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Research Article

Behaviour of Stainless-Steel Fibre-Reinforced Exterior Beam-Column Joints under Reverse Cyclic Loading

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The objective of this study is to evaluate the flexural behaviour of stainless-steel fibre-reinforced concrete beam-column (BC) joints under reverse cyclic loading. Based on the properties of concrete with various percentages of fibre, the optimized volume fraction was obtained as 0.75% of stainless-steel fibre. In the present work, two sets of beam-column joints with and without fibres were cast and tested under reverse cyclic loading. The beam-column joints were loaded up to five cycles, to study their behaviour, and examine the failure pattern of the joint. Based on test results, parameters such as ductility and the energy absorption capacity characteristics were evaluated. It is concluded that the inclusion of stainless-steel fibre improves the overall seismic resistance of RC beam-column joints.

1. Introduction

Concrete is economical in the long haul as compared to other engineering materials. As the concrete matrix is poor in tension and ductility, it has little resistance to cracking. When the concrete hardens, microcracks are formed, and these microcracks start developing along the planes, which may experience relatively low tensile strain with the application of load. To overcome these difficulties, enhancing the structural properties of concrete becomes important [1, 2]. Research, to overcome the above deficiencies, led to the development of various special structural concrete. Fibre-reinforced concrete is one such development in special structural concrete, which performs better where plain reinforced concrete has certain limitations and exhibits higher structural strength and cohesion due to the presence of fibres [3]. Fibre-reinforced concrete characteristics can be changed by altering the quantity, fibre substance, geometric configuration, dispersal, orientation, and fibre concentration. The addition of fibres to a great extent improves the tensile strength, crack resistance, and toughness of reinforced concrete [4]. When fibres are added comparatively to a small amount, they create a unique reinforcement in the cement matrix and eradicate the problem of crack development during plastic shrinkage [5]. Fibres are selected based on cost, availability, and fibre properties. The most regularly utilized fibres are steel, glass, asbestos, polypropylene, and polyester [6]. In addition to the above fibres, stainless steel fibre is a promising development that makes the reinforced concrete more durable as stainless-steel fibre contains chromium that avoids corrosion of fibres [7]. Stainless steel does not readily corrode, but under low oxygen, it also corrodes [8].

Beam-column joints in RC buildings are defined as the zone of connection of beams and columns and are vulnerable to seismic forces. The load-carrying capacity of joints is limited to the strength of the constituent materials. In most cases, beam-column joints are designed to resist earthquakes, as the earthquake forces, larger than the structural design, causes irreversible damage to the buildings [9, 10]. Earthquake-resistant structures should have good ductility and energy absorption capacity when subjected to lateral loads and should deform laterally [11]. The combined effect of micro and macro steel fibres on the hinged zone of RC beams enhances the flexural capacity [12]. The addition of 1% of steel fibres and 0.5% of polypropylene fibres improves the energy dissipation capacity and stiffness degradation [13]. The strength of deep beams is influenced by the amount of discrete fibres in the web reinforcement [14]. Steel fibres, when used in concrete, increase the tensile, flexural, and impact strength and thereby reduce cracks and shrinkage [15]. Flexural strength of concrete increases by 70%, 45%, and 35% for hybrid fibres of steel-polypropylene, steel-glass, and steel-nylon fibres [16]. The addition of hook fibres by 2% increases the modulus of elasticity by 58% and toughness by 19% [17]. Concrete with 10% of alccofine fibres increases compressive strength by 34.5% [18]. The seismic performance of beam-column joint reinforced with basalt fibres is about 71.6% when compared to conventional beam-column joints [19]. A maximum peak load of 11.05 kN is achieved for concrete reinforced with 0.75% of steel fibres [20]. The use of steel hook fibres shows significant improvement in pre and post behaviour of beam-column joints [21]. Fibre-reinforced concrete possesses higher strength, better ductility, and energy absorption capacity. Steel fibre-reinforced concrete is obtained by adding steel fibres in concrete while mixing creates a homogeneous reinforcement. The use of steel fibres in reinforced concrete results in the corrosion of steel fibres when the structure is exposed to aggressive environments [22]. Hence, to reduce this problem, stainless steel fibres are used which have excellent potential in resisting corrosion.

2. Experimental Investigation

The experimental study is divided into two portions: namely, the performance of the control beam-column joint (CC) and the stainless steel fibre-reinforced concrete beam-column joint (SSFBC) with 0.75% of fibres by volume fraction.

2.1. Materials Used. OPC 53 grade conforming to IS 12269-2013 [23] with a specific gravity of 3.17 was used, and river sand having a specific gravity of 2.60 was used as fine aggregate. A coarse aggregate of 20 mm size with a specific gravity of 2.65 conforming to zone II as per IS 10262 2019 [24] was used. Concrete having a compressive strength of 30 N/mm^2 grade concrete mix was designed as per IS 10262-2019 [24] guidelines. The specimens were cast and cured for 28 days and were tested immediately after the required curing period. The stainless-steel fibre used in this study was round crimped fibre which is shown in Figure 1, and its properties are shown in Table 1.

Figure 1: Stainless steel-round crimped.

Table 1: Fibre properties.

S.no	Property	Stainless steel
1	Length	25 mm
2	Diameter	0.50 mm
3	Aspect ratio	50
4	Modulus of elasticity	193 GPa
5	Tensile strength	610 MPa
6	Elongation	15%
7	Density	6.85 g/cm^3

2.2. Test Setup & Test Procedure. For this study, an exterior beam-column joint with a beam of 120 mm × 170 mm and a column of 120 mm × 230 mm was used. The column height and length of the beam are 700 mm and 450 mm, respectively. The reinforcement provided for the beam-column joint used in the present study is shown in Figure 2. The specimens were cast in two different test series one without fibres and another with stainless steel fibres. For the study on beam-column joints, a loading frame of 100 tonnes capacity was used, and the axial load was applied using a screw jack of 50 tonnes capacity. The load was applied cyclically at the end of the beam at regular intervals, and the deflection was measured under the load. The applied loads were recorded, and corresponding deflections were measured. Downward and upward displacements are measured using dial gauges and linear variable differential transformer (LVDT). The load setup of the beam-column joint is shown in Figure 3.

2.3. Load Sequence. Quasistatic reverse cyclic loading simulating earthquake load is applied on the exterior beam-column joints. The load was applied manually, and for each increment of load, the corresponding deflection was recorded. The load was increased and decreased in stages up to the final failure of the specimen. The maximum load in each cycle was increased by 10 kN. Once the maximum load is reached in each cycle, the loading will be reversed by placing the jack and proving ring on the bottom face of the beam and the dial gauge on the top face of the beam. The ultimate load of the CC specimen was observed during the fourth cycle whereas the ultimate load of SSFBC specimens was observed during the fifth cycle of loading. The load sequence history for various specimens is shown in Figures 4 and 5.

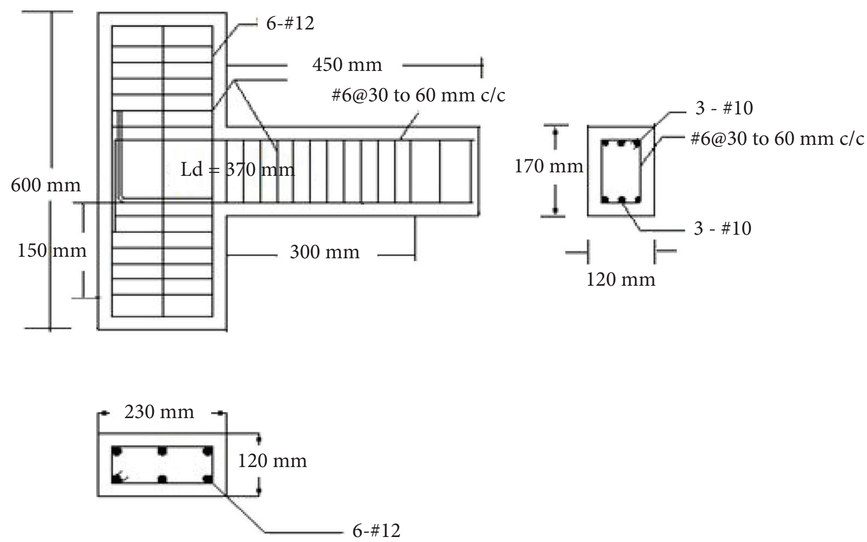

Figure 2: Reinforcement details of the beam-column joint.

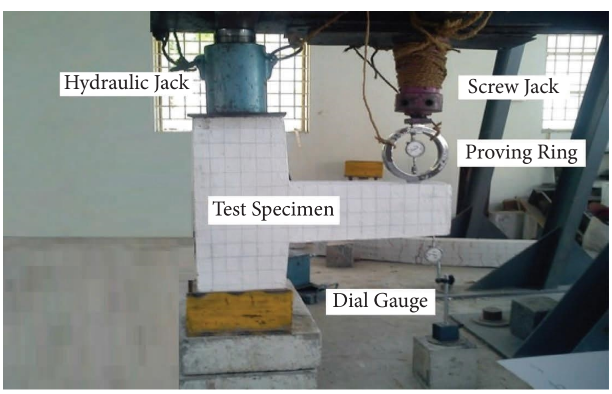

Figure 3: Cyclic loading test setup.

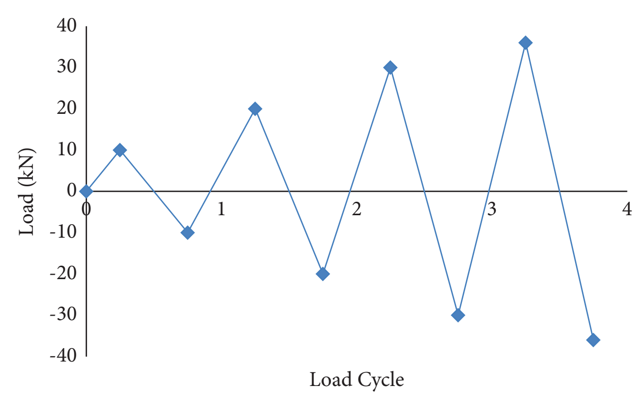

Figure 4: Load sequence diagram for CC.

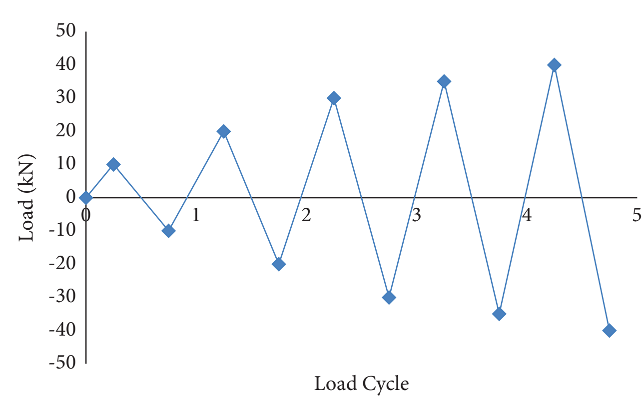

Figure 5: Load sequence diagram for SSFBC.

3. Results and Discussion

3.1. Load Deflection Behaviour. The first crack was observed during the second cycle at a load of 12 kN for the CC specimen, and similarly, 18 kN was observed for the SSFBC specimen. With the increase in loading, cracks developed further and widened. The CC specimen reached an ultimate load of 30 kN during the fourth cycle, but the SSFBC specimen's ultimate load of 34.5 kN was observed in the fifth cycle of loading. From the above results, it is evident that the fibres act as crack arrestors and fibres contribute significantly to prolong the life of a damaged member being

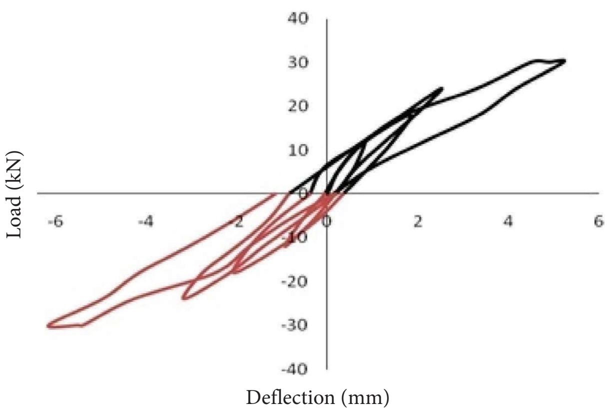

Figure 6: Load-deflection behaviour of CC.

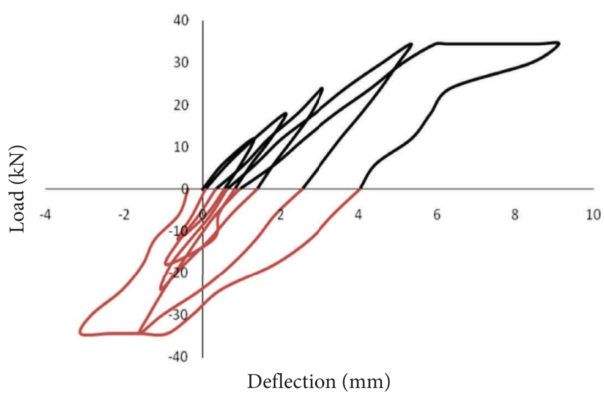

Figure 7: Load-deflection diagram of SSFBC.

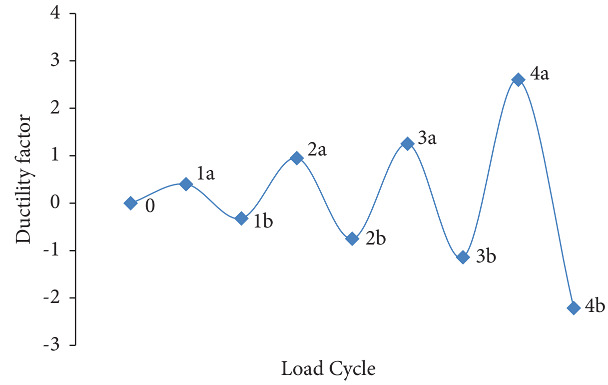

Figure 8: Ductility factor vs. load cycle for CC specimen.

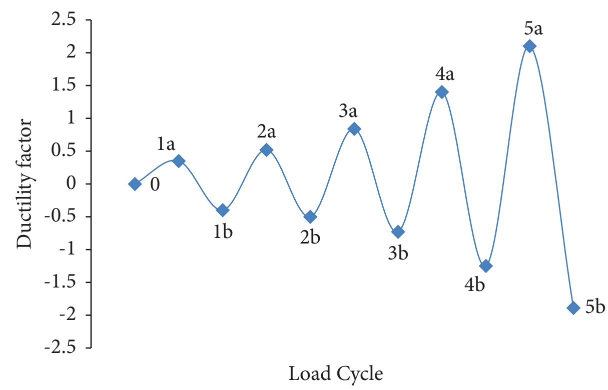

Figure 9: Ductility factor vs. load cycle for SSFBC specimen.

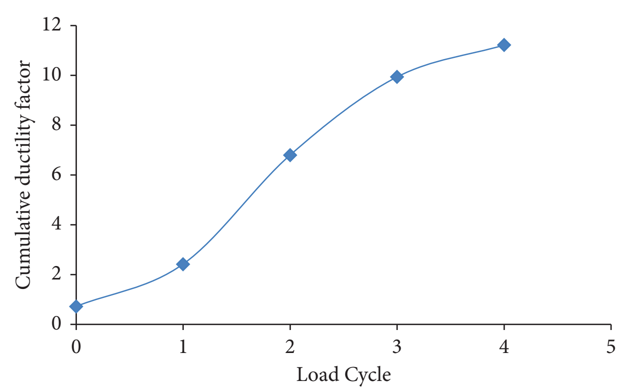

Figure 10: Variation of cumulative ductility factor for CC specimen.

subjected to cyclic loading which is the case with seismic loads. Even though the load-carrying capacity of fibre-reinforced concrete BC joints increased marginally by 4.5 kN from reinforced concrete beam-column joints, there was a better ductile behaviour seen in fibre-reinforced concrete BC joints. The load-displacement behaviour of all the BC joints is shown in Figures 6 and 7. Due to the presence of fibres, the SSFBC specimen exhibited better crack resistance than the CC beam-column joint.

3.2. Ductility Behaviour. From the load-deflection response ductility which is assumed as bilinear, the ductility factor can be calculated as the ratio of ultimate deformation to yield deformation as shown in the following equation:

$$\text{Ductility} = \frac{\text{Maximum deflectionat any load level, } \Delta_{max}}{\text{First yield deflection, } \Delta_y}. \quad (1)$$

The first yield deflection of the CC specimen is 2 mm for the forward cycle and 2.8 mm for the reverse cycle, and for the SSFBC specimen, it is 1.8 mm in the forward and 1.5 mm in the reverse cycle. The variation of ductility factor for forward and reverse cycles is shown in Figures 8 and 9. Cumulative ductility is an important earthquake-resistant parameter for a structure subjected to reverse cyclic loading and is obtained by adding the ductility at maximum load for each cycle. The cumulative ductility for CC beam-column joint increased from 0.72 in the first cycle of loading to 9.8 during the fourth cycle of loading, and for the SSFBC beam-column joint, it increases from 1.30 in the first cycle to 20.52 in the fifth cycle of loading. The cumulative ductility factor for several cycles is presented in Figures 10 and 11. The ductility of stainless steel BC joints shows better results than conventional reinforced concrete BC joints. Also, it was observed that improved integrity of fibre-reinforced concrete in the failure zone prevents the buckling of compression bars

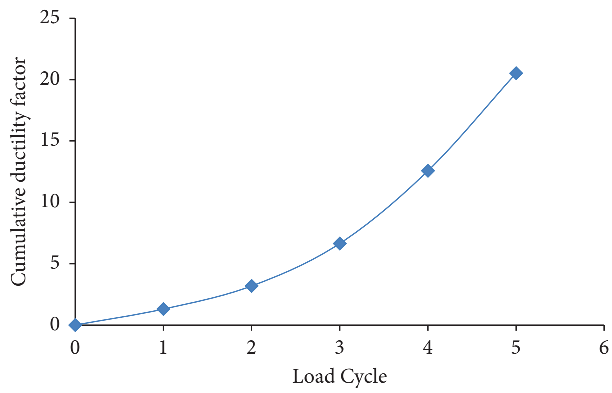

Figure 11: Variation of cumulative ductility factor for SSFBC specimen.

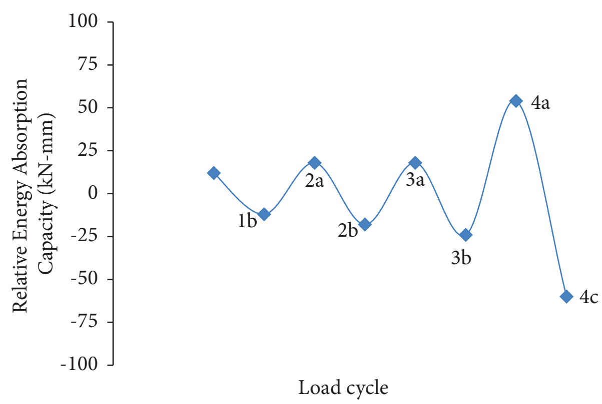

Figure 12: Relative energy absorption for CC specimen.

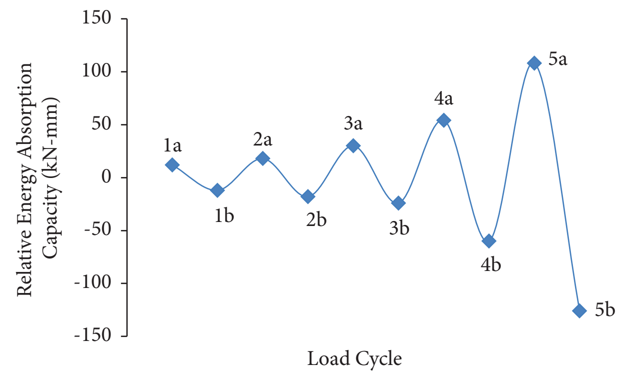

Figure 13: Relative energy absorption for SSFBC specimen.

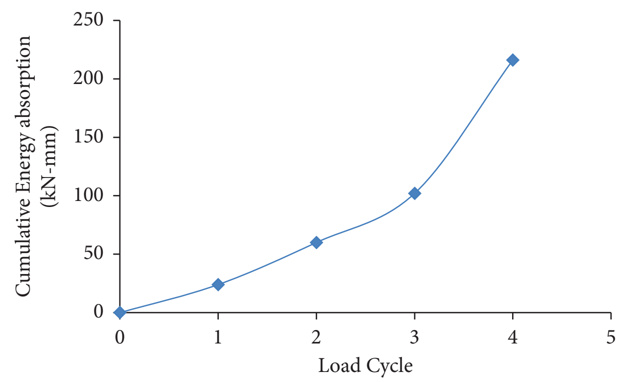

Figure 14: Cumulative energy absorption capacity for CC.

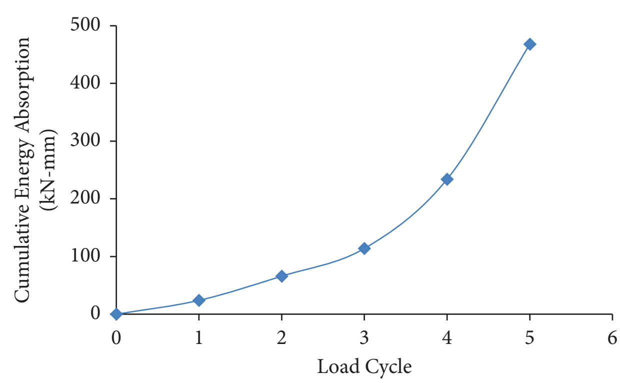

Figure 15: Cumulative energy absorption capacity for SSFC.

and provides better ductility to the fibre-reinforced concrete BC joint specimen.

3.3. Relative and Cumulative Energy Absorption Capacity. Energy is absorbed in each cycle in BC joints when they are subjected to reverse cyclic loading similar to an earthquake. Relative energy absorption capacity is found by adding the areas under load-deflection behaviour's hysteresis loop for each load cycle, and the cumulative energy absorption capacity is obtained as the sum of the energy absorption capacity of the joint in each cycle. For the CC specimen, the relative energy absorption capacity (shown in Figure 12) varies from 12 kN-mm in the first load cycle to 60 kN-mm in the fourth load cycle whereas for the SSFBC specimen, the relative energy absorption capacity (shown in Figure 13) varies from 12 kN-mm to 126 kN-mm in the fifth cycle of loading. The cumulative energy absorption capacity for the CC specimen (shown in Figure 14) is 216 kN-mm and for the SSFBC specimen (shown in Figure 15) is 468 kN-mm. Tables 2 and 3 show the experimental results of CC and SSFBC beam-column joints, respectively. The seismic energy injected into a structure during an earthquake must be absorbed by the structure to a greater extent, and then, the structure can resist earthquake forces. The energy absorption by the structural members before failure is an essential structural parameter, and from the results of relative and cumulative energy absorption studies, it is evident that the stainless-steel fibre-reinforced concrete BC joint absorbs energy much higher than the reinforced concrete beam-column joint.

3.4. Behaviour and Mode of Failure. The beam-column joints were loaded for up to five cycles to study their behaviour and failure pattern. All the specimens failed by crack propagation exactly at the intersection of the BC joint. Figures 16 and 17 show a crack pattern of CC and SSFBC, respectively.

Table 2: Experimental results of CC beam-column joint.

S. no	Load cycle	Maximum load in kN	Maximum deflection in mm		Ductility factor		Relative energy absorption capacity in kN-mm	
			Forward	Reverse	Forward	Reverse	Forward	Reverse
1	1	12	0.82	0.93	0.40	0.32	12	12
2	2	18	1.83	2.05	0.95	0.75	18	18
3	3	24	2.52	3.16	1.25	1.14	18	24
4	4	30	5.20	6.15	2.60	2.21	54	60

Table 3: Experimental results of SSFBC beam-column joint.

S. no	Load cycle	Maximum load in kN	Maximum deflection in mm		Ductility factor		Relative energy absorption capacity in kN-mm	
			Forward	Reverse	Forward	Reverse	Forward	Reverse
1	1	12	1.30	0.63	0.90	0.40	12	12
2	2	18	2.18	0.92	1.22	0.66	18	18
3	3	24	3.07	1.06	1.66	1.86	30	24
4	4	30	5.34	1.61	3.00	2.86	54	60
5	5	34.5	9.11	3.11	4.83	3.13	108	126

Figure 16: Failure pattern of CC specimen.

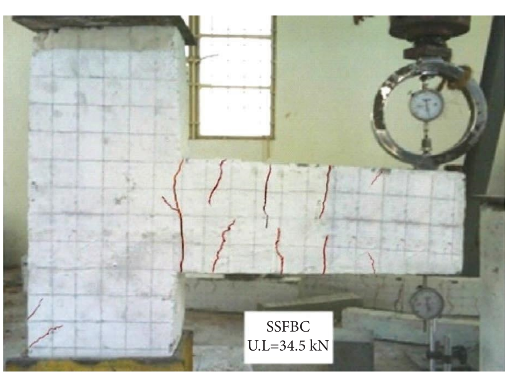

Figure 17: Failure pattern of SSFBC specimen.

Both the BC joint specimens displayed similar linear loading patterns from the initial load to the first crack load. The inclusion of fibres deferred the development of the initial crack in the fibre-reinforced concrete BC joint. Also, when the load was increased, more numerous cracks formed at the beam-column intersection for the CC joint when compared with the fibre-reinforced BC joint. The eventual load-carrying capacity of fibre-reinforced BC joint improved considerably due to the addition of fibres. There was also a considerable reduction in the spalling of concrete for fibre-reinforced BC joint specimens. It was also observed that the fibres present in the specimens acted as a secondary reinforcement and reduced the crack propagation thereby enhancing the ductile behaviour. The fibres acted as crack arrestors and enhanced the load-carrying capacity, energy absorption, ductility, and behaviour under all stages of loading.

4. Conclusion

The current study focuses on the behaviour of fibre-reinforced exterior beam-column joints under reverse cyclic loading with stainless-steel fibre. The following conclusions were drawn from the study:

(1) The maximum load-carrying capacity for the beam-column joints with 0.75% of stainless-steel fibres by volume fraction (SSFBC) was 15% higher than that of the control specimen (CC). Also, the cumulative energy absorption capacity of the BC joints with 0.75% of stainless steel fibres by volume fraction (SSFBC) was 100% higher than the control specimen (CC), which is a notable improvement. This further demonstrates the significance of steel fibres as a means of enhancing the strength at the structural joints.

(2) The SSFBC joint undergoes large displacements without developing wider cracks when compared with the CC beam-column joint indicating that stainless steel fibres impart higher ductility to the stainless-steel fibre-reinforced beam-column joint

which is one of the essential properties for a beam-column joint. Moreover, the fibres played a vital role in delaying the crack formation and crack propagation thereby enhancing the behaviour of the beam-column joints during seismic forces.

(3) The cumulative ductility value of the SSFBC specimen was twice as high as that of the control specimen (CC).

(4) It should also be noted that stainless steel is better known for corrosion resistance, and this also adds to the durability performance of the beam-column joints than the one with mild steel fibres. Overall, the addition of stainless steel fibre in concrete has better load-carrying capacity and better crack resistance and has high energy absorption capacity and better ductility which justifies its use in BC joints that are vulnerable to seismic forces.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Palaniappan Prasath contributed conceptualization, data curation, and investigation. Balaji Shanmugam collected resources, wrote the article, and reviewed and edited the article. Paul Awoyera developed the methodology and did project administration. All authors have read and approved the final manuscript.

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