the jacketed specimens withstood more number of cycles of loading and exhibited wider hysteresis loops, it clearly signifies that they have better energy dissipation capacities compared the control specimens. Table I shows that the energy dissipation capacities of R-NCJ 1 and R-NCJ 2 were better compared to R-CJ. It is mainly owing to the fact that the proposed jacketing schemes had higher values of ultimate defections and loads, and also had lager area enclosed by their hysteresis loops.

### F. Toughness index

The amount of energy absorbed by the specimens is equal to the area under the load-displacement curve. As per ASTM C1018 toughness index can be calculated by taking the ratios of energy absorbed at ultimate load ($E_u$) of the specimen to the energy absorbed up to the yield load ($E_y$). Energy absorption at the yield load was obtained by the area under the load deflection curve up to the yield load. Similarly the energy absorbed at ultimate load can be obtained by calculating the area under load deflection curve up to the ultimate load. It was seen that the toughness index of all the retrofitted specimens were higher than that of the control specimen. Among the retrofitted specimens, though there was not much variation in the values of energy absorption capacity at yield load, the higher values of energy absorption capacity at ultimate load for the improved jacketing schemes played a major role in improving their toughness index values by a large margin, compared to the conventionally jacketed specimens. This can be attributed to the fact that the comparatively higher values of deflection at ultimate loads for the improved jacketing schemes R-NCJ 1 and R-NCJ 2, helped in improving their energy absorption capacity at ultimate load. The reason is that the provision of collar bars and U-bars improved the ductile response of the jacketed specimens by improving the energy absorption values at ultimate loads.

### G. Crack patterns and failure modes

The cracking patterns of the tested specimens are shown in Fig.7 For the control specimens, initial diagonal hairline crack on the joint region occurred at the third loading cycle when the load reached 6 kN in upward direction. A major diagonal crack was developed at the beam-column interface which is a clear indication of brittle joint shear failure. In actual structures this can result in brittle shear failures which are highly catastrophic in nature. The cracking of the beam region occurred in the subsequent cycles and the specimen failed at an ultimate load of 9 kN. Though a partial beam hinging mechanism was observed in this case, the propagation of a large number of cracks to the column region and the formation of diagonal cracks at the joint region makes it a shear mode of failure. For the R-CJ specimens, first crack was observed on the fifth cycle of loading in the downward direction at a load of 10 kN. Due to the absence of additional reinforcements, a large number of cracks were observed in the jacket region. There were cracks propagating to the joint region of the jacket signifying the inadequacy of the jacketing scheme to resist joint shear failure. Though the ultimate failure



(a) CS (b) R-CJ (c) R-NCJ 1 (d) R-NCJ 2

Fig. 7. Crack patterns of tested specimens

occurred beyond the jacket portion, the excessive cracking of the joint region as well as the remaining portion of the jacket signified the need for additional reinforcement. The R-NCJ 1 specimens exhibited first crack on the seventh cycle on loading in the upward direction, at a load of 14 kN. Though there were a few cracks in the jacket, the provision of diagonal collar bars completely prevented the propagation of cracks to the joint region, thereby improving the shear strength of the specimens. The delayed crack formation as compared to the R-CJ specimens clearly signified an improvement in stiffness of R-NCJ 1. R-NCJ 2 specimens showed reduced number of cracks compared to R-CJ. The provision of U-bars improved the stiffness by a great deal and the jacket portion was devoid of any serious cracking. Though there were cracks initiated near to the joint region, their propagation was properly arrested by the U-bars. Though all the jacketed schemes failed by breaking of the beam beyond the jacket region, the better cracking behaviour of R-NCJ 2 makes it an attractive option for retrofitting actual structures.

## IV. CONCLUSION

Based on the test results of this investigation the following conclusions were drawn:

1) Non-ductile detailed exterior beam-column joints exhibit brittle shear failure when subjected to lateral loads.
2) Only slight improvement in ultimate load carrying capacity of the non-conventional jacketing schemes compared to the conventional.
3) The proposed schemes had significant improvement in stiffness compared to the conventional scheme due to the presence of collar bars and U-bars which tied together the stirrups.
4) Compared to the control specimens, the newly proposed jacketing schemes had 41% and 68% increase in displacement ductility whereas the conventional one had only 31% increase.
5) Jacketing with collar bars and U-bars resulted in 247% and 304% increase in energy dissipation capacity respectively, but conventional had only 85% increase.
6) Jacketing with collar bars and U-bars resulted in 44% and 58% increase in toughness index respectively, but conventional had only 7% increase.
7) The proposed schemes exhibited very less cracking in the jacket region signifying its superior lateral load response compared to conventional scheme.
8) The provision of collar bars and U-bars in the jacket reinforcement was found to be highly effective in improving the seismic response of the beam-column joint.

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