Flexural Behavior of Ferrocement Confined Reinforced Concrete (FCRC) Simply Supported Beams

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This paper presents the results of an experimental investigation carried out on Ferrocement Confined Reinforced Concrete (FCRC) beams. A total of 30 simply supported reinforced concrete beams, confined with ferrocement in addition to lateral stirrups at critical sections were tested in flexure. The confinement due to ferrocement enabled the RC sections with longitudinal steel above the balanced percentage to fail in a ductile manner.

LIST OF SYMBOLS

b, D	=	lateral dimensions of beam	α	=	$M_u / f_{ck} b d^2$
f_y	=	yield strength of longitudinal/ tie/ meshsteel (Table 2)	β	=	$M_{cr} / f_{ck} b d^2$
			γ	=	M_u / M_{uo}
f_{ck}	=	concrete cube strength	η	=	ϕ_u / ϕ_{uo}
f_{cm}	=	strength of mortar	δ	=	deflection at service
M_u	=	observed ultimate moment	ϕ_u	=	curvature at ultimate
M_{uo}	=	observed ultimate moment for tie confined RC beam	ϕ_y	=	curvature at yielding of steel
M_{cr}	=	moment at first crack	ϕ_{uo}	=	curvature at ultimate for tie confined concrete beam
S_f	=	specific surface factor [9]			

INTRODUCTION

The requirement of rotation capacity of Reinforced Concrete (RC) section increases with the degree of redundancy of structure. The beams provided with larger percentages of longitudinal tension steel near or above the balance percentage, do not give sufficient warning of failure therefore it exhibited brittle failure. Due to insufficient rotational capacity of such sections, full redistribution of moments cannot be ensured, especially in the case of highly indeterminate structures [1]. Hence, it becomes necessary to improve the deformable capacity of RC sections. This can be achieved by confining concrete in steel binders provided in the form of stirrups in beams and as ties in columns [1, 8, 15]. The investigations on tie confined concrete revealed that the quantity of stirrup reinforcement provided in excess of the quantity that is required to prevent shear failure can only provide the benefits of confinement [7, 10]. Hence, with the practical minimum spacing that can be provided at critical sections there is a limitation to the quantity of confinement which can be provided by the stirrups. In recent investigations, the ferrocement has been suggested as supplementary confinement to overcome the problem of limited confinement offered by the ties [2, 6, 13, 14]. Efforts in this direction revealed that the provision of ferrocement shell is an effective way of providing additional

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confinement of concrete in axial compression [3, 12, 16, 17]. Such concrete was termed as Ferrocement Confined Reinforced Concrete (FCRC). The investigations on FCRC indicated that the additional confinement with ferrocement shell improved the peak stress, the corresponding strain and the ductility of concrete[13, 14]. This paper presents an experimental investigation on the effect of ferrocement confinement on the flexural behavior of reinforced concrete simply supported beams.

EXPERIMENTAL INVESTIGATION

Outline of Experimental Program

The experimental program consisted of casting and testing of 30 simply supported beams of size 120 mm × 200 mm × 2100 mm, confined with ferrocement, in addition to the lateral ties, at critical section (the section at which the likely formation of plastic hinge, i.e., flexure zone) with a view to study the flexural behavior. The 30 beams consisted of two groups of 15 beams each representing two grades of concrete, viz., M15 and M20 grades designated as 'A' and 'B'. The longitudinal reinforcement in each group was varied to give three sets of beams, viz., under reinforced (U), balanced (B) and over reinforced (O) beams. In each set the Specific Surface Factor (S_r) 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 grade of concrete, the type of beam, the type of mesh and the number of layers of mesh i.e., specimen whose designation is AUM4, stands for 'A' type of concrete i.e., M15 grade, under reinforced beam with 'M' type of mesh placed in 4 layers. Table 1 gives the details of mechanical properties of the reinforcement bars and mesh wires. Table 2 gives the details of grade of concrete, steel reinforcement in beams tested.

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 43 grade conforming to IS 8112-1981 [5]. 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 and for the concrete fine aggregate passing 2.36 mm IS sieve was used. The mix proportion used for M15 grade of concrete was 1:2.8:4 with a water-cement ratio of 0.6 and for M20 grade of concrete it was 1:2.4:3.4 with a water-cement ratio of 0.55. The mortar used for ferrocement shell has the mix proportion of one part of cement and two parts of sand (i.e., 1:2) with water-cement ratio of 0.6. The water-cement of 0.6 was adopted to improve the flowability of mortar through the mesh layers during casting of specimens.

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 mold. The concrete was placed in the

Table 1 Mechanical Properties of Reinforcement Bars and Mesh Wires Used

Sl. No.	Diameter (mm)	Yield stress (f_y) (MPa)	Spacing of wires (mm)
Longitudinal Steel			
1	10	475.0	--
2	12	497.0	--
3	16	435.0	--
Stirrup Steel			
4	6	280.0	
G.I. Woven Wire Mesh (M Type)			
5	0.66	298.0	6.52

Table 2 Details of Concrete Grade and Steel Reinforcement Bars

Grade of Concrete	f_{ck} (MPa)	Type of Beam	Longitudinal Steel		Stirrup Steel		f_{cm} (MPa)
			Dia.(mm)	No. Of Bars	Dia.(mm)	Spacing (mm)	
M15	20.62	U	10	3	6	80	28.73
M15	20.03	B	12	3	6	80	30.06
M15	19.81	O	16	2	6	80	28.65
			12	1			
M20	28.28	U	12	3	6	80	28.93
M20	29.28	B	12	2	6	80	29.30
			16	1			
M20	29.23	O	16	3	6	80	30.02

Note:

Width of the Beam	=	120 mm
Overall depth of the beam	=	200 mm
Effective depth of the beam	=	175 mm
Overall length of the beam	=	2100 mm
Effective span of the beam	=	1700 mm

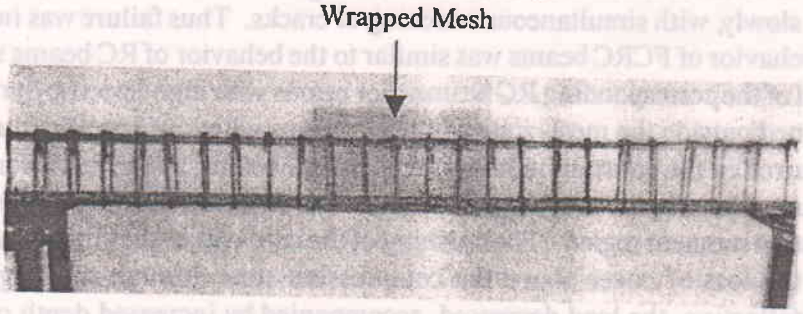


Fig. 1. Reinforcement cage with mesh wrapped on three sides.

beam except in the side covers in the mesh zone (critical zone), i.e., the gap between the mold and the reinforcement cage. 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 the 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 molds 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.

Testing

The beams were tested under symmetrical two point loading (with a constant moment zone of 300 mm) on a simply supported span of 1700 mm. Tinius Olsen Testing Machine of 1810 kN capacity was used for testing the beams. Strain rate control was adopted to obtain the complete profile of load deflection behavior especially in the post ultimate range. Specially fabricated curvaturemeters were used to measure the curvature in the critical sections. These curvaturemeters 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 Baty dial gages of 0.002 mm least count were 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 mid point of the beam by using the Baty dial gages with a least count of 0.01 mm. The sketch of the test set-up and the curvaturemeters is given in Fig. 2 and the photograph of the beam with curvaturemeters attachment is shown in Fig.3. Also the width of the 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 curvaturemeters, three deflectionmeter readings and crack widths were recorded at every half a 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 Figs. 4 to 9. The experimental moment curvature diagrams of a typical RC and FCRC section are shown in Fig. 10. The experimental results are presented in Table. 3. A few of the photographs of tested beams are shown in Fig. 11.

BEHAVIOR OF FCRC SIMPLY SUPPORTED BEAMS

Under Reinforced Beams

In all the beams, both reinforced (RC) and FCRC, of the under reinforced series, visible cracks developed at 30% to 35% of 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 of FCRC beams was 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 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 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

Table 3 Experimental Results of Simply Supported Beams Tested

Sl. No.	Desig. Of beam	S_f	α	β	ε_c	ε_s	ϕ_u	ϕ_y	δ	W_{cm}	W_{co}	γ	η
1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.
1	AUM0	0.000	0.2471	0.0667	7879	15990	136.41	33.42	3.82	0.2032	+	1.000	1.000
2	AUM1	1.649	0.2522	0.0695	8261	17230	143.25	34.57	3.15	+	0.0762	1.020	1.050
3	AUM2	3.298	0.2568	0.0782	9582	23660	191.09	35.17	3.00	0.0762	0.1016	1.039	1.400
4	AUM3	4.947	0.2595	0.0828	13301	32160	259.82	35.49	3.95	+	0.1524	1.050	1.904
5	AUM4*	6.597	0.2618	0.0884	22920	38370	346.35	34.60	3.60	+	0.1778	1.059	2.539
6	ABM0	0.000	0.3394	0.0948	8752	9940	103.31	42.05	3.90	+	0.0762	1.000	1.000
7	ABM1	1.576	0.3456	0.1071	9391	16530	148.12	46.73	3.24	0.0254	0.0762	1.018	1.433
8	ABM2	3.152	0.3681	0.1177	12040	18290	173.33	46.28	3.95	0.0508	0.1016	1.084	1.677
9	ABM3*	4.728	0.3730	0.1245	15102	18220	187.24	43.35	4.14	+	0.0762	1.098	1.812
10	ABM4	6.304	0.3798	0.1291	18817	31660	286.82	42.34	4.19	+	0.0762	1.119	2.776
11	AOM0	0.000	0.4018	0.1206	8655	7450	93.13	60.69	3.92	0.0508	+	1.000	1.000
12	AOM1	1.653	0.4122	0.1377	9577	10680	114.46	57.34	3.70	0.0408	0.1016	1.025	1.229
13	AOM2	3.307	0.4427	0.1424	10885	16760	157.97	61.00	3.60	0.0418	0.1270	1.101	1.696
14	AOM3*	4.960	0.4231	0.1442	12221	22710	197.40	61.68	3.72	+	0.1016	1.053	2.119
15	AOM4	6.614	0.4776	0.1665	15879	24920	238.62	59.25	3.41	+	0.1270	1.188	2.562
16	BUM0	0.000	0.2444	0.0701	8232	16120	137.62	34.60	3.83	0.0508	+	1.000	1.000
17	BUM1	1.637	0.2515	0.0752	10121	23370	191.40	36.00	3.76	0.0508	0.1016	1.029	1.390
18	BUM2	3.295	0.2576	0.0802	14327	33790	270.37	34.41	4.12	0.0254	0.1254	1.054	1.964
19	BUM3	4.912	0.2602	0.0854	16431	34310	288.35	36.78	4.15	0.0508	0.1254	1.64	2.095
20	BUM4*	6.550	0.2610	0.0901	18320	26130	248.32	33.80	4.16	+	0.0508	1.067	1.804
21	BBM0	0.000	0.3259	0.0978	9461	9789	111.91	42.73	3.90	0.0508	+	1.000	1.000
22	BBM1	1.621	0.3554	0.1042	11247	12503	133.42	45.81	3.96	0.0254	0.0254	1.090	1.192
23	BBM2	3.242	0.3488	0.1121	14540	26910	235.57	44.74	3.83	0.0254	0.0726	1.070	2.104
24	BBM3	4.863	0.3595	0.1185	16770	29020	261.71	44.00	3.70	+	0.0508	1.103	2.338
25	BBM4	6.484	0.3659	0.1270	19530	32170	292.09	42.21	4.19	+	0.0508	1.122	2.610
26	BOM0	0.000	0.4101	0.1249	8112	7305	88.60	58.83	4.69	0.0508	+	1.000	1.000
27	BOM1	1.577	0.4082	0.1329	9562	10930	114.52	58.65	4.35	+	0.0508	0.995	1.292
28	BOM2	3.154	0.4332	0.1505	12661	16580	160.67	58.65	5.10	0.0254	0.0508	1.056	1.806
29	BOM3	4.731	0.4665	0.1678	15283	22250	209.72	60.51	4.25	+	0.0508	1.137	2.367
30	BOM4	6.309	0.4755	0.1731	19124	27400	265.85	59.00	4.80	+	0.0762	1.159	3.000

Note: * - Test had to be stopped due to the instability of load transfer arrangement; + - No cracking was observed at service load

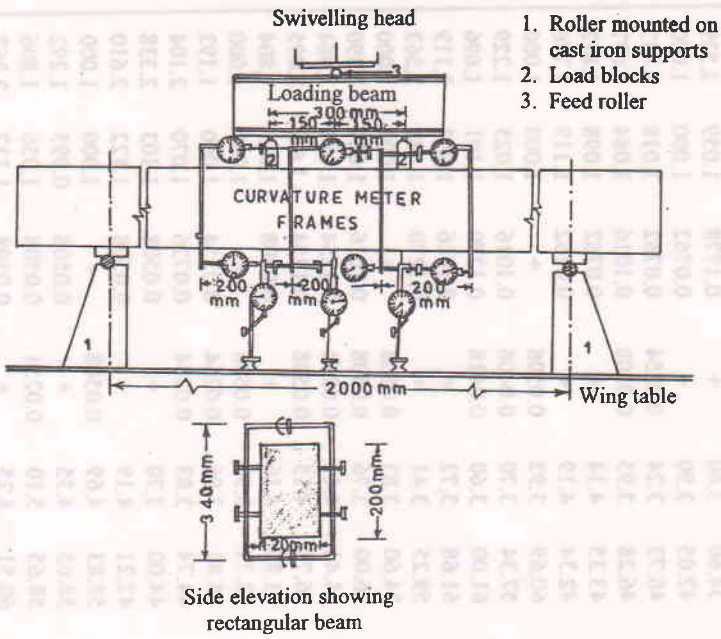


Fig. 2. Test set-up of curvature meters and deflectometers and cross-section of beam.

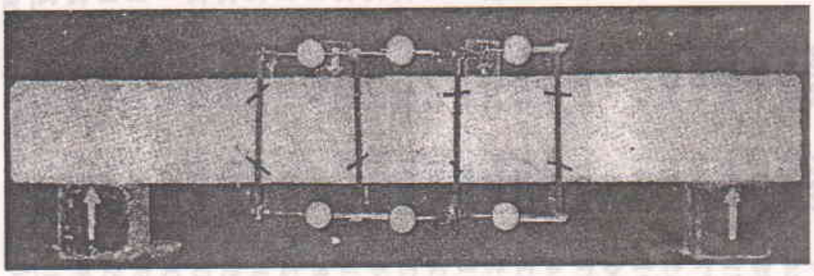


Fig. 3. Beam with curvaturemeter attachment.

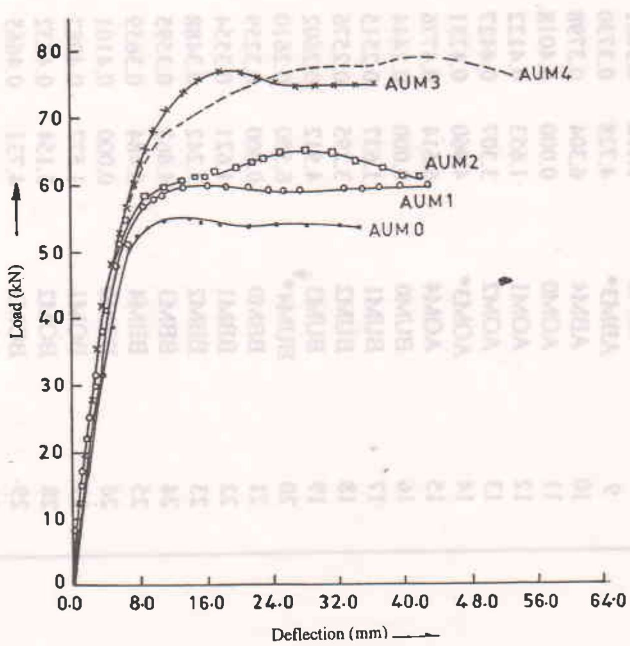


Fig. 4. Load-deflection diagrams under reinforced beams with FCRC at critical section.

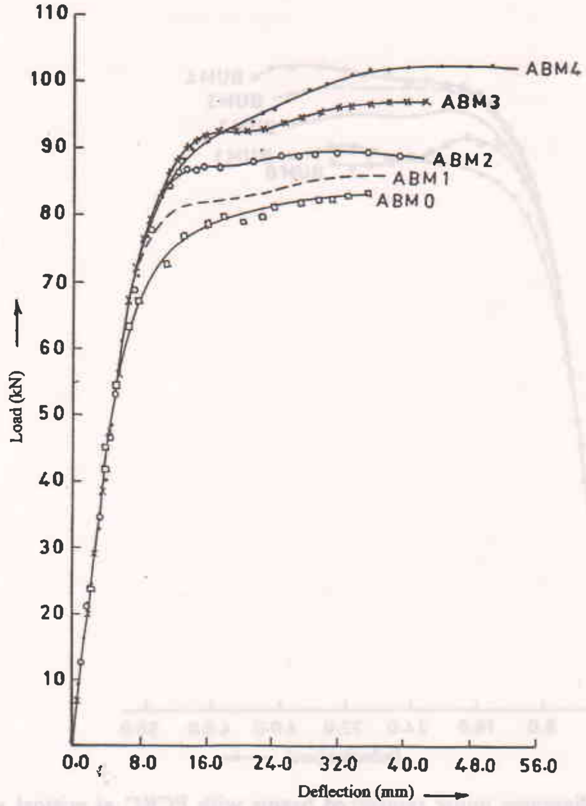


Fig. 5. Load-deflection diagrams under balanced reinforced beams with FCRC at critical section.

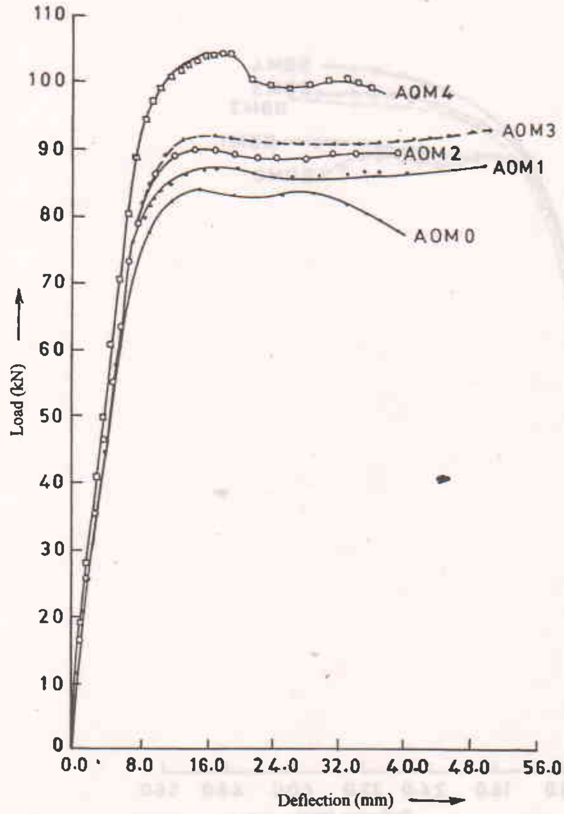


Fig. 6. Load-deflection diagrams over reinforced beams with FCRC at critical section.

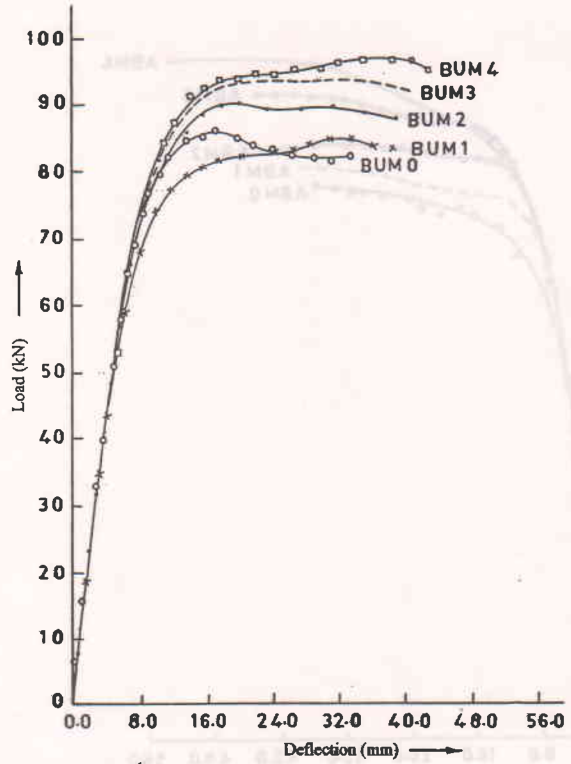


Fig. 7. Load-deflection diagrams under reinforced beams with FCRC at critical section.

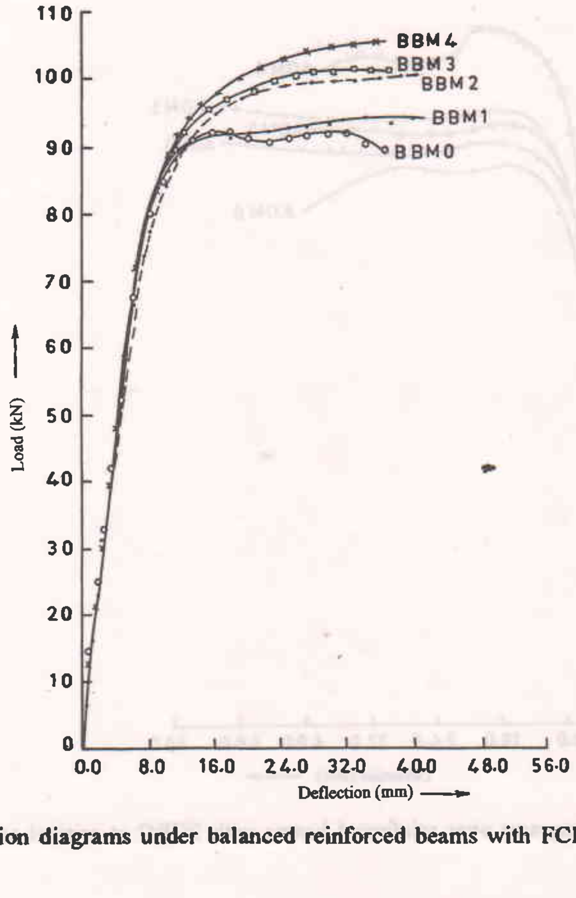


Fig. 8. Load-deflection diagrams under balanced reinforced beams with FCRC at critical section.

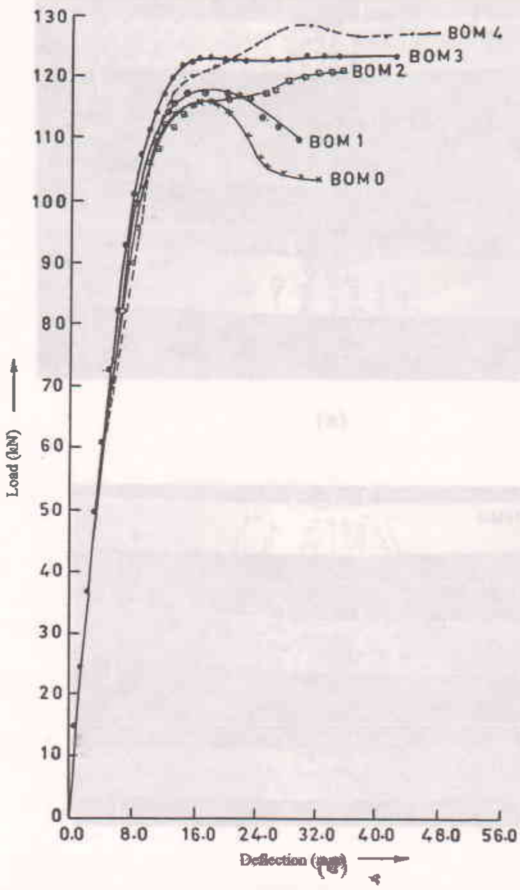


Fig. 9. Load-deflection diagrams over reinforced beams with FCRC at critical section.

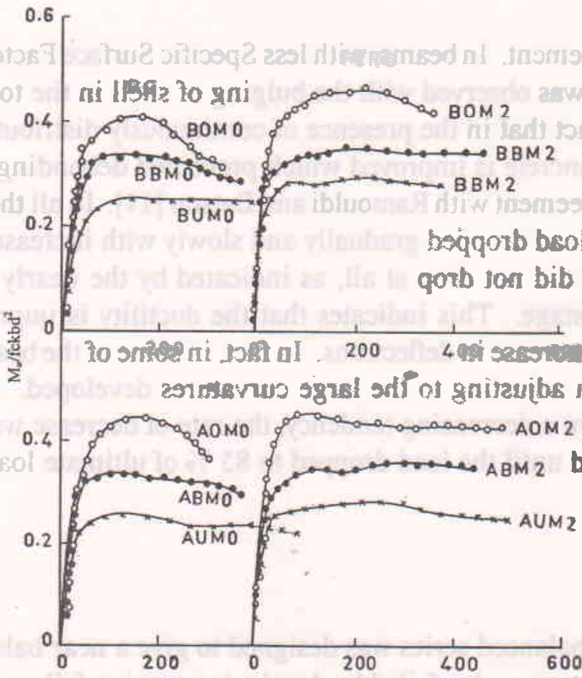
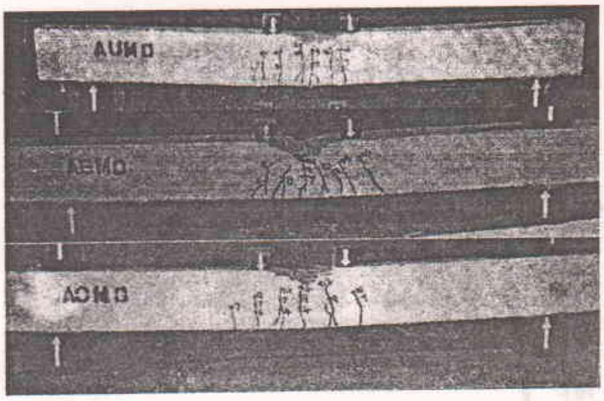
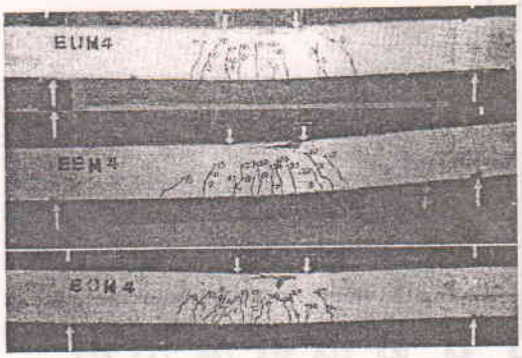


Fig. 10. Moment-curvature diagrams at RC and FCRC beams tested.



(a)



(b)

Fig. 11. Tested RC beams.

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, the tensile strain capacity of the concrete is improved which prevented debonding with the reinforcement. This observation is in agreement with Ramouldi and Batson [11]. In all the ten beams of under reinforced category tested, the load dropped gradually and slowly with increased deflections in the post ultimate stage or the load did not drop at all, as indicated by the nearly flat load deflection diagrams 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 the 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.

Balanced Beams

The RC beams in the balanced series was designed to give a near balanced failure. Even though the RC beams in this category also failed by developing tension failure, the deflections and curvatures at ultimate stage were less than the RC beams in the under reinforced series. There was a considerable increase in the values of deflections and curvatures at ultimate load as the confinement due to ferrocement increased. The behavior of beams with ferrocement shell as an additional confinement was similar to that of confined RC beams upto 70% to 75% of ultimate load of the later.

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 upto half to two third depth of the beam. The load continued to increase slowly with increased deflections. In case of beams without ferrocement shell, the crushing continued to increase with increased deflections upto ultimate load, after that the load dropped with increased deflections. In case of beams with ferrocement shell as additional confinement, the sudden reduction in the compressive force because of the spalling of the concrete was to some extent compensated by the increased strength of concrete. This caused the beam to behave more plastically and deformability of the beam was improved. Also in this category of beams with ferrocement shell as additional confinement the load deflection diagrams obtained are also flat showing that the provision of the ferrocement shell confinement results in additional ductility of beams with higher specific surface factor (S_f>3.0).

EFFECT OF SPECIFIC SURFACE FACTOR

Ultimate Moments

The Specific Surface Factor verses the ultimate moment capacity of each beam is presented in Column 4 of Table 3. A critical study of the values indicated that as Specific Surface Factor increases the ultimate moment capacity increases in all types of beams. This may be attributed to (i) the increase in ultimate strain capacity of concrete produce as indicated in Column 6 of Table 3, (ii) the increase in strain in steel (Column 7 of Table 3) at ultimate stage due to ferrocement confinement, leading to an increase in the value of tensile force, and (iii) the reduced depth of neutral axis. Apart from these reasons, confinement by discrete rectangular stirrups and by ferrocement shell improved the strength of concrete.

The improvement in ultimate moment capacity, however, depends upon the percentage of longitudinal steel. The increase is proportional to the increase in the quantity of longitudinal steel. In the case of under reinforced beams, the increase in the moments is in the range of 4% to 6%, which is not pronounced. In the case of balanced beams the improvement in the moment capacity is in the range of 9% to 12% and in the case of over reinforced beams, the improvement is in the range of 15% to 18%, which is significant. It was also observed that, not only the strength has improved but also the nature of the failure was changed from a brittle failure to a ductile failure with the increase in the level of ferrocement confinement especially in over reinforced beams.

Moment at First Crack

The load at first crack, and hence moment at first crack increased whenever the ferrocement shell is present as an additional confinement (Column 5 of Table 3). This may be because of increased tensile strain capacity of concrete due to the presence of ferrocement shell alround resulting in delaying of crack occurrence in concrete in flexure.

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. As the Specific Surface Factor increases the ultimate strain in concrete increases, as indicated by the experimental values of strain given in Column 6 of Table 3.

Ultimate Strain in Steel

The values of the strain in longitudinal steel at ultimate moment presented in Column 7 of Table 3, indicated that the steel has yielded not only in beams with ferrocement but even in beams which are confined with stirrups only.

Deflections at Service Load

The deflections corresponding to the service load, which is taken as taken as two thirds of ultimate load are presented in Column 10 of Table 3. These deflections for all beams are less than that deflections allowed [4] for simply supported beams as per IS 456 - 1978, which is 1/325 of span. This means that the limit state of serviceability of deflections is not violated by providing additional confinement with ferrocement shell.

Crack Width at Service Load

None of the beams exhibited crack width (Columns 11, 12 of Table 3) of more than the allowable crack width [4] of 0.3 mm, as per IS 456 - 1978, at service load. The crack widths measured outside the mesh zone, was considerably more than the crack width measured inside the mesh zone, but even they were less the allowable limits at limit state of service. Hence, it can be stated that by providing the additional ferrocement shell confinement to the beams ,the limit state of service regarding the crack width has not been violated.

Curvatures at Ultimate Moment

The ultimate curvatures increased with an increase in Specific Surface Factor as could be seen by a study of ultimate curvatures tabulated in Column 8 of Table 3. The increase in curvature is represented by the ratio of ultimate curvature with ferrocement to the ultimate curvature without ferrocement as given in Column 14 of Table 3. The increase in the ratio is as high as 2.5. The increase in curvature of FCRC section over a stirrup confined RC section is due to two factors: (i) increase in failure strain in concrete due to continuous confinement, and (ii) the reduction in depth in neutral axis due to large strains developed in the longitudinal steel with the additional ferrocement confinement. Hence, there seems to be sufficient experimental evidence to prove that necessary redistribution of moments can take place in the case of statically indeterminate structures, if the sections are properly and adequately confined by ferrocement in additional to rectangular stirrup confinement at possible zones of plastic hinge occurrence.

CONCLUSIONS

1. Provision of ferrocement shell improves the flexural behavior of reinforced concrete beams.
2. In the case of normally under reinforced beams the increase in moment carrying capacity is very little with ferrocement shell confinement and can be ignored.
3. In the case of balanced beams, the increase in moment carrying capacity is about 9% and in over reinforced beams, the increase in moment capacity is as much as 15%.
4. The improvement in curvatures is observed in all the beams irrespective of type of beam and these curvatures at ultimate are improved with ferrocement shell confinement. The increase in ultimate curvature in under reinforced, balanced and over reinforced beams is about 120%, 160% and 180%, respectively.
5. Over reinforced beams can be made to develop ductile (tension) failure by additional confinement of critical sections.
6. The provision of ferrocement shell as an additional confinement increases the value of cracking moment of RC sections.
7. The post ultimate behavior of FCRC section (with $S_f > 3.0$) resembles that of a steel section in that it has a large deformation plateau.
8. The serviceability of FCRC structure will be as good as that of the corresponding RC structure, since upto 80% load capacity, the behavior of FCRC is similar to the concrete confined with stirrups alone.

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