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Behavior of Reinforced Concrete Beams Provided with Hybrid Ferro Fiber Concrete (HFFC) at Critical Sections

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Abstract - **This paper presents the behavior of reinforced concrete beams provided with Hybrid ferro fiber concrete (HFFC) at critical sections. A total of 24 simply supported reinforced concrete beams, with Hybrid Ferro Fiber Concrete (HFFC) at critical sections were tested in flexure. The tension reinforcement in the beams was varied to give two types of basic behavior viz., under reinforced and over reinforced. The Hybrid Ferro Fiber Concrete at critical sections of all category beams enabled the reinforced concrete sections to fail in ductile manner.**

Keywords – Reinforcing Index, Confinement Index, Ductility, Strain Rate of Loading, Specific Surface factor, Moment-Curvature, aspect ratio, Weight fraction.

I. INTRODUCTION

In the case of highly indeterminate structures, full redistribution of moments cannot be ensured due to insufficient rotational capacity of sections. The requirement of rotation capacity of reinforced concrete section increases with the indeterminacy of the structure. The beams provided with larger percentages of longitudinal steel do not give sufficient warning before failure, as they fail in brittle manner. To avoid this brittle failure, the deformability of reinforced concrete sections has to be improved. At present this can be achieved by confining concrete in steel binders such as ties in columns and stirrups in beams. The previous investigations [5] revealed that the quantity of stirrup reinforcement provided in excess of the quantity that is required to prevent shear failure could only provide the benefits of confinement. There is a limitation to the quantity of confinement provided by the stirrups at critical sections due to practical restriction over the spacing of stirrups. In the recent investigations, the combination of ferrocement, fiber reinforced concrete and lateral ties termed as Hybrid ferro fiber concrete (HFFC) [10] has been suggested as an alternative to Overcome the problem of limited confinement offered by the ties. This paper presents an experimental investigation on the behavior of simply supported RC beams with HFFC at critical section under flexure.

II. EXPERIMENTAL PROGRAMME

A. *Scheme of Experimental Work*

The experimental program consisted of casting and testing of 24 simply supported beams of size 120 mm x 200 mm x 2100 mm, with Hybrid ferro fiber concrete (HFFC) at critical section (the section at which the likely formation of plastic hinge, i.e., flexure zone) to study the behavior under flexure. The 24 beams consisted of two groups of 12 beams. In the first group the HFFC was made with 0.5% volume fraction fibers (RI =1.23) and in the second group with 1.0% volume fraction fibers (RI =2.46). The longitudinal reinforcement in each group was varied to give two sets of beams, viz., under reinforced (U) and over reinforced (O) beams. In each set the Specific surface factor (S_f) was the only variable, which controls the behavior of ferrocement. The Specific surface factor was varied by varying the number of layers of mesh provided at the critical section. Thus each specimen was designated by the type of the beam, the volume fraction of the fiber and the number of layers of mesh i.e., specimen whose designation is UA 02, stands for under reinforced concrete beam with HFFC at critical section made with 'A' type fiber reinforced concrete i.e., 0.5% volume fraction FRC and ferrocement shell provided with 2 layers of mesh. Table .1 gives the details of Hybrid ferro fiber concrete beams tested.

TABLE.1. DETAILS OF SIMPLY SUPPORTED RECTANGULAR BEAMS TESTED

S. No.	Desig-nation of Beam	Reinforcement Details			Stirrup Steel			Fiber Details			G.I.Wire Mesh Details			f_{cm} MPa	f_{ck} (MPa)	S_f
		Dia. mm	No. of Bar	f_y MPa	Dia mm	Spacing mm	f_y MPa	Dia. in (mm)	f_y MPa	RI	Dia. in (mm)	Spacing (mm)	f_y MPa			
1.	U0	10	2	430	6	80	405	-	-	-	-	-	-	-	49.11	-
2.	UA0	10	2	430	6	80	405	0.45	288	1.23	-	-	-	-	46.73	-
3.	UA1	10	2	430	6	80	405	0.45	288	1.23	0.48	2.4	288	37.86	45.35	2.94
4.	UA2	10	2	430	6	80	405	0.45	288	1.23	0.48	2.4	288	37.86	43.70	5.88
5.	UA3	10	2	430	6	80	405	0.45	288	1.23	0.48	2.4	288	37.86	43.70	8.82
6.	UA4	10	2	430	6	80	405	0.45	288	1.23	0.48	2.4	288	37.86	45.35	11.76
7.	U2	10	2	430	6	80	405	-	-	-	-	-	-	-	49.11	-
8.	UB0	10	2	430	6	80	405	0.45	288	2.46	0.48	-	-	-	47.06	-
9.	UB1	10	2	430	6	80	405	0.45	288	2.46	0.48	2.4	288	20	47.06	5.56
10.	UB2	10	2	430	6	80	405	0.45	288	2.46	0.48	2.4	288	20	50.69	11.13
11.	UB3	10	2	430	6	80	405	0.45	288	2.46	0.48	2.4	288	20	46.40	16.70
12.	UB4	10	2	430	6	80	405	0.45	288	2.46	0.48	2.4	288	20	43.70	22.27
13.	O1	10 16	1 3	430 569	6	80	405	-	-	-	-	-	-	-	43.00	-
14.	OA0	10 16	1 3	430 569	6	80	405	0.45	301	1.23	-	-	-	-	48.0	-
15.	OA1	10 16	1 3	430 569	6	80	405	0.45	301	1.23	0.48	2.4	288	23.85	48.51	4.66
16.	OA2	10 16	1 3	430 569	6	80	405	0.45	301	1.23	0.48	2.4	288	23.85	38.76	9.32
17.	OA3	10 16	1 3	430 569	6	80	405	0.45	301	1.23	0.48	2.4	288	23.85	43.90	13.98
18.	OA4	10 16	1 3	430 569	6	80	405	0.45	301	0	0.48	2.4	288	23.85	43.00	18.64
19.	O2	10 16	1 3	430 569	6	80	405	-	-	-	-	-	-	-	45.28	-
20.	OB0	10 16	1 3	430 569	6	80	405	0.45	301	2.46	-	-	-	-	53.26	-
21.	OB1	10 16	1 3	430 569	6	80	405	0.45	301	2.46	0.48	2.4	288	23.85	52.10	4.66
22.	OB2	10 16	1 3	430 569	6	80	405	0.45	301	2.46	0.48	2.4	288	23.85	52.10	9.32
23.	OB3	10 16	1 3	430 569	6	80	405	0.45	301	2.46	0.48	2.4	288	23.85	52.10	13.98
24.	OB4	10 16	1 3	430 569	6	80	405	0.45	301	2.46	0.48	2.4	288	23.85	52.10	18.64

Fig. 1.Reinforcement cage with wrapped mesh at critical zone

B. *Materials Used*

The galvanized woven wire mesh of square grid fabric was used in ferrocement. The stirrups and longitudinal steel used in beams were made of mild steel and tor steel respectively. The cement used was OPC of 53grade conforming to IS 12269 [3]. Machine crushed hard granite chips passing through 12.5 mm IS sieve and retained on 4.75 mm IS sieve was used as coarse aggregate throughout the work. River sand procured locally was used for fine aggregate. For the ferrocement shell, fine aggregate passing 1.18 mm IS sieve was used for the concrete fine aggregate passing 2.36 mm IS sieve was used. The mix proportion for concrete used was 1:1.6:2.5 with water-cement ratio of 0.45. The mortar used for ferrocement shell has the mix proportion of one part

TABLE.2. EXPERIMENTAL RESULTS OF SIMPLY SUPPORTED BEAMS TESTED

Sl.No.	Designation of beam	S_f	α	β	$\varepsilon_c(10^{-6})$	$\varepsilon_s(10^{-6})$	$\phi_u(10^{-6})$	$\phi_y(10^{-6})$	δ	γ	η
1	2	3	4	5	6	7	8	9	10	11	12
1	U1	-	0.0950	0.0541	2130	22080	138	13	4.98	1.00	1.00
2	UA0	-	0.0972	0.0591	2980	23460	151	15	4.75	1.023	1.094
3	UA1	2.94	0.1038	0.0625	3200	24560	163	20	4.32	1.093	1.181
4	UA2	5.88	0.1063	0.0704	4000	25000	175	25	3.93	1.118	1.268
5	UA3	8.83	0.1134	0.0729	4980	25500	179	30	5.10	1.193	1.297
6	UA4	11.76	0.1179	0.0753	5100	26750	187	40	4.10	1.241	1.355
7	U2	-	0.0950	0.0575	2230	22480	145	15	4.94	1.00	1.00
8	UB0	-	0.1008	0.0605	3740	25860	174	20	3.98	1.061	1.2
9	UB1	5.56	0.1018	0.0634	4000	28780	192	25	4.68	1.071	1.324
10	UB2	11.13	0.1079	0.0716	4900	32510	220	32	3.30	1.135	1.517
11	UB3	16.70	0.1116	0.0738	5750	34510	236	45	5.00	1.174	1.627
12	UB4	22.27	0.1165	0.0756	6250	26850	200	52	4.70	1.226	1.379
13	O1	0	0.283	0.118	5140	1160	38.45	14.6	1.83	1.0	1.0
14	OA0	0	0.307	0.125	5343	2895	50.23	24	1.64	1.084	1.306
15	OA1	4.66	0.312	0.125	5925	6375	75.00	28.5	1.89	1.102	1.9505
16	OA2	9.32	0.320	0.162	10500	7500	109.00	32	1.83	1.130	2.834
17	OA3	13.98	0.323	0.189	11500	8900	124.39	40	3.35	1.140	3.23
18	OA4	18.64	0.343	0.234	12850	9650	137.19	46	3.55	1.212	3.56
19	O2	0	0.283	0.118	5080	1260	38.45	14.8	1.94	1.0	1.0
20	OB0	0	0.308	0.138	5510	1423	42.27	27	4.82	1.088	1.099
21	OB1	4.66	0.318	0.201	5757	1636	48.00	30	4.10	1.124	1.248
22	OB2	9.32	0.325	0.221	18813	2135	136.00	36	1.51	1.148	3.53
23	OB3	13.98	0.352	0.237	26408	2604	176.23	43	3.70	1.243	4.58
24	OB4	18.64	0.369	0.242	26420	2822	184.88	50	4.53	1.304	4.808

of cement and two parts of sand (i.e., 1:2) with water - cement ratio of 0.5.

C. Preparation of Specimens

After preparing the reinforcement cages for beams, galvanized iron woven wire meshes of predetermined number of layers were wrapped over the stirrups in the flexure zone (critical zone), over a length of 450 mm, i.e., 225 mm from center of the beam on each side. The length of critical zone was determined based on plastic hinge length criterion for confined beams proposed by Baker [1]. The mesh was wrapped and tied on three sides (i.e., bottom and two sides) of reinforcement cage over the stirrups and kept open at the top to facilitate the concrete to be placed during casting (Fig.1). The prepared reinforcement cage was kept on cover blocks in the mould. The fiber reinforced concrete was placed in The critical zone of the beam (i.e., central 450 mm length) except in the side covers in the mesh zone (critical zone) i.e., the gap between the mould and the Reinforcement cage. The remaining length of the beam was filled with the same concrete as that provided in the critical zone without fibers. The cement mortar was placed in the side covers of the mesh zone. The concrete was placed in two layers and each layer was compacted thoroughly by needle vibrator. After placing the concrete the top edges of mesh were overlapped and stitched tightly. The cement mortar was placed on the stitched mesh and the whole beam was compacted with platform vibrator. The beam moulds were stripped 24 hours after concreting and the specimens were covered with wet gunny bags for curing. After curing the specimens were white washed before testing.

D. Testing

The beams were tested under symmetrical two point loading (with a constant moment zone of 300 mm) on a simply supported span of 1900 mm. Tinius Olsen Testing Machine of 1810 KN capacity was used for testing the beams. Strain control rate of loading was adopted to obtain the complete profile of load deflection behavior especially in the post-ultimate range. Specially fabricated curvature meters were used to measure the curvature in the critical sections. These curvature meters consisted of rectangular frame made out of 12 mm square mild steel bar. Each frame can be fixed to the beam by means of two screws of 6 mm diameter on either side of the beam, leaving clearance on each side. Two dial gages of 0.002 mm least count was fixed between two successive rectangular frames, one at the top and the other at bottom. The deformations indicated by the dial gages divided by the gage length of 200 mm gave the strains at that level. From top and bottom strains the average curvatures were calculated. Deflections were measured at the two load points, the midpoint of the beam by using the dial gages with a least count of 0.01 mm. The sketch of the test set-up and the curvature meters is given in Fig.2 and the photograph of the beam with curvature meters attachment is shown in Fig.3. Also the width of cracks was measured both in the mesh zone and outside the mesh zone. During the test the load, the six dial gage readings of the curvature meters, three-deflection meter readings were recorded at every half-minute interval. The test was continued until the load had fallen to 0.85 times the ultimate load observed. From the recorded readings, the load-deflection diagrams were drawn. The representative diagrams are presented in Fig. 4. The experimental and theoretical moment curvature diagrams of a typical RC and HFFC section are shown in Fig.5. The experimental results are presented in Table.2. A few of the photographs of tested beams are shown in Fig.6.

III. BEHAVIOUR OF HFFC SIMPLY SUPPORTED BEAMS

A. Under Reinforced Beams

In all the beams, both reinforced (RC) and HFFC, of the under reinforced series, visible cracks developed at 60% to 70% of the ultimate load of the RC beam. The visible cracks propagated into the compression zone slowly, with simultaneous widening of cracks. Thus failure was initiated by yielding of steel. The behavior HFFC beams were similar to the behavior of RC beams up to about 80% of the ultimate load of the corresponding RC beams. For beams with high specific surface factor, first flexural crack formed outside the mesh zone while for the beams with low specific surface factor, the visible cracks occurred in the constant moment zone. In RC beams, as the load increases to a value near their maximum strength, the crushing of concrete was observed at the compression face in the middle of the constant moment region. The crushing of the core within the stirrups and

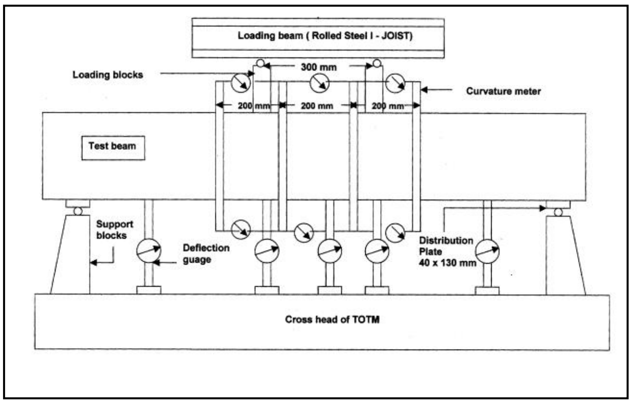


Fig.2.Test Set up of Simply Supported beam

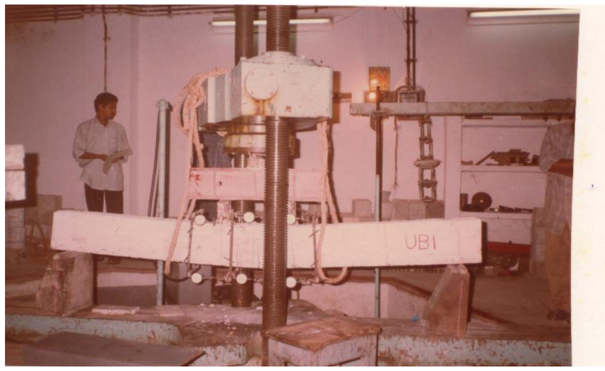


Fig.3.Photograph with the curvature meter

Compression steel began after the loss of cover above the compression steel through spalling. With further increase in beam deflection, the load decreased, accompanied by increased depth of spalling. The crushing zone could not be observed or it is less within the mesh zone whenever ferrocement shell in provided as an additional confinement. In beams, with less Specific Surface Factor of the ferrocement shell, the crushing of concrete was observed with the bulging of shell in the top compression face. This may be attributed to the fact that in the presence of continuously distributed ferrocement and the randomly distributed fiber in the fiber reinforced concrete; the tensile strain capacity of the concrete is improved, which prevented de-bonding with the reinforcement. This observation is in agreement with Ramouldi and Batson [6]. In all the 12 beams of under reinforced category tested, the load dropped gradually and slowly with increased deflections in the post ultimate stage. This indicates that the ductility is improved without much increase in the load along with increase in deflections. In fact, in some of beams the load transfer mechanism became unstable in adjusting to the large curvatures developed. Even in the case of beams where the load has shown a decreasing tendency, the rate of decrease was almost negligible and tests could not be continued until the load dropped to 85% of ultimate load in the descending portion.

B. Over Reinforced Beams

The RC beams in the over reinforced series were designed for over reinforced type of failure. The failure in RC beams was initiated by spalling of concrete in the compression zone. At the time of occurrence of spalling the cracks propagated up to half to two third depth of the beam. The load continued to increase slowly with increased deflections. In the case of beams without HFFC in the middle zone, the crushing continued to increase with increased deflections. In case of beams with HFFC as additional confinement, the sudden reduction in compressive force because of spalling of the concrete was to some extent compensated by the increased strength of concrete. This has made the beam to behave more plastically and deformability of the beam was improved.

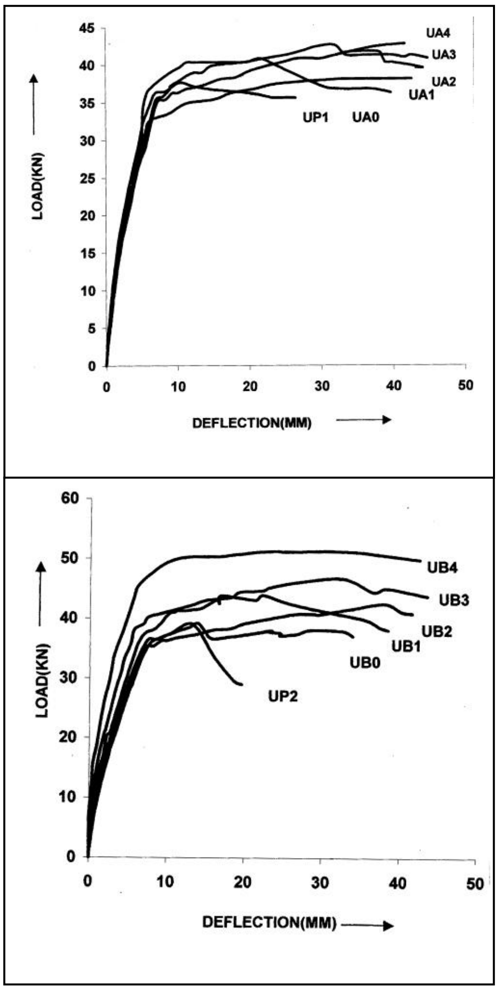
Also in the case of over reinforced beam category, with HFFC as additional confinement the load deflection diagrams obtained are also showing flat region, which indicates that the provision of HFFC as additional confinement results in additional ductility of beams.

IV. EFFECT OF HFFC ON THE STRENGTH AND DEFORMATION

A. *Ultimate Moments*

The specific surface factor (S_f) versus the ultimate moment carrying capacity of each beam is presented in column 4 of table.2. A critical study of the values indicated that as specific surface factor increases the ultimate moment capacity for given reinforcing index (RI) increases in all types of beams. This may be due to (a) the increase in ultimate strain capacity of concrete as indicated in column 6 of table.2, (b) the increase in strain in steel (column 7 of table.2) at ultimate stage due to HFFC additional confinement leading to increase in the value of tensile force and (c) the reduced depth of neutral axis. In addition to these reasons, confinement due to combination of ferrocement, fiber reinforced concrete and stirrups, which is termed as HFFC confinement improved the strength of concrete.

The improvement in ultimate moment capacity however depends upon the percentage of longitudinal



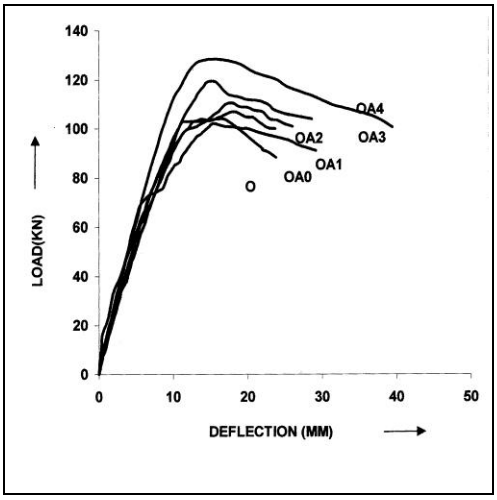


Fig. 4.Typical Load deflection curves

steel. The increase is proportional to the increase in the quantity of longitudinal steel. In the case of under reinforced beams, the increase in moments is in the range of 2% to 30%. In the case of over reinforced beams, the improvement is in the range of 8 to 20%. It was also observed that, not only the strength has improved but also the nature of failure changed from brittle failure to a ductile failure with the increase in the HFFC confinement especially in over reinforced beams.

B. *Moment at First Crack*

The load at first crack, and hence moment at first crack increased whenever the HFFC is present as additional confinement (Column 5 of Table 2). This may be because of increased tensile strain capacity of concrete due to presence of HFFC in critical region resulting in delaying of crack occurrence in concrete in flexure.

C. *Ultimate Strain in Concrete*

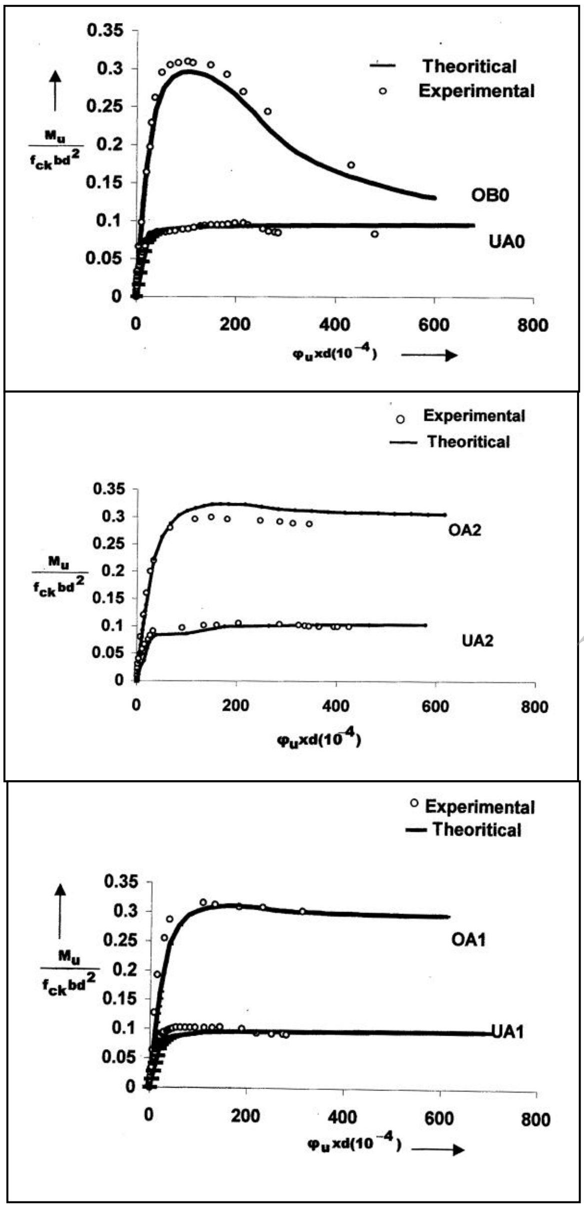
The experimental observation of strain in concrete at ultimate moment indicated that there is a very prominent effect of Specific Surface Factor on ultimate strain in concrete for a given reinforcing index (RI). As the Specific Surface Factor increases the ultimate strain in concrete for a given reinforcing index as indicated by the experimental values of strain given in column 6 of Table 2.

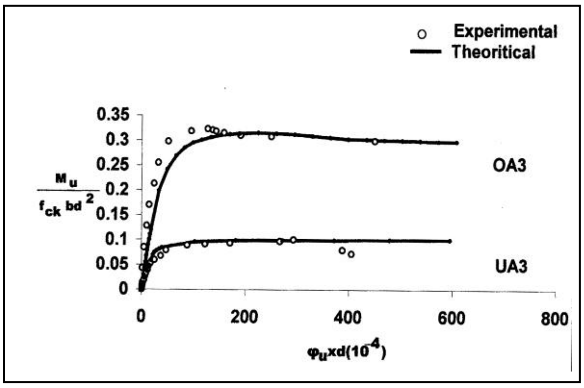
D. *Ultimate Strain in Steel*

The values of the strain in longitudinal steel at ultimate moment presented in column 7 of Table 2, indicated that the steel has yielded in beams with HFFC as additional confinement.

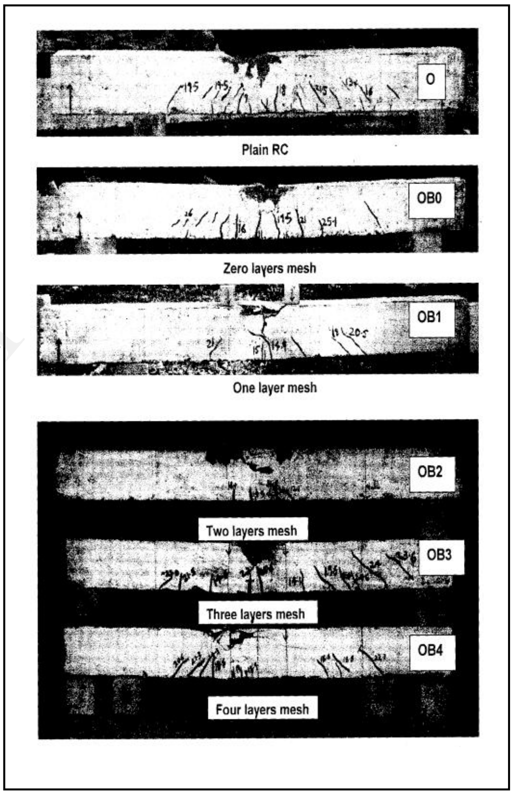
E. *Curvatures at Ultimate Moment*

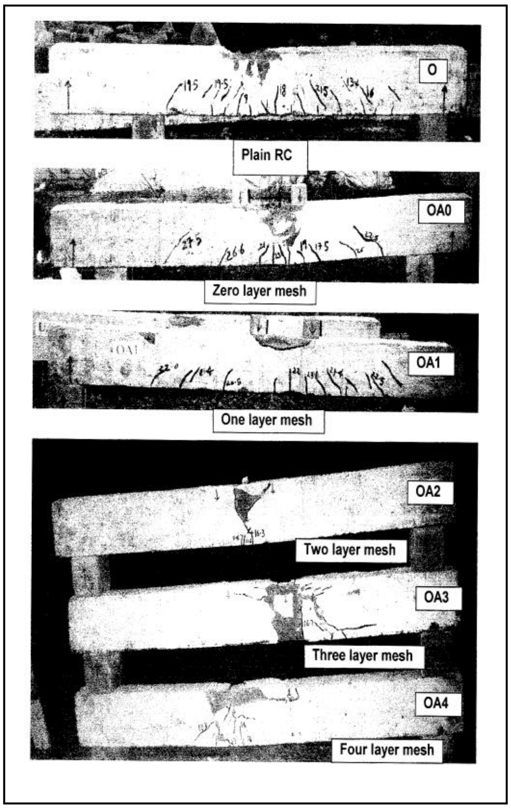
The ultimate curvatures increased with an increase in Specific Surface Factor of ferrocement shell for a given reinforcing index (RI) of fiber reinforced concrete as could be seen by a study of ultimate curvatures tabulated in column 8 of Table 2. The increase in curvature is represented by the ratio of ultimate curvature with HFFC to the ultimate curvature without HFFC as given in column 12 of Table 2. The increase in curvature of HFFC section over a stirrup confined RC section is due to two factors: (i) increase in failure strain in concrete due to effective confinement due to HFFC, and (ii) the reduction in depth in neutral axis due to large strains developed in the longitudinal steel with the additional HFFC confinement. Hence this seems to be sufficient experimental evidence to prove the necessary redistribution of moments can take place in the case of statically indeterminate structures, if the sections





Fig,5. Typical Moment Curvature diagrams of some beams





Fig, 6.Crack Patterns of some of the tested beams

are properly and adequately confined by HFFC at possible hinge occurrence.

F. Deflections Corresponding to the Service Load

The deflections corresponding to the service load, which is taken as two thirds of ultimate load are presented in column 10 of Table 2. These deflections for all beams are less than that deflections allowed [2] for simply supported beams as per IS 456 - 2000, which is 1/250 of span. This means that providing additional confinement with HFFC does not violate the limit state of serviceability of deflections.

G. Crack width at service Load

None of the beams exhibited crack width of more than the allowable crack width of 0.3 mm, as per IS 456 - 2000, at service load. The crack width measured outside the central HFFC zone, was more than the crack width measured inside the HFFC zone, but even they were less than the allowable limits at limit state of service. The cracks are finer in the HFFC zone when compared to the out side the central HFFC zone. Hence it can be stated that by providing the additional HFFC confinement to the beams, the limit state of service regarding the crack width has not been violated.

V. CONCLUSIONS

1. Provision of Hybrid Ferro Fiber Concrete (HFFC) improves the flexural behavior of reinforced concrete beams.
2. Over reinforced beams can be made to develop ductile (tension) failure by additional confinement of critical sections.
3. The provision of HFFC as an additional confinement increases the value of cracking moment of RC sections.
4. The post ultimate behavior of HFFC section resembles that of a steel section in that it has large deformation plateau.
5. The serviceability of HFFC structure will be as good as that of the corresponding RC structure, since up to 80 % load capacity, the behavior of HFFC section is similar to the concrete confined with stirrups alone.
6. In all beams with HFFC as additional confinement, the improvement in the moment carrying capacity is observed. The improvement is about 2% to 30% observed in both under reinforced and over reinforced beams.
7. The improvement in curvatures is observed in all beams irrespective of type of beam and these curvatures at ultimate are improved with HFFC additional confinement. The increase in ultimate curvature in under reinforced and over reinforced beams is about 200% and 300% respectively.

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NOTATIONS

b,D	=	Lateral dimensions of beam
f_y	=	Yield strength of longitudinal / tie / fiber mesh steel
f_{ck}	=	Concrete cube strength
f_m	=	Strength of mortar
M_u	=	Observed ultimate moment
M_{uo}	=	Observed ultimate moment for tie confined RC beam
M_{cr}	=	Moment at first crack
S_f	=	Specific surface factor
α	=	$\frac{M_u}{f_{ck}bd^2}$
β	=	$\frac{Mcr}{f_{ck}bd^2}$
γ	=	$\frac{M_u}{M_{uo}}$
η	=	$\frac{\varphi_u}{\varphi_{uo}}$
δ	=	Deflection at service
φ_u	=	Curvature at ultimate
φ_{uo}	=	Curvature at ultimate of tie Confined RC beam
φ_y	=	Curvature of yielding of steel
RI	=	Reinforcing index = $W_f \times \frac{l}{d}$
W_f	=	Weight fraction (Ratio of weight of fibers to the weight of concrete)
$\frac{l}{d}$	=	Aspect ratio of fiber