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FLEXURAL AND CYCLIC BEHAVIOUR OF HOLLOW AND CONCRETE- FILLED STEEL TUBES

Arivalagan .S[1], Kandasamy.S[2]

ABSTRACT

This paper presents a study on the flexural and cyclic behaviour of concrete filled steel hollow beam sections. The specimens in-filled with normal mix concrete, fly ash concrete, quarry waste concrete and low strength concrete (Brick-bat-lime concrete) and hollow steel sections were tested. Measurements of strains and deflections were made under two-point loading. A theoretical model was also developed to predict the moment carrying capacity. The capacities of the beams were compared with the ultimate capacity obtained using the international standards EC4-1994, ACI-2002 and AISC-LRFD-1999. The result of the experimental investigation showed that the moment carrying capacity increases based on the compressive strength of the filler materials. Energy absorption capacity also increase due to in filled materials. Analytical results show good agreements with experimental results.

Key words: 1) Steel hollow sections, 2) in-filled concretes, 3) static test
4) Cyclic test 5) FEM

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1. INTRODUCTION

Concrete-Filled Hollow Steel sections (CFHS) are used in some special application. In the past,many research works were carried out on the behaviour of concrete-filled HSS columns and beam-columns. But relatively little research was reported on the structural behaviour of concrete-filled HSS beams. Assi.I.M., et al. tested thirty-four simply supported beams; 1000 mm long filled with lightweight concrete and foamed concrete (polyurethane) to obtain the ultimate moment capacity. Fully plastic stress block of the concrete at its maximum cylinder strength was used in the analysis. Analytical formulae for the ultimate moment capacity of concrete-filled RHS and SHS beams were suggested. They suggested that lightweight aggregate concrete and foamed concrete can be used in composite construction to increase the flexural capacity of steel tubular sections. Han L.M. conducted test on series of concrete filled square and rectangular beams, the depth to wall thickness ratio ranges from 20 to 50 and compressive strength of 28 days concrete cube of 30Mpa. to determine maximum moment capacity of the specimen and also to investigate the failure pattern. Elchakakani.M et al have tested 12 concrete filled steel CHS beams. The test specimens were selected to examine the effects of different d/t ratios ranging from 12 to 110 with the concrete cylinder strength 23.4 MPa. The test results showed that CFT were subjected to large deformations under pure bending, from which it was concluded that void filling prevented local buckling for very large rotations. Hussain K.M.A. conducted series of tests on thin walled composite beams with normal and lightweight volcanic pumice concrete as infill. It was observed the thin walled composite beam sections with volcanic pumice concrete exhibited satisfactory performance compared with normal concrete. Jane Helena.H. and Samuel Knight.G.M., carried out series of tests on hollow and concrete-filled cold-formed steel sections subjected to axial and bending forces. The effects of eccentricity ratio and strength of in-fill on the behaviour of these sections were studied. Even though the behaviour of concrete filled compression members are well understood the flexural behaviour of these sections needs to be investigated for better understanding. The objective of the present investigation is to study the flexural and cyclic load behaviour of rectangular hollow section beams in filled with different concrete materials and also to develop a empirical model for the analysis of the flexural behavior for concrete-filled HSS beams.

2. MATERIALS AND TESTING ARRANGEMENT

2.1 Material

All the experiments were carried out using commercially available RHS sections. They were produced by TATA STEEL INDUSTRIES, India. The ratio of tube depth to wall thickness (d/t) is 29.25. All the steel tubes used in this investigation were factory made products The length of the specimen was 1.2 m. The depth, breadth, and wall thickness of the rectangular section were 100×50×3.2 mm . The grade of steel was Yst310 as per IS 4923:1997 “INDIAN STANDARD HOLLOW STEEL SECTIONS FOR STRUCTURAL USE – SPECIFICATIONS”. In order to determine the material properties of the steel tubes the coupon tests were conducted in accordance with the code of practices IS: 1608-1972 “METHOD FOR TENSILE TESTING OF STEEL PRODUCTS”. Three coupons were cut from the three flat surfaces and the 0.2% proof stress was adopted as the yield stress for the steel tubes. The mean values of material properties of the steel specimens were shown in Table 1.For Concrete-Filled RHS beam specimens, ordinary portland cement (OPC-43 Grade) was used. The required quantity was procured in a single batch. The physical properties of the concrete were shown in Table 1. Locally available river sand conforming to zone II of IS: 383-1970 was used. The coarse aggregate of the granite stone 8 to 10 mm size was supplied by the local quarry. Ordinary potable water available in the laboratory was used for the experimental investigations and for curing purposes. Fly ash procured from Neyveli Thermal Power Plant had been used as replacement to cement. Quarry wastes procured from the quarry mines in and around Salem city and Fat limes were used.

2.2 Composite Beam Specimens

The details of the tested specimens filled with different types of concrete are shown in Tables 1 and 2 such as the specimen label, the sectional dimensions, the depth to wall thickness ratio (d/t), the type of mix, the yield strength of steel and characteristic compressive strength of concrete. Each mix proportions consist of three specimens. They are designated as Normal Mix Concrete (NMC), Fly Ash Concrete (FAC), Quarry Waste Concrete (QWC), Low Strength Concrete (LSC), and Rectangular Hollow Section (RHS).

Table 1 Group designation of the test specimen (Under Static Load)

Sl.No	**Specimen Label**	**Sectional Dimensions D×B×t (mm)**	**d/t**	**Type of mix, f_y(MPa) and f_{ck}(MPa)**
1	RHS-1	100×50×3.2	29.25	Rectangular Hollow Section f_y =338
2	RHS-2	100×50×3.2	29.25	
3	RHS-3	100×50×3.2	29.25	
5	NMC-R-1	100×50×3.2	29.25	Normal Mix Concrete f_{ck}=32.3
5	NMC-R-2	100×50×3.2	29.25	
6	NMC-R-3	100×50×3.2	29.25	
7	FAC–R-1	100×50×3.2	29.25	Fly Ash Concrete f_{ck}=27.5
8	FAC–R-2	100×50×3.2	29.25	
9	FAC–R-3	100×50×3.2	29.25	
10	QWC-R-1	100×50×3.2	29.25	Quarry Waste Concrete f_{ck}=21.63
11	QWC-R-2	100×50×3.2	29.25	
12	QWC-R-3	100×50×3.2	29.25	
13	LSC-R-1	100×50×3.2	29.25	Low Strength Concrete f_{ck}=0.88
14	LSC-R-2	100×50×3.2	29.25	
15	LSC-R-3	100×50×3.2	29.25	

Table 2 Group designation of the test specimen(Under Cyclic Reversal load)

Sl.No	**Specimen Label**	**Sectional Dimensions D×B×t (mm)**	**d/t**	**Type of mix, f_y(MPa) and f_{ck}(MPa)**
1	RHS-1	100×50×3.2	29.25	Rectangular Hollow Section f_y =338
2	RHS-2	100×50×3.2	29.25	
3	RHS-3	100×50×3.2	29.25	

4	NMC-R-1	100×50×3.2	29.25	Normal Mix Concrete f_{ck}=37
5	NMC-R-2	100×50×3.2	29.25	
6	NMC-R-3	100×50×3.2	29.25	
7	FAC–R-1	100×50×3.2	29.25	Fly Ash Concrete f_{ck}=35
8	FAC–R-2	100×50×3.2	29.25	
9	FAC–R-3	100×50×3.2	29.25	

The specimens were filled with concrete in many layers and carefully compacted by a steel rod to avoid voids inside the specimen. Three cubes of 150 mm size were prepared for each type of concrete to determine the average compressive strength. These cubes were cured in water and tested according to the guidelines specified in the code of practices (IS 456:2000).

Table 3 Average material properties of steel sections

Sectional Dimensions D×B×t (mm)	**Yield Stress f_y (MPa)**	**Ultimate Stress f_u (MPa)**	**Young's Modulus E_s (MPa)**	**f_u/f_y**
100×50×3.2	338	480	2.28×10^5	1.42
72×72×3.2	345	510	2.2×10^5	1.48

Table 4 Average Material Properties of in-filled Concrete

Filler material	**Density (kg/m^3)**	**Compression strength (MPa)**
Normal Mix Concrete (NMC)	2400	32.3& 37
Fly Ash Concrete (FAC)	2100	27.55& 35
Quarry Waste Concrete (QWC)	2150	21.63
Low Strength Concrete (LSC)	2000	0.88

2.3 Test On Static Load

Fifteen beam specimens consisting of three hollow steel specimens and twelve Concrete-Filled Steel Tubular beam specimens (CFSTs) were selected. The twelve Concrete-Filled Steel Tubular (CFST) beam specimen consists of three in-filled with normal mix concrete, fly ash concrete, quarry waste concrete and low strength concrete three members in each case. The sizes of RHS sections were selected as 100 × 50 × 3.2 mm. The length of the specimen was 1.2 m. The details of the test specimens are shown in Table 1. A simply supported beam set up was adopted. Beams were tested under two-point load in a 1000 kN capacity Universal Testing Machine. The beams were placed over simple supports with an effective span of 1.00m. Two point loading was applied at the centre of a very rigid plate, to ensure the distribution of the load as shown in Figure 1. The test specimens were instrumented to measure load, strains and deflections. Deflections of the beam specimens were measured by three dial gauges, one is placed at the mid span of the specimen, and the other two were placed under concentrated loads. Strain values were measured using the strain gauges at every incremental of load applications. The strain gauges were fixed at the centre, on the top and at the bottom flanges of the beam specimen to measure the tensile and compressive strain. A load interval of less than one-tenth of the estimated load capacity was used. Each load interval was maintained for about 2-3 minute at each load increment. Load and the corresponding deflections and strains were measured upto ultimate stage.

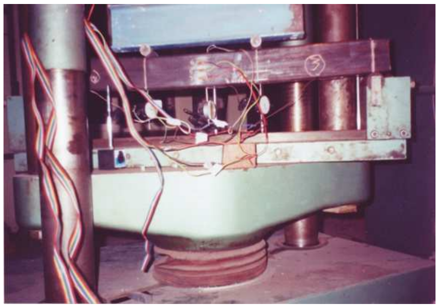


Figure 1 Test set up

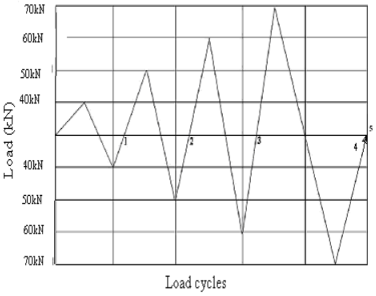


Figure 2 Cyclic loading diagram

2.4 Test On Cyclic Reversal Load

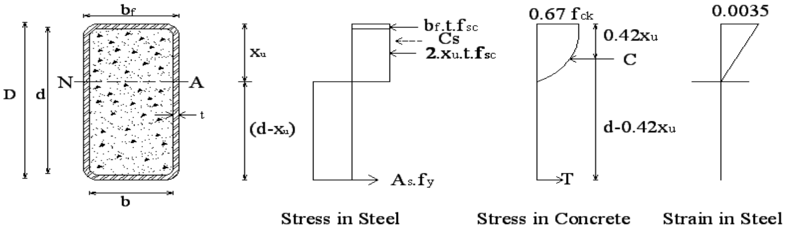
A total of nine specimens consisting of three hollow steel specimens and six Concrete-Filled Steel Tube beam specimens (CFSTs) consisting of three RHS in-filled with normal mix concrete and fly ash concrete specimens were casted and tested. The sizes of RHS sections were selected as 100 × 50 × 3.2 mm. The length of the specimen was 1.2 m. They are summarized in Table 2. The 400 kN capacity UTM (Universal Testing Machine) was used to perform the test. Each specimen was subjected to cyclic reversible bending. The test procedure of cyclic load is described below.

The test specimen was arranged in a simply supported condition. The load was applied by two-point method at one-third distance of the span of the specimen. The load was applied gradually through a jack at an increment of 5kN. In the first cycle, load was applied to a maximum of 40kN. Then the specimen was unloaded with a decrement load of 5kN. The load was brought to zero. Afterwards the specimen was turned over and arranged again in the position. Then cyclic test was performed as described above. Thus one complete cycle of loading and unloading was performed .In second, third, fourth and fifth cycles, the maximum load of each cycle was 50kN, 60kN, 70kN and 80kN respectively. Deflectometers were placed under the loading point and the centre (midspan) of the specimen to measure the deflections. Strain gauges were also used to measure the strain values. These are fixed at the centre (midspan) of the beam specimen and in the top and at the bottom faces of the beam specimen. The readings of the deflectometer and the strain gauge were recorded. From the deflection and strain values, Moment Vs Strain, Load Vs Deflection and Load Vs Strain behavior were studied. Figure 2 shows the cyclic loading arrangement.

3. ANALYTICAL STUDY

3.1 Ultimate moment of resistance based on strain compatibility at the interface (By Stress-Strain Block approach)

This analysis is based on the consideration of the hollow steel section for fully plastic at the time of failure. For the calculation of ultimate strength of concrete, the rectangular and semi parabolic stress block concept of the reinforced concrete design is adopted (By Stress-Strain block approach) according to Indian code IS456-2000.



Stress in Steel Stress in Concrete Strain in Steel

Figure3 Stress-Strain distribution in concrete-filled hollow steel section at Mu

where, b_f - External breadth of the section; b - Internal breadth of the section; D -External depth of the section; d - Internal depth of the section; t - Thickness of steel section; xu - Depth of neutral axis; f_{ck} - Characteristic strength of concrete; f_y - Yield strength of steel tube; f_{sc} -compressive stress on the extreme compression fiber of the tube; C_c-compressive force in concrete;C_s-Compressive force in steel, C-total compressive force;T-Total tensile force in tension flange of steel.

This is based on full plastic stress distribution in steel. A uniform compressive stress is assumed for concrete. Since the above consideration is approximate, an accurate model developed in the present investigation based on the stress block of IS: 456-2000. In addition to the usual assumptions of flexural theory, the following is assumed.

1. Initially plane sections remain plain after bending and normal to neutral plane.
2. At ultimate stage, steel in tension zone is subjected to yield stress of f_y.
3. The compressive stress on the extreme compression fiber of the tube is $f_{sc}=0.9f_y$.
4. At ultimate stage of bending the failure of the concrete deemes to have been reached, when the extreme fiber compressive stress ε_{cu} reaches 0.0035.
5. The maximum compressive strength of the concrete is assumed to be 0.67times of laboratory characteristic compressive strength $(\frac{2}{3}\ f_{ck})$.

6. The contribution of concrete in tension zone is ignored.

the ultimate moment of resistance can be obtained by taking moments about the tension flange of the composite section and the ultimate moment of resistance can be calculated using the equation 4.12,

$$M_u = 0.545\ f_{ck}\ b\ \ x_u(d - 0.42\ x_u) + f_{sc}\ A_{sc}\left(D - {}^{x_u}\!/_{2}\right) \quad \text{------ (1)}$$

3.2 Finite Element Analysis of the Flexural Behaviour of Hollow Steel and Concrete-Filled Beams

Material properties used for the steel and the concrete in the Finite Element Analysis are taken from the results of material testing. The average stress-strain curve for linear materials of the steel RHS and SHS tubes used in this model was determined by idealization from the tensile coupon tests. An elastic-perfectly plastic model was used. The stress-strain curve for concrete material provided by the ANSYS is linear. The boundary conditions were applied correctly, at support located at 100mm from end. At support nodal translations are restrained along all axes and rotations about x axis only permitted. A figure 3 shows the FEA Concrete-filled Beam model with boundary condition.

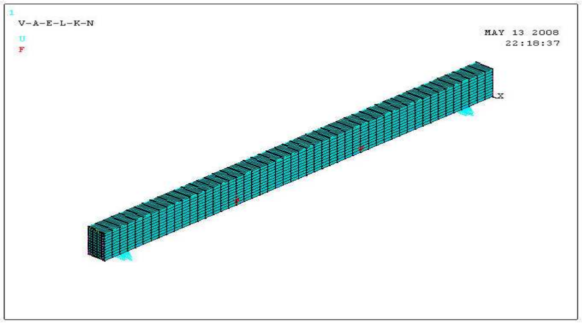


Figure 4 FEA Concrete-filled Beam model with boundary condition

The hollow steel is modeled by shell 43 elements. The shell 43 is well suited to model non-linear, flat or warped, thin to moderately thick shell structures. In concrete filled steel tubular sections the concrete core is meshed by three-dimensional solid concrete (solid 65) element. The model of the beam is presented in the Figures 4 for concrete filled section. The model presented in the figure is global co-ordinate system represented in x, y and z-axes. The span of the beam is 1200 mm. A static linear analysis has been conducted .A reasonably fine mesh of 50 mm is adopted for mesh modeling of the steel shell and the concrete core. It is assumed that the strain compatibility exists at the steel-concrete interface.

4. RESULT AND DISCUSSION

4.1 Load Vs Deflection

Figure 5 presents the Load Vs Deflection behaviour of hollow steel section and hollow steel section filled with normal mix concrete, fly ash concrete, quarry waste concrete and low strength concrete. Both rectangular section and square section are taken into consideration. From the above figure it is observed that the initial stiffness increases due to the infill materials. The increase in stiffness in the case of normal mix concrete, fly ash concrete, quarry waste concrete is about 3 times more than that of the hollow steel sections. Even in low strength concrete, the initial stiffness increases by 2.25 times. From the Figure 5 it can be seen that in the case of normal mix concrete, fly ash concrete, quarry waste concrete increases the loads with slight increasing the deflection whereas in low strength concrete the increase in the deflection with reducing load is noticeable. This strength and deflection mainly depend on the strength of filler materials. The Figures 5 shows that concrete-filled beams yield load and the ultimate load is increased when compared to hollow steel specimens. It is also observed that in specimens filled with low strength concrete, only a marginal increase is observed.

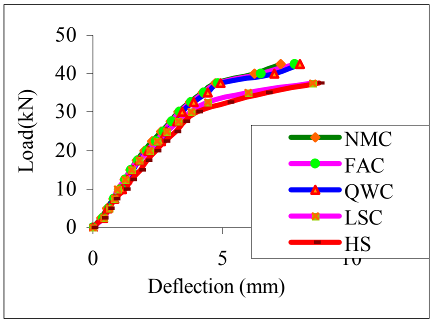


Figure 5 Load Vs Deflection

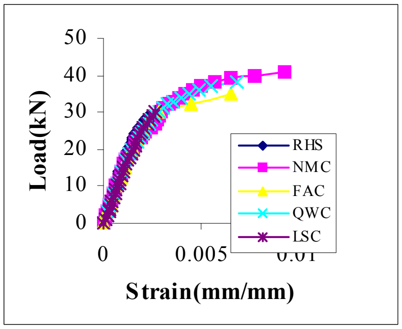


Figure 6 Tensile Strain

4.2 Load Vs Tensile Strain

In Figure 6 present tensile strains against load for different flexural members under each configuration of rectangular and square sections. Once again for concrete-filled specimens ultimate range and stiffness is noticeable although full curve is not available due to an early peeling of strain gauges. For all the specimens yield strain values are within the limits of 0.002 to 0.003. The Load Vs Strain plots in Figure 6 show the strain readings of hollow steel sections and their premature failure due to less stiffness. Its strain non-linearity gests start at 75% of its ultimate load value. From the above figures of Load Vs Deflection curves it can be observed that the stiffer curves of composite beams filled with different materials (NMC, FAC and QWC). In-case of in-filled sections filled with normal mix concrete, fly ash concrete and quarry waste concrete its strain non-linearity gets starts at 85% of its ultimate load value. For low strength concrete it strain non-linearity gets starts at 80% of its ultimate load value. Improved performance of the tensile concrete is due to the strength of filler materials.

4.3 Comparison of Moment Carrying Capacities

4.3.1 Moment Carrying Capacity of Hollow Steel Beams

The details of the RHS beam test specimen and its corresponding moments are presented in Table 5. A comparison of experimentally observed moment carrying capacity of the hollow steel section beams with plastic moment carrying capacity calculated with the Indian standard codal provisions is shown in Table 5. It is observed that the experimental values reasonably agree with the plastic moment capacity.

Table 5 Moment carrying capacities of Hollow steel Beams

Sl.No	**Specimen Label**	**Sectional Dimensions DxBxt (mm)**	**f_y (MPa)**	**$M_{u(exp)}$ (kN m)**	**M_{Plas} (kN m)**	**$M_{u(exp)}$/ M_{Plas}**
1	RHS-1	100×50×3.2	338	10.56	10.00	1.056
2	RHS-2	100×50×3.2	338	10.40	10.00	1.04
3	RHS-3	100×50×3.2	338	10.40	10.00	1.04

4.3.2 Moment Carrying Capacity of Concrete-filled Beams

Twelve RHS beams filled with normal mix concrete, fly ash concrete, quarry waste concrete and low strength concrete members were tested under flexure. The detailed test results of its experimental and theoretical test values and its comparisons are presented in Table 6.Theoretical ultimate moment capacity of concrete-filled beams is calculated based on the analytical expression derived (Eqn.1)in the present work and it is presented in Table 6 along with the experimental moments. It can be seen that analytical expression closely predicts experimental ultimate moment carrying capacity.

Table 6 Moment carrying capacities for concrete-filled Beams

Sl.No	**Specimen Label**	**Sectional Dimensions DxBxt (mm)**	**$M_{u(exp)}$ (kN m)**	**$M_{u(the)}$ (kN m)**	**$M_{u(exp)}$ /$M_{u(the)}$**
1	NMC-R-1	100×50×3.2	13.86	13.21	1.05
2	NMC-R-2	100×50×3.2	13.70	13.21	1.04
3	NMC-R-3	100×50×3.2	13.70	13.21	1.04
4	FAC–R-1	100×50×3.2	13.20	12.97	1.02
5	FAC–R-2	100×50×3.2	12.87	12.97	0.99
6	FAC–R-3	100×50×3.2	13.04	12.97	1.005
7	QWC-R-1	100×50×3.2	13.04	12.64	1.03
8	QWC-R-2	100×50×3.2	12.87	12.64	1.02
9	QWC-R-3	100×50×3.2	12.71	12.64	1.006

10	LSC-R-1	100×50×3.2	10.73	11.29	0.95
11	LSC-R-2	100×50×3.2	10.89	11.29	0.96
12	LSC-R-3	100×50×3.2	10.56	11.29	0.94

It is observed that when compared to hollow steel section, in the beams filled with normal mix concrete, fly ash concrete and quarry waste concrete there is an increase in moment carrying capacity. But in the case of specimen filled with low strength concrete only a marginal increase of moment carrying capacity is observed.

4.3.3 Moment Carrying Capacities of standards

A comparison of the moment carrying capacity between various standard codes and experimental results are shown in Table 7. The partial safety factor was not considered during comparison. It is observed that the codal equations of EC 4:1994, ACI-318:1989 and AISC-LRFD: 1999 considerably underestimate the experimentally obtained moment capacities of the specimens. The Eurocode(EC4) yield better predictions of the moment carrying capacity than ACI and AISC codes**.** It is observed that beam specimen filled with normal mix concrete, fly-ash concrete and Quarry waste concrete behaves in a similar manner. From the above results it is seen that the flexural capacity of tube is increased when it is filled with concrete materials and this increase depends on the strength of the filled materials.

Table 7Comparison of Moment Carrying Capacity between Experimental results and Standard Codes

Sl. No	**Specimen Label**	**$M_{u(exp)}$ (kN m)**	**EC4**		**ACI**		**AISC**	
			M_{EC4} (kN m)	**M_{EC4} /$M_{u(exp)}$**	**M_{AIJ} (kN m)**	**M_{ACI} /$M_{u(exp)}$**	**M_{AISC} (kN m)**	**M_{AISC} / $M_{u(exp)}$**
1	NMC-R-1	13.86	10.10	0.73	10.03	0.72	9.65	0.70
2	NMC-R-2	13.70	10.10	0.74	10.03	0.73	9.65	0.70
3	NMC-R-3	13.70	10.10	0.74	10.03	0.73	9.65	0.70
4	FAC-R-1	13.20	10.03	0.76	10.00	0.76	9.65	0.73
5	FAC-R-2	12.87	10.03	0.78	10.00	0.78	9.65	0.75
6	FAC-R-3	13.04	10.03	0.77	10.00	0.77	9.65	0.74
7	QWC-R-1	13.04	9.95	0.76	9.90	0.76	9.65	0.74

8	QWC-R-1	12.87	9.95	0.77	10.30	0.77	9.65	0.75
9	QWC-R-3	12.71	9.95	0.78	9.90	0.78	9.65	0.76
10	LSC-R-1	10.72	9.70	0.90	9.70	0.90	9.65	0.90
11	LSC-R-2	10.89	9.70	0.89	9.70	0.90	9.65	0.89
12	LSC-R-3	10.56	9.70	0.92	9.70	0.92	9.65	0.91

4.4 COMPARISON OF FINITE ELEMENT ANALYSIS REULTS WITH EXPERIMENTAL RESULTS

The loads Vs deflection response of the composite beams are plotted in the Figure 7. From the Figure7 of rectangular hollow steel section in filled with concrete, FEA yield load value is 5% and 10% is higher when compared to experimental yield load value. In general it has been observed that the difference between the predicted and observed values increases with increase in load. The higher values predicted by FEA may be attributed to the following limitations in the present analysis. In the present analysis, compatibility of steel and concrete at the interface during loading has been assumed. However, a more realistic approach is use interface elements with appropriate material model. Also elastic perfectly plastic behaviour has been used to model the behaviour of steel and ANSYS provide linear stress-strain behaviour for concrete. It is known that concrete develops cracks at higher load and crushes as well. Therefore the consideration of this aspect is required in modeling the behaviour of composite section. Analysis also carried out for a RHS without filling. The Load-deflection response of the comparison is presented in Figures 7. For the hollow steel section, a Finite Element result agrees well with the experimental results until the ultimate load is reached. After the ultimate load the experimental results showed sharp loss of stiffness and ductility which is due to the local buckling. While in comparison the analysis indicates the beam is stiffer than that observed in the experiments. Figure 8 shows the FEA diagram of filled beam.

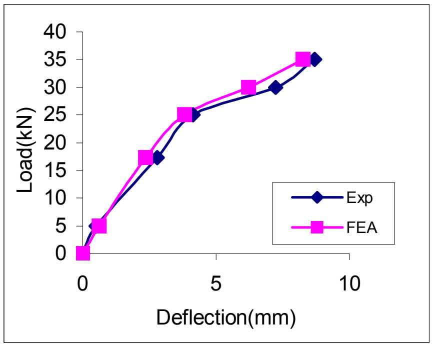


Figure 7 FEA and Experimental Load Vs Deflection

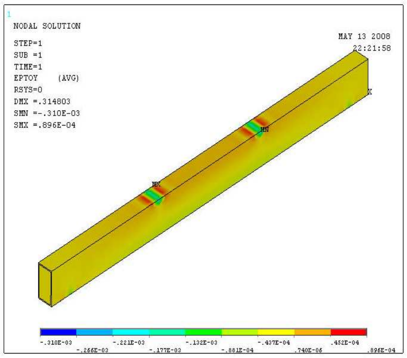
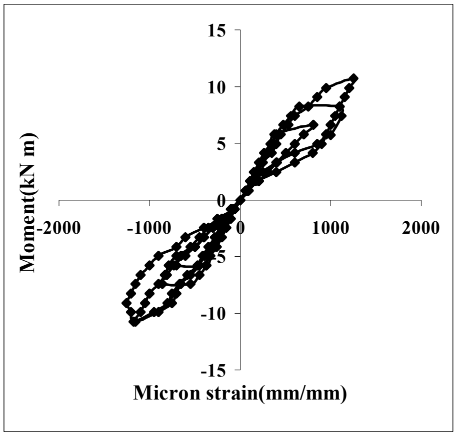


Figure 8 FEA Strain Contour of Concrete-filled RHS Beam

4.5 Hysteretic Behaviour

4.5.1 Moment Vs Strain hysteretic Behaviour

The typical variation of moment carrying capacity with respect to strain for hollow steel and concrete-filled beams is shown in Figures 9. It is observed that Moment Vs Strain behaviour of tension flange of rectangular section filled with normal mix concrete, moment carrying capacity increases upto four cycles and thereafter it remains constant. The value of capacity beyond four cycles is slowly reduced. From the above observation it is observed that upto four to five cycles the moment carrying capacity increases after that once the local buckling takes place suddenly reduced the moment carrying capacity. The yield strain values are within 0.002 to 0.003.



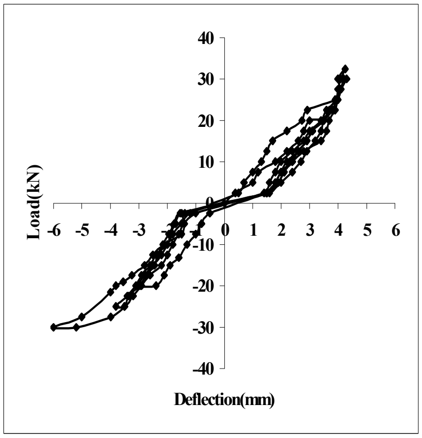


Figure 9 Cyclic Moment Vs Strain Figure10 Cyclic Load Vs.Load Vs Deflection

4.5.2 Load Vs deflection hysteretic Behaviour

The deflection variation for the rectangular section filled with normal mix concrete is presented in Figure 10. It can be seen that deflections are generally positive. The beam could not be deflected upward due to the resistance of the reversal load. The variation is uniform upto four cycles and after that due to reducing capacity the deflection become negative. It is observed that the increase of deformation is very difficult to control just after the peak, although the load is constant at certain loading level. Accordingly, the stiffness decreases rapidly in concrete-filled beams after it attains the ultimate load.

4.6 Energy Absorption Capacity

The concrete-filled specimens have showed significantly higher energy absorption capacity when compared to hollow steel beam specimens. The increased in energy absorption capacity of rectangular section filled with normal concrete and fly ash concrete is 1.53 times and 1.49 times when compared to hollow steel section.

5. CONCLUSION

1. Beam specimens filled with normal mix concrete, fly ash concrete, quarry waste concrete and low strength concrete behave flexurally and are capable of developing the full flexural strength of their sections.
2. The test results show that there is an increase of 28%, 27% and 25% in the moment carrying capacity of normal mix concrete, fly ash concrete and quarry waste concrete respectively when compared to hollow steel section.
3. The theoretical expression developed for the calculation of moment of resistance based on Indian code stress block (Equation 1) closely predicts the flexural behaviour.
4. The existing international codal formulae (without safety factor) under-estimates the moment carrying capacity of the concrete filled beams.
5. Concrete filling increases the residual load capacity of thin RHS and SHS beams to resist cyclic load especially when the transverse displacement increases.
6. Concrete filling increases the energy absorption especially for hollow steel sections.

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NOTATIONS:

Asc	Area of steel tube under compression.
b_f	External breath of the section
b	Internal breath of the section
D	External depth of the section
d	Internal depth of the section
t	Thickness of steel section
xu	Depth of neutral axis
Z , Z_p , W_{pa}	Plastic section modulus of the hollow steel tube
W_{ps}	Plastic section modului of the reinforcement
W_{pa} , Z_{con}	Plastic section modului of the concrete part of section
	(for the calculation of W_{pc} the concrete is assumed to be uncracked)
f_c	Concrete cylinder strength
fc_d	Design strength for the concrete
f_{ck}	Characteristic strength of concrete
f_{cu}	Characteristic 28-day cube strength of concrete
f_{yr}	Yield strength of reinforcement steel
f_y	Yield strength of steel tube
f_{yd}	Design strength for the structural steel
f_{sd}	Design strength for the reinforcement