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Research Article

An experimental study on composite steel encased portal frame under cyclic loading

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Abstract

This research paper discusses the study on steel encased portal frame, which utilizes the shear connectors within the specimen to enhance ductility and ultimate load carrying capacity. Shear connectors can significantly boost the specimen's overall strength and load bearing capability. To investigate this behaviour, cyclic static load test on one bare frame and three portal frames were conducted. The specimens have shear connector of spacing variation as 75mm, 100mm and 125mm which were tested at the rate of ±0.1 tonne per cycle. It has been noticed that when shear connector spacing reduces, the ultimate load bearing capacity improves. These tests enabled a detailed analysis through experimental process of failure, hysteresis curve plot, for all the three portal frames. In hysteresis curve, no pinching effect was found whereas yield strength was found to be increased.

1. Introduction

Compressive strength and stiffness of concrete members are greater, and tensile strength and ductility of steel members are greater. When steel and concrete components are combined as composite members, the favourable qualities of both materials are realized. Concrete filled tubular (CFT) members offer advantages such as enhanced axial load capacity, increased ductility efficiency, increased energy absorption capacity, and less strength degradation.

The hollow steel section and the core concrete work together to make the CFT members stronger. The steel tube supports the load, acts as reinforcement and keeps the concrete core inside. The concrete core adds strength to steel tube and stops the steel tube from buckling inward. Typically, vertical loads are transmitted from the steel tube to the core concrete by means of a bond between the steel tube and the concrete. In the last few decades, numerous studies have been undertaken to study the bond strength between the steel tube and concrete in CFST (Concrete Filled Steel Tube) columns. Roeder et al. [1] conducted push-out tests on circular CFST columns, where the in-filled concrete was of moderate shrinkage or little shrinkage. The test findings demonstrated that the shrinkage of the concrete had a negative impact on the bonding in the CFST columns. Chang et al. [2] tested the bond behaviour in CFST columns with expansive concrete. The results demonstrated that expansive concrete enhanced the short-term bond strength of CFST columns.

To provide the dependable transmission of the vertical load at beam-column joints, shear connectors are often placed to the inner wall of the steel tube to ensure the performance

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of the steel tube and concrete. Among the various forms of shear connectors, the shear studs are widely used as the shear connectors. Shakir-Khalil [3] carried out a series of push-out tests with different types of shear connector, and the results suggested that the ultimate push-out load was a function of the interface type, cross-section shape and size, which led to a better understanding of the load transfer mechanism in beam-column connections in composite construction. Li An et al. [4] presented push-out tests of studs in normal and high strength concretes. The results demonstrated that the compressive strength of the concrete had a substantial impact on the strength of the stud connections. Pil-Goo Lee and Chang-Su Shim [5,6] investigated the static and fatigue behaviours of large shear studs up to 30 mm diameter, which were beyond the limits of the current design codes. Weichen Xue [7] conducted push-out tests on the shear studs in order to investigate the factors that affect stud behaviour. The mechanism of shear studs was investigated, a new description of the stud load-slip relationship was presented, and a model for determining the shear stud bearing capacity was established.

Because CFT is so important, it has been the subject of a lot of research for a while now.

Beam column junction is the most important part of a reinforced concrete frame. It is subjected to extreme of stress when the ground shakes a lot. This has a direct effect on the structure. Shear connectors must be added to the CFT in order for the structure to perform well. The spacing of shear connectors was adjusted during this study, and the differences in the findings for the same load increments were observed and compared experimentally for each specimen.

2. Research Background

Various ways for resisting seismic load have been investigated throughout the years in terms of materials, geometry, and design. In recent years, a new branch has been noted to have piqued the interest of numerous researchers, which is "Concrete filled steel tubes." Within this category, testing with shear studs has showed a lot of promise in terms of load carrying capacity and ductility.

Study was carried out by Yang Wen [8], Lai-Yun [9], Matsui C [10], Ben Mou [11], Shuaike Feng[12] regarding analysis of Seismic Behaviour of CFRST (Concrete Filled Rectangular Steel Tube) Beam and Column Joints. According to the research, CFRST beam and column joints exposed to minor cycle reversal loads have plump hysteretic loops, increasing strength and stiffness degeneration, and high stiffness. After the joints achieved the ultimate load, significant ductility and subsequent deformation capability were detected, indicating that the joints met the seismic design criteria.

Jingbo Liu [13], Liu Y B [14], Seyed Rasoul [15] presented the theoretical effect of the column-to-beam strength ratio and axial compression ratio on the failure mechanism of concrete-filled square steel tube frame structures. The researchers looked at multi-storey composite bay frames with varied column-to-beam strength ratios and axial compression ratios. For the strong column-weak beam failure, solutions for acceptable column-to-beam strength ratio values with varying column axial compression ratios were established.

Faxing Ding [16], Aslani, F [17], Ellobody, E [18] , Jingfeng Wang [19], Qi-shiZhou[20] investigated about CFST (Concrete Filled Steel Tube) column to steel-concrete composite beam under lateral cyclic loading. In Single storey one-bay in-plane frames the seismic performance was investigated using some parameters like the slenderness ratio. These composite frames were found to perform well during earthquake.

Kun Wang [21], L. Fang, B. Zhang [22], K. Wang [23], K. Wang [24] analysed the Theoretical study of the hysteretic actions of prestressed composite joints with CFST. Lateral cyclic loading was applied to pre-stressed and unstressed composite specimens. Shear failure within the panel zone and flexural failure at the beam ends were seen in pre-stressed joint specimens; only flexural failure at the beam ends was observed in non-stressed joint specimens. Specimens exhibited typical hysteretic behaviour after testing.

Studies were carried out by Toshiaki Fujimoto[25], Gia Toai Truong[26], Jiansheng Fan [27], A.Niroomandi [28] on seismic behaviour of SRC columns and beam-column junctions in Composite Structural Systems. It was discovered that CES columns and beam-column junctions perform better seismically than SRC columns.

Nader Fanaie [29], Bin Wang [30], Xian Li [31] conducted experiments to learn more about the behaviour of a rigid connection between a steel beam and a CFT column with external T stiffeners. Concentrated stress at the place where the stiffener groove welds to the beam flange and column web leads in an unexpected brittle failure, hence reducing the connection's ductility.

Vijayalakshmi, D.D [32], Hallam [33], Fanaie, N [34], Yong Fang[35], Yansheng Du[36], Xianggang Liu[37], Jiepeng Liu[38], Faesal Alatshan[39], Xuetao Lyu[40], Fang Yuan[41] conducted experimental study on confined column behaviour under axial load. It was done to learn about the distribution of shear connectors in thin-walled short Concrete Filled Steel Tube (CFST) columns and found that smaller the gap between shear connectors, the greater the CFST efficiency.

Studies were carried out by John Francis. K [42], Ahmed Elremaily [43], Dalin Liu a [44], Georgios Giakoumelis [45], Sherif M [46] on Confined column behaviour under axial load. The link between shear connector distribution and the action of thin-walled, short Concrete Filled Steel Tube (CFST) columns was researched, and it was revealed that the closer the shear connectors are, the more efficient the CFST.

Hsuan-Teh Hu [47], Zhi-Liang Zuo [48], Qiyun Qiao[49], Yanlei Wang[50], Morteza Naghipour[51], Yanlei Wang[52], S.Seangatith[53], Bin Wang[54], BaochunChen[55] conducted experimental study on the columns of CFT exposed to an axial compressive force and bending moment. Using the nonlinear finite element program ABAQUS, researchers compared CFT columns with varying cross sections to experimental data. The square CFST column has less confining effect than circular CFST columns, however square CFST columns stiffened with reinforcing ties give the same confining effect as circular CFST columns.

Young-chan Kim[56] , Hollow Steel Section (HSS) and Concrete-Filled Steel Tube (CFST) sections were utilised in the simulation process, and it was discovered that the HSS system is vulnerable to damage even when seismic protection measures are taken into account.

Qian Wang[57] demonstrated that the shear resistance and shear stiffness of large-diameter, high-strength studs are greater than those of conventional stud connectors. Nadiah Loqman[58], The purpose of this paper is to examine the applicability and efficiency of composite beams with precast concrete slabs and bolted shear connectors by analysing the structural behaviour of composite beam systems, such as their strength, stiffness, slip behaviour, failure mode, and sustainability, as determined by experiment and numerical studies. K.Sathish Kumar[59], the general behaviour of composite beams with shear connectors under bending, the influence of a variety of significant characteristics was investigated. Rahul Tarachand Pardeshi[60], review of several types of shear connectors, their uniqueness and characteristics, testing techniques, and conclusions from the last decade were studied. The literature, effectiveness, and applicability of the various types of shear connectors, such as headed studs, perfobond ribs, fibre-reinforced polymer perfobonds, channels, pipes, Hilti X-HVB, composite dowels, demountable bolted shear connectors, and shear connectors in composite columns, are investigated in depth. Raj[61], the efficient and economical use of shear connectors in Steel-Concrete composite sections is examined.

Despite the fact that this research involves a progressive trend, it has mostly concentrated on steel encased columns and steel encased beams. Many researchers proved that the members with steel enclosed columns and steel encased beams successfully enhance the ultimate load bearing capacity and ductility when compared to typical RCC. There has been very little experimental work on steel enclosed column and beam frames, and little theoretical research has been done. Because it is well known that the 'Beam Column junction' is the most essential component of the structure and is very certain to break during seismic loading, this research study was experimentally focused on the combined effect of steel encased column and beam.

3. Materials and Methods

3.1. Material Properties

The concrete with load carrying capacity of 25MPa was made in accordance to IS456:2000 and IS10262:2009 where the slump of concrete was kept to be 200mm for the ease of flow in the mould. The mild steel rods as shear connectors were of 6mm diameter and 150mm length, having 7850kg/m3 density and yield strength of 250N/mm2 were used. These rods increased the shearing capacity of the frame by connecting the concrete and the steel tube. The Galvanised Iron steel plate of 1.2mm thickness with various lengths was used. This plate provided the confinement to the concrete infill, which resulted in increase in load carrying capacity.

The shear connectors shall be spaced so as to transmit shear and to prevent separation between the concrete and the steel, considering an appropriate distribution of design shear force. The advantages of shear studs over other forms of connectors are that the welding process is quick and simple permit more satisfactory compaction of the concrete around the connectors, and provide equal shear strength in all directions. Shear connectors must be designed to provide static strength, and for fatigue loading.

Grade designation	M25 concrete
Type of cement	OPC 53 grade
Maximum Nominal size of aggregate	20mm
Minimum cement content	300kg/m^3 (As per IS456 Table 5 page 20)
Maximum water cement ratio	0.50
Workability	75- 100mm
Specific gravity of cement	3.15
Specific gravity of Coarse aggregate	2.74
Specific gravity of Fine aggregate	2.68 (M sand)
Mild steel rods as shear connectors	6mm diameter and 150mm length
Density	7850kg/m^3
Yield strength	250N/mm^2
Galvanized Iron steel plate	1.2mm thickness
Density	7800kg/m^3
Yield strength	250N/mm^2

3.2. Test Specimen

A series of 3 portal frames sections were filled with concrete and were given static cyclic loading to observe the behaviour of frames. All the 3 frames had the height of 1.1m and width of 1.15m with the sectional area of 150mm x 150mm (Fig 1). Concrete of the grade M25 was filled within the hollow frame and the open faces were cured for 28 days.

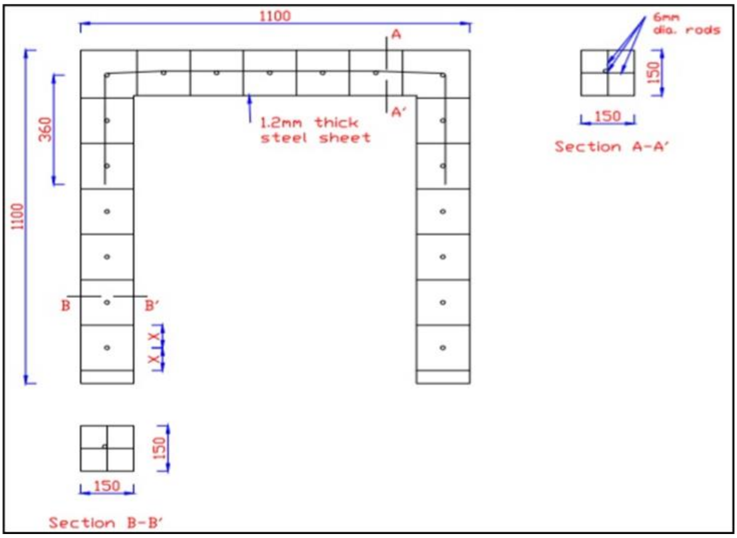


Fig 1. General Schematic Diagram of portal frame (all units in mm)

All the steel used for this research was GI sheet. The steel plate was 1.2mm thick; this as done to reduce the percentage of steel used and makes the specimen as "Thin walled structure". Fig 1 shows the general geometry of all the three specimens.

The parameters selected to research were the spacing and number of shear connectors in the portal frame and the others such as size of beam, beam width, height of column, column size, shell thickness; steel rod section and qualities of concrete were kept unchanged throughout the research. The portal frames were named as SP-75, SP-100 & SP-125. SP-75 had the shear connector spacing of 75mm, SP-100 had the shear connector spacing of 100mm & SP-125 had the shear connector spacing of 125mm. These shear connectors were welded inside the frame section such that they connected two opposite faces of the square section.

The steel casing was made into a C-shape first such that one faces of the specimen is open; this was done for the ease to weld the internal shear rods, once the shear rods were welded in place, a rod was placed in the beam with development length of it going into the columns. Then the open face was closed by welding a steel plate. This steel plate was also connected with inner shear rods via welding as well. The steel plate was welded fully along the edges to ensure maximum strength as well as to avoid concrete slurry spillage while filling. Once the steel mould was ready, a high workability M25 concrete was poured from the column openings into the steel encasement. The maximum aggregate size was 12mm; this size was used to avoid blocking of the concrete due to aggregates getting stuck in spaces.

The specimen was kept upside down and the concrete was poured and the casing was tilted and manually shaken to help the concrete to compact properly along with regular tamping with a 16mm rod.

Fig 2 and Fig 3 shows the reinforcement details of raft footing which is connected to the concrete filled steel tube (CFST) frame.

3.3. Experimental Test Setup

The necessary specimens were named and arranged with a spacing of 5 cm prior to testing. All specimens were tested with the help of removable base under fixed support conditions on both sides, i.e. front and back.

Fig 2. Welded shear connectors

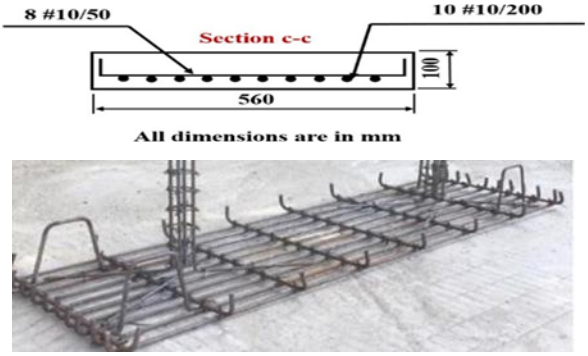


Fig. 3 Reinforcement details of raft footing

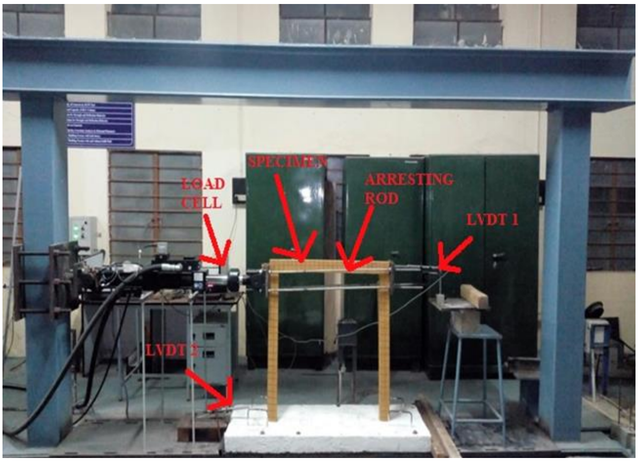


Fig. 4 General Test Setup

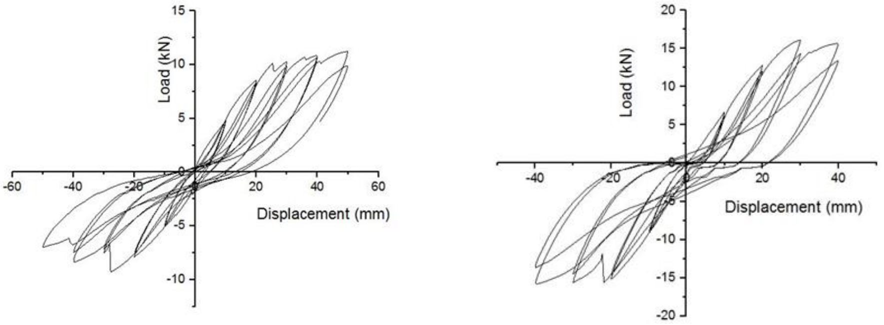
All the specimens were tested under a cyclic loading frame of 50T capacity (Fig. 4) to observe their behaviour under static cyclic loading. The load was applied at the beam column joint via a hydraulic jack coupled with a load cell to observe the deflection. The load was applied at the rate of ±0.1 tonne per cycle. With loading gap of 1kN, 3 cycles of loading were applied for each loading resulting in 10 cycles of loading per specimen. Simultaneously, two LVDTs were fixed on the specimen, of which one was fixed at the middle of the top edge (LVDT 1) and one was fixed at the centre of the column (LVDT 2).

These were used to note the corresponding deflections for each load. Out of these two LVDTs, only the readings from LVDT-1 were taken and LVDT-2 was used only as a control. 3.3.2. Specimen Specification. A total of 3 specimens and bare frame specimen were cast and subsequently tested.

Table 1. Specimen Specification

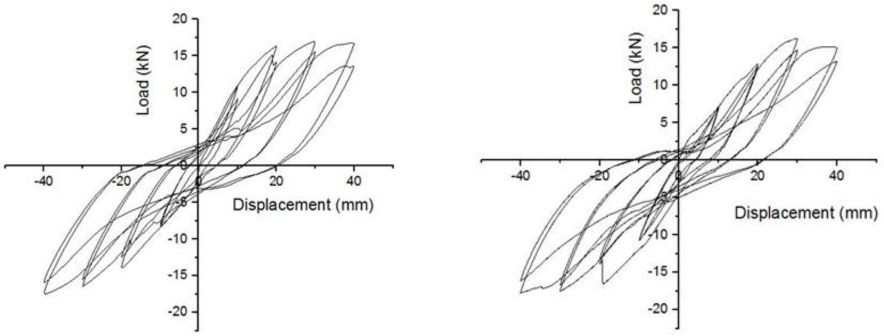
Spacing of studs	Specimen ID	No. of Specimens
	Bare frame	1
75mm	SP-75	1
100mm	SP-100	1
25mm	SP-125	1

4. Results and Discussions



(a) Bare frame hysteresis curve

(b) SP-75 hysteresis curve



(c) SP-100 hysteresis curve

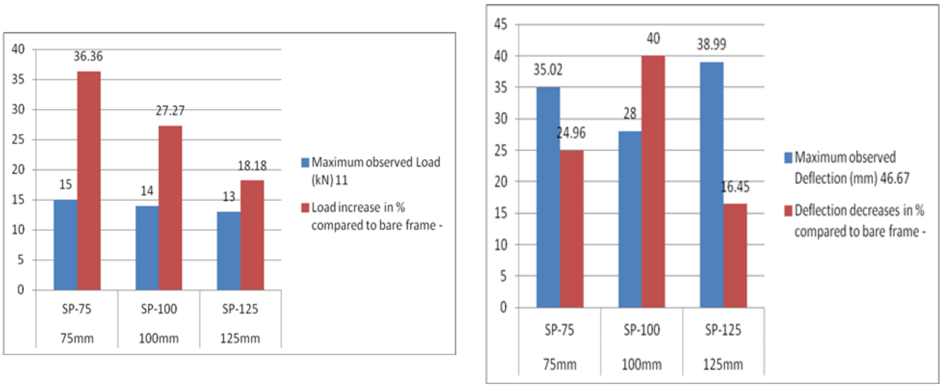
(d) SP-125 hysteresis curve

Fig. 5 Hysteresis Curves

Figure 5 depicts the lateral load-displacement hysteretic curves for all specimens. Throughout the early period, the hysteretic curves followed a straight line, indicating the specimens were in a state of elastic deformation. After yielding, the regions of the hysteretic loops started rising gradually, likely to result in plump forms, and a few residual deformations were noticed after unloading; after the peak value was achieved, the lateral loads decreased dramatically as the lateral displacements increased, demonstrating high ductility. Overall, all specimens performed well since the hysteretic curves were plump and there was no substantial pinching.

Table 2. Load – Deflection observed values

Spacing of studs	Assigned Name	Maximum observed Load (kN)	Load increase in % compared to bare frame	Maximum observed Deflection (mm)	Deflection decreases in % compared to bare frame
	Bare frame	11	-	46.67	-
75mm	SP-75	15	36.36	35.02	24.96
100mm	SP-100	14	27.27	28	40
125mm	SP-125	13	18.18	38.99	16.45



(a) (b)

Fig. 6 (a) Maximum Load and percentage increment (b) Maximum Deflection and percentage decrement

From Table 2, the load-carrying capacities of the three specimens' viz., SP-75, SP-100 and SP-125 were comparatively more than the bare frame compared with displacement. The maximum load-carrying capacity observed in SP-75 was 15 kN. SP-75 outperformed the bare frame by 36.36 percent in load-carrying capacity. Similarly, when compared to the bare frame, the SP-100 and SP-125 improved by 27.27 percent and 18.18 percent, respectively. Fig 6 (a) shows the maximum observed load and load increase in % compared to bare frame and Fig 6 (b) shows the maximum observed deflection and deflection decreases in % compared to bare frame. According to BS 8110 total deflection is Span/250 with limiting span/depth ratio. Further, the deflection occurs after constructing the finishes and partitions is Span/500 or 20mm, whichever is lesser.

Eurocode 2 also limits the deflection to Span/250 and span over effective depth ratio is used to check the limits. The method of calculation is little different from the BS 8110 Part 1. Further, it also limits the deflection that occurs due to the construction of finishes and partitions to Span/500. Eurocode 2 does not provide a table as BS 8110 Part 1, but it provides equations and charts to check the deflections.

Table 3. Area under the curve

Spacing of studs	Assigned Name	Area Under the Curve (mm^2)
-	Bare frame	428.47
75mm	SP-75	532.14

100mm	SP-100	775.91
125mm	SP-125	727.88

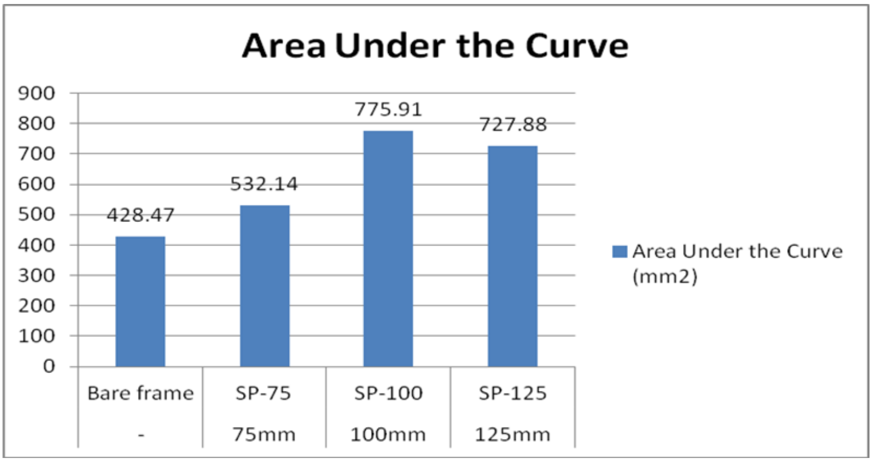


Fig. 7 Area under the curve

One of the most essential criteria for estimating the seismic behavior of specimens is their energy dissipation capability. Because of the development of the plastic hinges, the energy dissipation capacity of specimens SP-100 and SP-125 was clearly greater than the others after yielding. However, according to table 3 and figure 6, the energy dissipation capacity for bare frame and SP-75 was lower.7

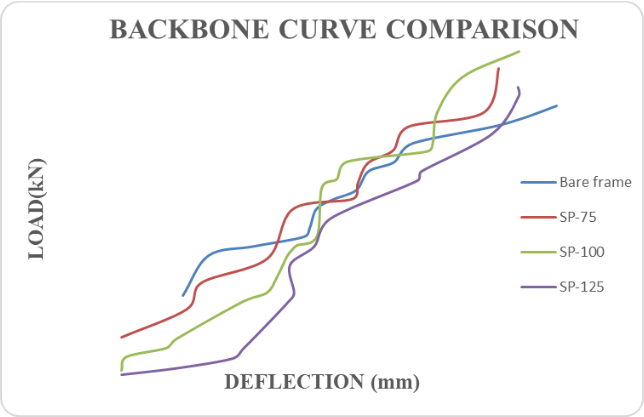
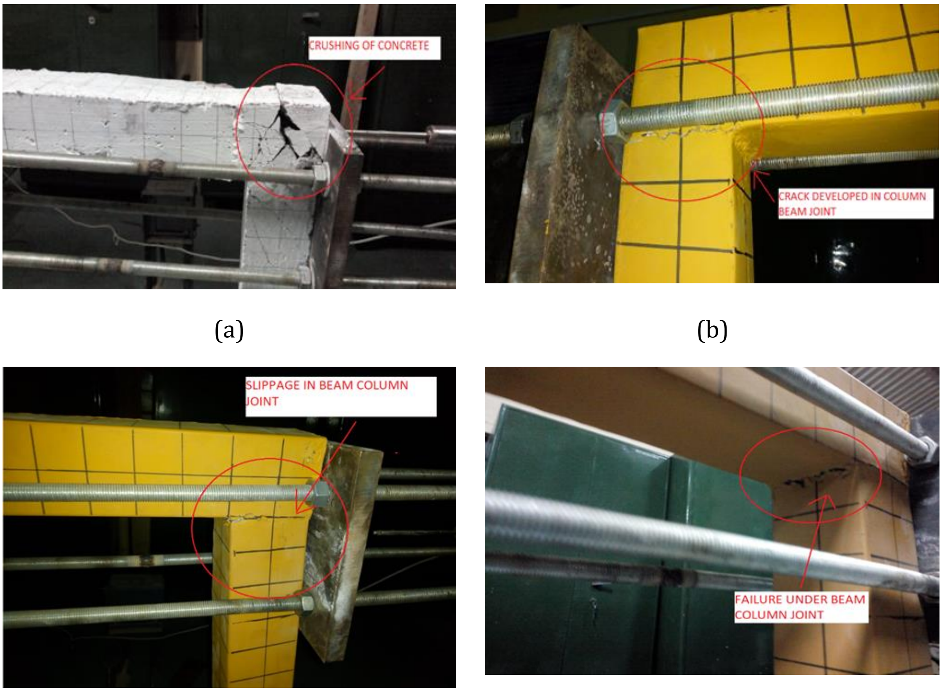


Fig. 8 Comparison of backbone curves of bare frame, SP-75, SP-100 & SP-125

Backbone curves are used to reflect the significance of lateral load and ductility properties. It demonstrates that lateral loads have improved and ductility has improved. In the above Fig 8 with regard to the negative loads we are able to observe that, the area under each curve is in ascending order, which confirms the actual fact that lesser shear connector spacing increases the ductility of the specimen. Thus it can even be said that with increase in shear connector spacing the specimen gets more brittle. It can be concluded the shear connector spacing of 75mm takes more load with considerably more deflection. As a result, it's clear that as the gap between shear connectors shrinks, the ultimate load bearing capacity increases.

4.1 Failure Mode

Specimen bare frame has crushing of concrete on the surface as shown in Figure 9 (a). As shown in Figure 9 (a), the crushing of concrete is mainly concentrated in the corner of the specimen. In Figure 9 (b), for specimen SP-75 cracks are observed at the beam and column joint, which are highlighted in the red circle. In Figure 9 (c), for specimen SP-100 the area inside the red circle is the slippage occurred in beam-column joint after the test. In Figure 9 (d), for specimen SP-125, crack occurred below beam-column joint. After the completion of all the tests, the steel tube has been cut open so as to observe the side of the core concrete. From the observation, there is significant shear failure in the concrete, while there are no significant damages to the rest of the concrete. Usually, for the shear connectors inside a CFST tube, there is shear failure of the concrete or the shear failure of the shear connector.



(a) (b)

(c) (d)

Fig. 9 (a) Failure of bare frame, (b) Failure of SP-75 (c) Failure of SP-100 (d) Failure of SP-125

5. Conclusions

Composite frames made of steel tubular reinforced concrete columns and beams showed high ductility. As the spacing between shear connectors reduces, the ultimate load bearing capacity improves owing to the increased confinement effect and the improvement in ductility is evidenced by the presence of a broad plateau in the load deflection curves obtained for specimens with varying spacing's of shear studs. No pinching effect is observed in any of the hysteresis loop, which is attributed to the effective confinement attained due to steel encasement. The member takes load even after the concrete inside is crushed which could be observed from the load cells and LVDTs. The encasement avoids the spalling of the concrete, which can increase the safety for the people who are evacuating. It is speculated that the ultimate load carrying capacity increases due to the confinement effect of the steel.

In the Figure 8, with regard to the negative loads it can be clearly observed that, the area under each curve is in ascending order, which confirms the actual fact that lesser shear connector spacing increases the ductility of the specimen. Thus it can even be said that with increase in shear connector spacing the specimen gets more brittle. It can be concluded the shear connector spacing of 75mm takes more load with considerably more deflection. As the spacing of shear connectors decreases, the ultimate load carrying capacity increases due to the enhancement in confinement effect. As the spacing of shear connectors decreases, the ductility increases which is evident from the large plateau in the load deflection curves obtained for the specimens with different spacing of shear studs. Steel welds should be avoided near the beam column joints.

Later this study will be done analytically using software and also experimentally with other specimen sample and the comparative study will be done.

From previous literature work it is observed that, behaviour of CFST (Concrete Filled Steel Tube) frame structure is needed to be considered for study. Therefore, in this research, to attain strength against seismic load and economy in construction, uses of CFST (Concrete Filled Steel Tube) frames were studied.

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