International Journal of Advanced Research in Engineering and Applied Sciences
ISSN: 2278-6252

FLEXURAL BEHAVIOUR OF *FRP* STRENGTHENED *RC* BEAMS: MONOTONIC LOADING

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Abstract: *An experimental investigation on flexural behaviour, in terms of strength and deformation capacity, of Reinforced Concrete (RC) beams strengthened using Fiber Reinforced Polymer (FRP) under monotonic loading is presented. An experimental program consisting of two point loading tests on nine FRP strengthened and three unstrengthened RC beams was conducted under monotonic loading. The parameters of research were percentage of internal tensile steel in beams, FRP configuration and combination thereof. Mode and mechanism of failure, effectiveness and efficiency of the scheme applied for flexural strengthening using FRP under monotonic loading have been discussed. It was observed that flexural strengthening of RC beams provides additional strength but with brittle mode of failure and at cost of ductility. FRP strengthened beams after FRP rupture show behaviour of unstrengthened beams with yielded steel. In no case end span debonding has been noticed, extending FRP to supports effectively mitigated concrete cover delamination, However, mid-span debonding has been noticed in some cases. Strengthening using FRP is found more effective in case of under reinforced RC beams having lower amount of steel. Distributing FRP over the tension face provides more effective and better configuration.*

Keywords: *Monotonic loading, Flexural behaviour, Fiber Reinforced Polymer (FRP), Reinforced Concrete (RC) Beam, Repairing, Restoration, Strengthening.*

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I. INTRODUCTION

Fiber Reinforced Polymer (FRP), a new construction material with proven structural application, is showing increased use. It is largely used for repairing and strengthening of Reinforced Concrete (RC) structures.[1] Strengthening of RC structures using FRP is a relatively new, attractive and efficient technique. FRP has tremendous potential and has great advantage over conventional materials and techniques of retrofitting of RC structures.[2] It is established that using this technique flexural strength can be increased considerably.[3,4,5] The information regarding its short term behaviour is in abundant and well documented too. Various design manuals, codes and standards on FRP strengthening are also prevailing.[6,7,,8,9,10]

Many experimental and analytical studies have been conducted on flexural behaviour of FRP strengthened RC beams under monotonic loading.

In this paper experimental study conducted on FRP strengthened RC beams under monotonic loading is presented. Main objective of the present work is to study the flexural behaviour of FRP strengthened beams under monotonic loading in terms of strength and deformation capacity.

II. EXPERIMENTAL PROGRAM

The experimental program consists of testing of in all 9 FRP strengthened and 3 unstrengthened small scale RC beams under monotonic loading. Test beam specimens were designed to fail in bending under two point loading. The beams were cast with three different percentage of internal tensile steel reinforcement and applied with three different FRP configurations.

A. Description of Test Specimens

The 120mm x 240mm x 1900mm size 12 RC beams were cast in 3 groups of 4 in each, with 3 different amount of main steel reinforcement viz- 10mm dia tor steel- 2 nos (Group A),-3 nos (Group B), -4 nos (Group C). In this way tensile steel in beams of group A, B and C is 0.545%, 0.818% and 1.09% of beam cross sectional area respectively. Three out of four beams in each group were strengthened with same amount of FRP externally bonded to tension face but with three different FRP configuration viz- one 50mm wide strip of FRP placed at centre at bottom of beam from support to support (configuration 1), two 25mm wide strip of FRP 65mm apart symmetrically placed about the center line at bottom of beam from support to support (configuration 2), two 25mm wide strip of FRP placed in two layers at the center line at bottom of beam from support to support (configuration 3). One beam in each group was kept unstrengthened as control beam. This scheme is adopted to investigate the effects of percentage of tensile steel reinforcement, FRP configuration and combinations thereof on behaviour of FRP strengthened beams. The dimensions of the beams were adopted for practical reasons.

Closed rectangular shear stirrups made of 6 mm dia mild steel bars, were provided at 150 mm c/c spacing for beams of group A and B. For beams of group C, spacing of the stirrups was 120 mm c/c. All the beams were provided near top face with 2 nos -8 mm dia tor steel longitudinal bars. These bars near top face were provided so that beams could be safely inverted for the application of the FRP. All the beams were under reinforced and were designed to fail in bending. Typical geometry and reinforcement details of Group B beams are given in Fig.1.

The concrete mix for casting of RC beams was designed for characteristic compressive strength at 28-days as 30 MPa by IS method of mix design (IS :10262-1982)[11] and mix proportion of cement, sand and coarse aggregate was obtained as 1:1.3:2.9 by weight with water to cement ratio of 0.5. The materials and mix proportions for all the concrete used in this research were the same. 43 grade Ordinary Portland Cement, natural river sand, crushed stone aggregate of maximum size 20 mm were used. For both fine and coarse aggregates a sieve analysis confirming to IS : 383-1970 was carried out.[12] Material was weighed on balances and mixed in electrically operated concrete mixer. With this concrete 5 beam specimens and 10-12 cubes were cast per day. Wooden moulds were made for casting of beam specimens. Moulds were lubricated with oil before the concrete was poured. Beams were filled in 4-5 layers each of approximately 50 mm deep. Each layer was rammed properly and the concrete was very well compacted. The side forms of moulds were stripped after 24 hours of casting. Beams were transported to curing pond after 48 hours. After 28 days beams were taken out of curing pond and left for air curing till the time of test.

B. Strengthening of Test Specimens

Scheme of Strengthening and Designation of Test Specimens : As per the scheme described in section (II. A), strengthening of test specimens has been carried out. In all 9 RC beam test specimens -3 from each group A, B, C were flexurally strengthened. All the test specimens have different designations and designated as X-Y-Z, where X- indicates type of group (A, B or C), Y- indicates FRP strengthening configuration number (1,2 or 3) and for unstrengthened beams Y is 0, Z- indicates test type- for current study it is M i.e. monotonic loading test. For example, the beam specimen A-1-M is the beam from group A, strengthened using FRP strengthening configuration number 1 and tested under monotonic loading.

FRP Material: Nitowrap EP (CF) -a carbon fibre composite wrapping system from Fosroc Chemicals (India) Pvt. Ltd., was used for strengthening purpose in this investigation. In this system, Nitowrap (CF) fabric was used in conjunction with an epoxy sealer cum primer; Nitowrap 30 and a high build epoxy saturant Nitowrap 410. Primer and saturant both come in two pack system (base and hardner).

C. External bonded FRP Application

In the present investigation, at least 6 months after casting of the beams the strengthening process was begun. The surface region of the concrete was effectively dried out and the concrete gained sufficient strength before handling and inverting of the RC beams for FRP application by this time. The CFRP strips were externally bonded in three configurations as discussed in section (II. A), to the tension faces of the 9 beams-3 from each group. During the application of both the epoxy and the CFRP, the manufacturer's instructions for installation were followed. Safety precautions were also taken care of.

Application of FRP: Strengthening of the beams begun after the beams had sufficiently cured, and carried out as per the FRP manufacturer's instructions. The CFRP was ready for application as the CFRP was cut to desired size and the concrete surface was prepared. For convenience, the application of FRP has been done with the tension faces of beams up as opposed to field application where application has to be carried out 'up hand' from beneath of the beams. The mixed material of Nitowrap 30 epoxy primer was applied uniformly within the pot life, over the prepared and cleaned surface of tension face of the beam. It was ensured that all the surface area to be in contact with CFRP had a layer of epoxy.

Wearing good quality hand gloves, the application was carried out using a one inch brush and allowed for drying for about 24 hours before application of saturant.

To apply strips of the Nitowrap CF fabric ready for installation, the mixed material of Nitowrap 410 saturant was applied uniformly over the tack free primer using separate brush. The strip of desired size was laid on to the saturant applied area, at the desired place for getting the required strengthening configuration. The strip was then pressed by gloved hand, starting from the center of the beam and moving outward toward the supports. The strip was then pressed firmly into the saturant to remove air bubbles or any voids in the saturant with uniform pressure from hard rubber rollers and fingertips, squeezing excess saturant out along the edges of the strip. In this way a uniform application is obtained. One more coat of the saturant was applied over the carbon fabric after a time lapse of 30 minutes. Care was taken to ensure that the fibre orientation is not disturbed while applying the second coat of saturant. The same procedure was followed for double layer strengthening configuration. The whole process of application of saturant and the installation of strips on it was carried out within the pot life of the saturant. The strengthened specimens were allowed to cure at room temperature for at least 7 days before testing. Fig.2 show the FRP applied beams left for air curing.

D. Test Setup

All the beam specimens were tested with the same test setup. A 500 kN capacity loading frame was used for testing of beams. Beams were simply supported over a span of 1700 mm. The load was applied through 250 kN capacity hydraulic jack connected to mechanically operated high pressure oil pump. For two point loading, the load was distributed as two line loads kept 100 mm apart symmetrical to center of the span on the top face of beam. Two 20 mm steel rods were welded to a 20 mm thick plate at 100 mm *c/c* distance for application of line load. A load cell of 100 kN capacity was placed between test frame and load distributor placed on the test specimen. Gap in between test frame and plate was filled by spacers. Loading arrangement for beam specimens is shown in Fig. 3

E. Instrumentation

The beam specimens were instrumented to measure maximum deflection at mid span of the beams. The LVDT (linear variable displacement transducer) and load cell were used to record deflection and load respectively. A high precision dial gauge was also placed nearby LVDT to put a cross check on measurements.

X-Y plotter was used to plot load- deflection response of test beams. LVDT output was connected to X-axis of X-Y plotter and Load cell output was connected to Y-axis of plotter. A 12 volts D.C. battery provides input to LVDT.

F. Test Procedure

The experimental programme includes testing of unstrengthened and FRP strengthened beams under monotonic loading. Loading arrangement, instrumentation etc. are as shown in Fig. 3. Test beam specimens were kept simply supported over a span of 1700 mm and tested under two point loading. Two line loads 100 mm apart were placed at center of the beam. A continuous graphic plot of load vs deflection was obtained throughout the test. In addition, loads and deflections were measured at frequent intervals with the load cell through load meter and dial gage, respectively.

III. TESTING OF BEAM SPECIMENS

The complete experimental setup showing loading arrangements and instrumentations for testing of beam specimens is visible in Fig. 4. Under two point loading monotonic loading tests were conducted. The test results for these beams are presented in Table 1.

The test conducted was a monotonic loading test on RC and CFRP strengthened RC beams in which the load was increased gradually up to failure to obtain load-deflection curve. Due to limited space, only representative load-deflection curves for specimen A-0-M and A-1-M are shown in Fig. 5 and Fig.6 respectively.

IV. TEST RESULTS AND DISCUSSION

A. Mode and mechanism of failure

Failure modes for all unstrengthened and FRP strengthened beams were observed and failures of only a few beams are shown in Fig. 7. Load capacity of beams under monotonic loading at different stages of loading is presented in Table 1.

Load-deflection curves under monotonic loading for specimen A-0-M and A-1-M are shown for example in Fig. 5 and Fig.6 respectively. The beams considered in present study were all under reinforced, and four significant points are observed in their load-deflection curves which are discussed below.

The point 1 corresponds to the stage of initial cracking of concrete when the beam cracked in the tension zone, which is determined from the first abrupt change in slope of load deflection curve. Beyond this point the stiffness of beam is reduced compared to that of uncracked section and the slope of load-deflection curve changed accordingly. The load corresponding to this point is termed as First crack load (P_{fc}). Before cracking, deflection was directly proportional to load applied. After first crack though stiffness of beam reduced, however, the load-deflection behaviour remained almost linear till yield load.

The second significant stage in load-deflection curve was the yield point i.e. point 2, which is determined by the intersection of the elastic tangent and the post yield tangent on load deflection curve. The load corresponding to this point is Yield load (P_y). As the members were under-reinforced, the tension steel yielded before the development of crushing strains in concrete and till this stage no cracks on top face of beams were observed, however, the flexural cracks developed near bottom face get little widened and propagated upwards. By this time, the moment at nearby sections of central zone also crossed the first cracking moment resulting in development of more flexural cracks on either side of central zone of beam.

Beyond yield point a gradual change in slope of load-deflection curves associated with comparatively more deflections was observed, non-linearity in load-deflection curve is clearly visible. In this way the yield point has its own importance as it marked the boundary between elastic and inelastic behaviour as observed from load-deflection curves. After yield point, deflections increased at faster rate. It was also observed at the time of testing that near this load small horizontal cracks were developed at the top face of beam in the vicinity of central line of beam span and small chips of concrete spalled out. On tension face the initial flexural cracks propagated upwards. The second stage cracks also became well distinct resulting in development of yield moment at that section.

The point 3 corresponds to maximum load on the load deflection curve (P_m). The load-deflection curve became almost horizontal at point 3 in case of RC beams. It indicates that concrete has reached to its full capacity. It was observed during testing that at this stage cracks lying on the top face of beam got spread horizontally as well as vertically onwards causing crushing of concrete on comparatively bigger area. In case of FRP strengthened RC beams, as beams were under reinforced and very small amount of FRP has been used for strengthening, FRP reached to its maximum capacity and failed suddenly in most of the cases due to FRP rupture at a load too high for the yielded steel to handle, resulting in catastrophic failure. At the same time concrete crushing at top of beam was also observed in all cases.

The fourth significant stage is point 4 corresponding to ultimate load (P_u), which corresponds to failure of the beam. Failure is defined here as when load can not be sustained or when large deflections in the order of 40-50 mm occur, whichever occurs first. In case of FRP strengthened beams, this point corresponds to sudden failure of FRP. However, to grasp overall behaviour, testing was continued till 40-50 mm central deflection or till the load could not be sustained, whichever occurred first. After maximum load level and FRP failure, FRP strengthened beams behaved like unstrengthened beams with yielded steel. In case of unstrengthened beams, continuous loading caused excessive deflections thereby resulting in more and more widening of flexural cracks. The cracking of compression concrete got spread over bigger area, big pieces of concrete spalled out and in some cases stirrups and top reinforcement got exposed. Finally, failure of the unstrengthened beams has been considered with large deflections in the order of 40-50 mm or when load could not be sustained, whichever occurred first.

As all beams tested in this program were under reinforced and FRP strengthened beams were strengthened with very small amount of FRP (only 0.00053 percentage), in general, failure of the FRP strengthened beams were initiated by yielding of steel followed by sudden FRP rupture with sound, at the same time concrete crushing at top of beam was also observed in all cases. However, in no case end-span debonding has been observed. Extending FRP to the supports i.e. zero moment regions effectively mitigated the concrete cover delamination. Concrete cover delamination involves full depth of concrete cover, while with mid-span debonding (observed in some cases beyond the scope of present investigation) only thin layer of concrete is peeled off with FRP. In case of specimen C-3-M, mid-span debonding has been noticed (shown in Fig. 7) with sound of debonding, which was also occurred almost instantly with sudden loss of load. Mid-span debonding initiated at location of high moment to shear ratio, at toes of flexural/ flexural -shear cracks in the shear span of the beams and propagated in the direction of decreasing moment i.e. towards the nearest support. FRP is detached from the beam taking with it a thin layer of concrete.

Failure of unstrengthened beams was ductile failure, with large deflection in the order of 40-50 mm at ultimate load.

B. Effectiveness and efficiency of the scheme applied for flexural strengthening using FRP

Effect of Strengthening using FRP related to mode of failure has been discussed previously**.** From the load-deflection curves and the Tables 1, 2, 3 and 4 (generated from the load-deflection curves), effect of strengthening using FRP on strength and deformation capacity is observed as follows-

1. It is observed that flexural strengthening of RC Beams using FRP provides additional strength but with brittle mode of failure. Though use of higher percentage of FRP may result in higher increase in strength, it will be at cost of ductility and will show highly brittle behaviour with catastrophic failure.
2. As already seen and discussed in previous section, failure of FRP strengthened under reinforced RC beams initiates with yielding of steel followed by sudden FRP rupture causing sudden loss of load. FRP fails elastically at a load too high for the yielded steel to handle, resulting in catastrophic failure. After FRP rupture, beams show behaviour of unstrengthened beams with yielded steel.
3. As observed from Table 3, deflection at maximum load of FRP strengthened RC beams is very less as compared to unstrengthened RC beams. Maximum percentage decrease in deflection at maximum load is observed as 13.71, 37.97 and 73.87 due to strengthening using FRP (with only 0.00053 percentage of FRP), for the three groups- A, B and C of beams with 0.545, 0.818, 1.09 percentage of steel respectively. Decrease in deflection due to FRP strengthening can be very useful to overcome excessive deflection problem of under reinforced RC beams having very small amount of tensile steel.
4. Extending FRP to the supports i.e. zero moment regions effectively mitigated the concrete cover delamination. However in case of specimen C-3-M, mid-span debonding has been observed.
5. In case of strengthened beams of group A , higher additional strength provided by the same amount of FRP (Refer Table 1 and 2) and better deformation capacity (Refer Table 3 and 4) has been observed as compared to strengthened beams of other two groups viz B and C which were reinforced with higher amount of internal tensile steel. Maximum percentage increase in strength is observed as 24.24 for beams of group A as compared to

18.92 and 13.52 for strengthened beams of other two groups viz B and C. Maximum percentage decrease in deflection at maximum load is observed as 13.71 for beams of group A as compared to 37.97 and 73.87 for strengthened beams of other two groups viz B and C due to strengthening using FRP. Maximum percentage decrease in deflection at ultimate load is observed as 24.29 for beams of group A as compared to 61.23 and 73.87 (with only 0.00053 percentage of FRP). This observation indicates that strengthening using FRP is more effective and better in case of under reinforced RC beams having lower amount of steel.

6. In general more number of thinner cracks, increased values of first crack load and ultimate load however not that significant, and better deformation capacity (as % decrease in deflection is less) were observed in case of FRP configuration no. 2, where two symmetrically placed FRP strips were used in single layer as compared to other two configurations of the same group of beams, where in configuration no. 1- single FRP strip was placed at center, and in configuration no. 3 – two FRP strips were placed in double layer at center; amount of FRP being the same in all the three configurations. This is observed for all the three groups- A, B and C of beams having different amount of steel. Distributing FRP over the tension face provides more effective and better configuration.

V. CONCLUSIONS

As discussed above following are the conclusions drawn from the experimental program conducted to obtain flexural behaviour of FRP strengthened RC beams under monotonic loading. In general these conclusions are also confirmed by the experimental program conducted under cyclic loading, reported elsewhere.

Flexural strengthening of RC Beams using FRP provides additional strength but it will be at cost of ductility and will show highly brittle behaviour with catastrophic failure.

Failure of FRP strengthened under reinforced RC beams initiates with yielding of steel followed by sudden FRP rupture/debonding. After FRP rupture, beams show behaviour of unstrengthened beams with yielded steel.

Extending FRP to the supports effectively mitigated the concrete cover delamination/end-span debonding, However mid-span debonding has been observed.

Strengthening using FRP is more effective and better in case of under reinforced RC beams having lower amount of steel.

Distributing FRP over the tension face provides more effective and better configuration.

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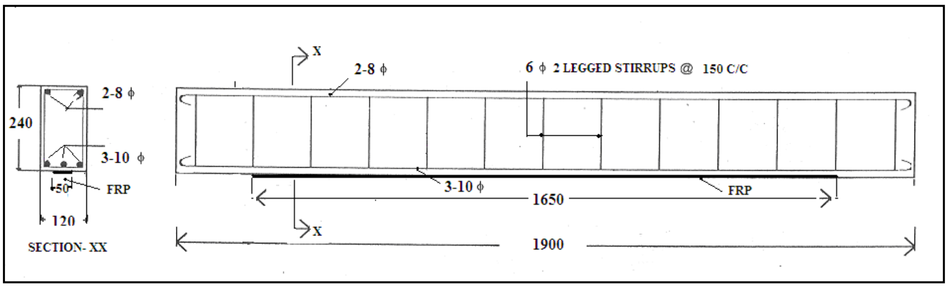

FIG. 1: TYPICAL GEOMETRY, REINFORCEMENT DETAILS AND FRP CONFIGURATION OF BEAMS (Group B-Config. 1)

FIG. 2 : *FRP* APPLIED BEAMS LEFT FOR AIR CURING

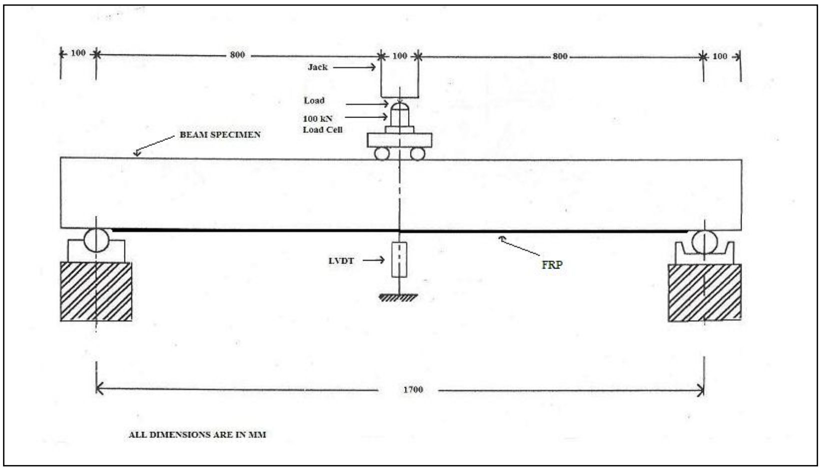

FIG. 3: LOADING ARRANGEMENT FOR BEAM SPECIMENS

FIG. 4: EXPERIMENTAL SETUP

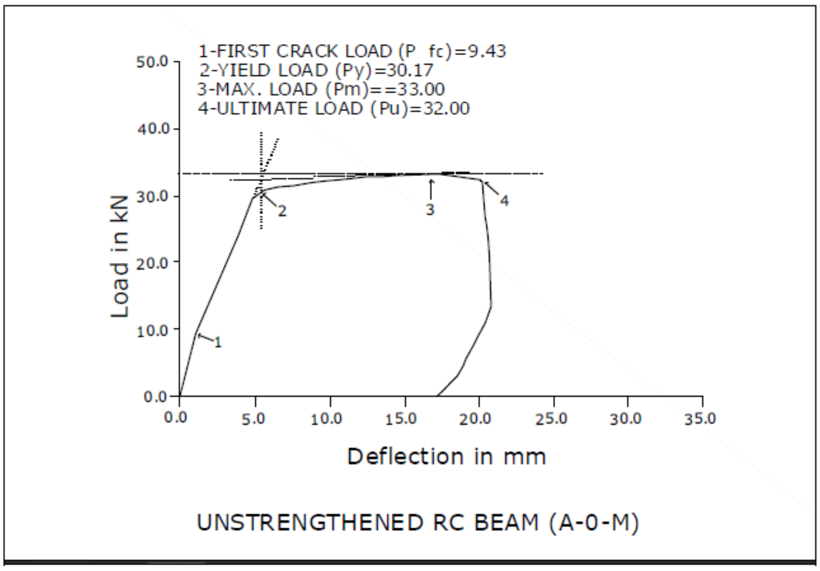

FIG. 5: Load- Deflection Curve under Monotonic Loading Test (Beam Specimen A-0-M)

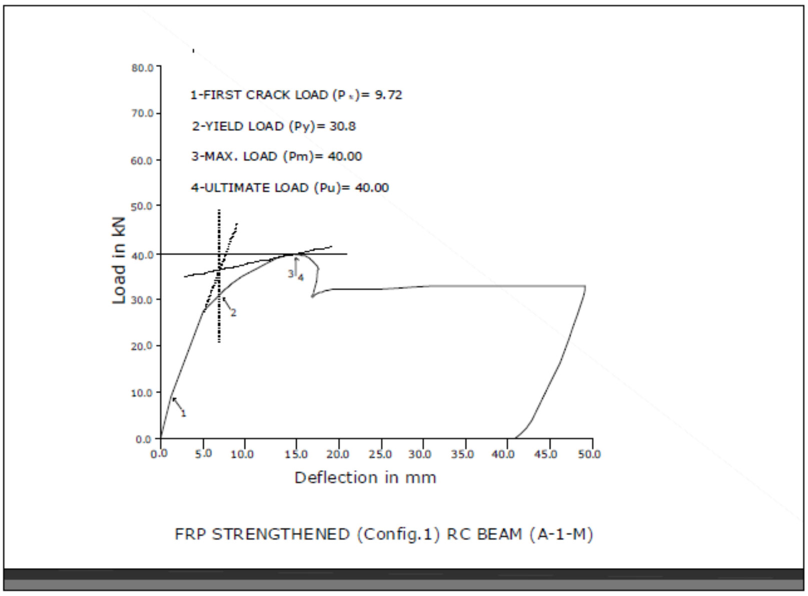

FIG.6: Load- Deflection Curve under Monotonic Loading Test (Beam Specimen A-1-M)

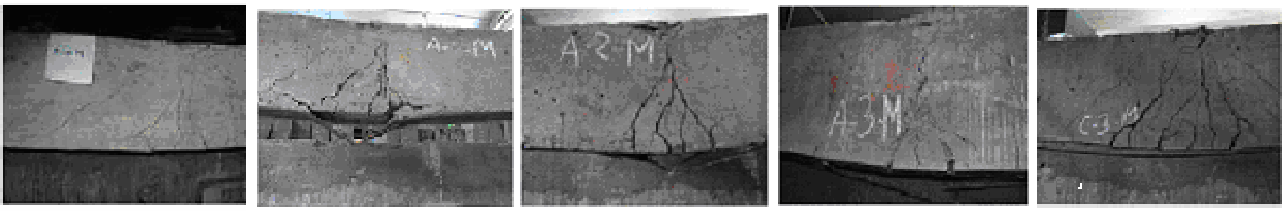

Fig. 7 Failure Mode of Beams A-0-M, A-1-M, A-2-M, A-3-M and C-3-M

TABLE 1

Load Capacity of Beams Under Monotonic Loading

Sr. No.	Beam Designation	Load at First Crack P_{fc} (kN)	Load at Yield P_y (kN)	Maximum Load P_m (kN)	Ultimate Load P_u (kN)	Type of Test
Group 'A' Beams						
1	A-0-M	9.43	30.17	33.00	32.00	Monotonic Test
2.	A-1-M	9.72	30.80	40.00	40.00	
3	A-2-M	10.66	35.00	41.00	41.00	
4	A-3-M	10.19	31.90	39.12	39.12	
Group 'B' Beams						
1	B-0-M	9.37	39.00	46.25	41.25	Monotonic Test
2	B-1-M	12.40	45.20	54.81	54.81	
3	B-2-M	13.05	47.00	55.30	55.30	
4	B-3-M	12.80	45.75	54.30	54.30	
Group 'C' Beams						
1	C-0-M	13.50	50.20	58.14	58.14	Monotonic Test
2	C-1-M	12.30	51.70	66.00	66.00	
3	C-2-M	19.00	55.20	66.03	66.03	
4	C-3-M	14.00	51.10	63.76	63.76	

TABLE 2

Increase in Maximum Load due to FRP Strengthening of RC Beams (Monotonic Loading)

Sr. No.	Type of Beams	Maximum Load (kN)	Percentage Increase in Maximum Load Due to FRP Strengthening
Group 'A' Beams			
1	Unstrengthened (A-0-M)	33.00	-
2	FRP Strengthened (A-1-M)	40.00	21.21
3	FRP Strengthened (A-2-M)	41.00	24.24
4	FRP Strengthened (A-3-M)	39.12	18.50
Group 'B' Beams			
1	Unstrengthened (B-0-M)	46.25	-
2	FRP Strengthened (B-1-M)	54.81	18.70
3	FRP Strengthened (B-2-M)	55.30	18.92
4	FRP Strengthened (B-3-M)	54.30	17.41
Group 'C' Beams			
1	Untrengthened (C-0-M)	58.14	-
2	FRP Strengthened (C-1-M)	66.00	13.52
3	FRP Strengthened (C-2-M)	66.00	13.52
4	FRP Strengthened (C-3-M)	63.76	9.67

TABLE 3

Decrease in Deflection at Maximum Load due to FRP Strengthening of RC Beams (Monotonic Loading)

Sr. No.	Type of Beams	Deflection at Maximum load (mm)	Percentage decrease in deflection at Maximum load Due to FRP Strengthening
Group A			
1	Unstrengthened (A-0-M)	17.50	-
2	FRP Strengthened (A-1-M)	15.71	10.23
3	FRP Strengthened (A-2-M)	16.76	4.23
4	FRP Strengthened (A-3-M)	15.10	13.71
Group B			
1	Unstrengthened (B-0-M)	25.39	-
2	FRP Strengthened (B-1-M)	15.75	37.97
3	FRP Strengthened (B-2-M)	20.25	20.24
4	FRP Strengthened (B-3-M)	15.94	37.22
Group C			
1	Untrengthened (C-0-M)	49.75	-
2	FRP Strengthened (C-1-M)	13.00	73.87
3	FRP Strengthened (C-2-M)	19.23	61.35
4	FRP Strengthened (C-3-M)	13.54	72.78

TABLE 4

Decrease in Deflection at Ultimate Load due to FRP Strengthening of RC Beams (Monotonic Loading)

Sr No.	Type of Beams	Deflection at Ultimate load (mm)	Percentage decrease in deflection at Ultimate load Due to FRP Strengthening
Group A			
1	Unstrengthened (A-0-M)	20.75	-
2	FRP Strengthened (A-1-M)	15.71	24.29
3	FRP Strengthened (A-2-M)	16.76	19.23
4	FRP Strengthened (A-3-M)	15.10	27.22
Group B			
1	Unstrengthened (B-0-M)	40.63	-
2	FRP Strengthened (B-1-M)	15.75	61.23
3	FRP Strengthened (B-2-M)	20.25	50.16
4	FRP Strengthened (B-3-M)	15.94	60.76
Group C			
1	Untrengthened (C-0-M)	49.75	-
2	FRP Strengthened (C-1-M)	13.00	73.87
3	FRP Strengthened (C-2-M)	19.23	61.35
4	FRP Strengthened (C-3-M)	13.54	72.78

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