Cyclic Loading Response of *RC* Beams Strengthened in Bending With *FRP*: A Common Point Approach

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ABSTRACT *Out of a vast experimental programme conducted to find out response of Reinforced Concrete beams strengthened in bending with Fiber Reinforced Polymer under cyclic loading, only common point approach is presented here. Common point approach is less accurate but far quicker as compared to stability point approach, and can be considered for indicative purpose. Two point loading tests on overall twelve RC beams- three unstrengthened and nine FRP strengthened were conducted under cyclic loading to find common points. Parameters of research were percentage of internal tensile steel in beams, FRP configuration and combination thereof. Load deflection curves were obtained from the tests, and with the help of these curves, common points were obtained, and common point curves were drawn. Comparisons of curves were made. Failure pattern, effect of the FRP strengthening, and permissible load capacity of FRP strengthened beams under cyclic loading have been discussed.*
Flexural strengthening of RC beams with FRP gives extra strength though at cost of ductility. However it is observed that distributing FRP over the tension face provides more effective and better configuration. Common point curves show that the maximum load be reduced in case of cyclic loading.

Keywords: *Cyclic loading, Fiber Reinforced Polymer (FRP), Reinforced Concrete (RC) Beam, Strengthening.*

I. INTRODUCTION

Fiber Reinforced Polymer (FRP) materials were developed mainly for aerospace and defense industries in the 1940s and are commonly used in many industries today, including aeronautic, marine, automotive, sports and electrical engineering. FRP is showing augmented use in construction industry also with the continuing cost reduction in high-performance FRP materials and the rising need for new materials to renovate/strengthen civil infrastructures (Zihong, 2007; Shrivastava et al, 2009a).

FRP materials are generally made of immensely strong high performance fibers (such as carbon, glass or aramid) placed in a polymer resin matrix (such as polyester, epoxy). The primary load carrying component is the fiber, while the matrix acts as binder, as environmental protector and stress distribution phase of the composite. It is known as composite, as composite consist of two or more physically distinct and mechanically separable components which are combined together to form a new material which posses properties that are notably different from those of its individual components (Shrivastava et al, 2009b).

FRP has wonderful potential and has great advantage over conventional materials and techniques of retrofitting of Reinforced Concrete (RC) structures like its non-corrosiveness, high strength to weight ratio, ease of handling and application at site, less downtime, fatigue resistance, non magnetic and non electrical conductance, non-metallic nature, high degree of formability and tailorability, capability to shield electromagnetic interference, low maintenance and long life, no unnecessary joint as endless tapes available, no transportation problem as available in rolls, and above all use of FRP can be cost effective also in various applications (Shrivastava et al, 2010; El-Dieb et al, 2012; Shrivastava et al, 2009b). Using this technique axial compressive strength, flexural strength, and shear strength can be increased considerably (Saadatmanesh et al, 1990; Alagusundaramoorthy et al, 2003; Duthinh et al, 2004). The information regarding its short term behaviour is in abundant and well documented too (Shrivastava et al, 2009c). However, uncertainty is still remaining in their long-term performance. Indeed, lack of proper understanding of the durability of the FRP-strengthened RC structures has in return impeded a wider adoption of this technique in practice (Tan et al 2006; Bank, 2006; ACI Committee, 2008; National Research Council (CNR), 2004; Canadian Standard Association, 2007). Because of the limited information, codes and standards also could not give the perfect recommendations/ guidelines in this regard by now (Shrivastava et al, 2009c). For understanding long-term effect on FRP strengthened beams more studies related to sustained loading, cyclic loading, temperature variation, fatigue loading, effect of adverse environment, and combined effect of fatigue loading and adverse environment are required. Several analytical and experimental studies have been done on flexural response of FRP strengthened RC beams under repeated loading (Meier et al, 1992; Inoue et al, 1995; Heffernan et al, 2004; Barnes et al, 1999; Papakonstantinou et al, 2002; Papakonstantinou et al, 2001; Harries et al, 2007; Kim et al, 2008).

This paper presents response of *RC* beams strengthened in bending with *FRP* under cyclic loading with a common point approach. An estimate of permissible load level for cyclic loading has been suggested.

II. EXPERIMENTAL PROGRAM

The experimental investigation consists of nine FRP strengthened and three unstrengthened i.e. in all twelve small scale RC beams testing under cyclic loading for common points. Beam specimens were so designed as to fail in bending under two point loading. The beams were cast with three different percentage of tensile steel and strengthened with same amount of FRP but in three different FRP configuration schemes. Carbon Fiber Reinforced Polymer (CFRP) was used for strengthening. Details of test specimens, FRP strengthening, test setup and instrumentation can be found elsewhere (Shrivastava et al, 2013a, 2013b). However the geometry and reinforcement details of Group B beams are given in Fig.1 for illustration. Fig. 2 shows FRP and FRP strips and, Fig. 3 shows FRP applied beams left for air curing.

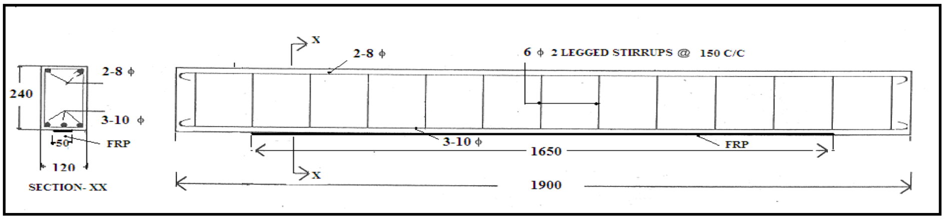


FIG. 1: TYPICAL GEOMETRY, REINFORCEMENT DETAILS AND FRP CONFIGURATION OF BEAMS (Group B-Config. 1)

FIG. 2: FRP and FRP strips **FIG. 3: FRP APPLIED BEAMS LEFT FOR AIR CURING** **FIG. 4: EXPERIMENTAL SETUP**

2.1. Test procedure

The experimental setup showing loading arrangements and instrumentations for testing of beam specimens is seen in Fig. 4. Loading arrangement and instrumentation etc. for the test is as shown in Fig. 5. The experimental program includes testing of three unstrengthened and nine FRP strengthened beams under cyclic loading for common points. Using X-Y plotter, a continuous graphic plot of load versus deflection was obtained throughout the test. Additionally, loads and deflections were measured at frequent intervals with the load cell through load meter and dial gage, respectively. The continuous plot was particularly useful in observing the intersection point of unloading and reloading curves, needed for the cyclic loading test for obtaining common points. The plot was also useful in observing the shape of unloading-reloading curves.

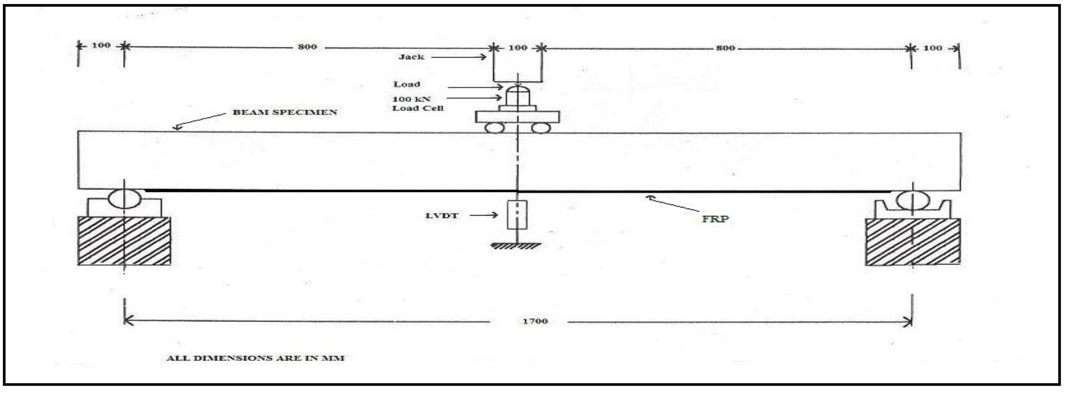


FIG. 5: LOADING ARRANGEMENT FOR BEAM SPECIMENS

III. TESTING OF BEAM SPECIMENS

The experimental setup showing loading arrangements and instrumentations for testing of beam is visible in Fig. 5. Under two point loading, cyclic loading test to get common points were performed on the twelve test specimens prepared as explained elsewhere (Shrivastava et al, 2013a, 2013b). In Table 1 test results for these beams are given. Test procedure is explained below.

The test conducted on unstrengthened RC and FRP strengthened RC beams was a cyclic loading test to get common points [for example Fig. 6], in which the loading started at zero loads and raised to the point coinciding approximately with the envelope load-deflection curve obtained under monotonic loading tests reported elsewhere (Shrivastava et al, 2013a), and then released to zero. The incremental load and deflection were chosen so that the loading curve, in each cycle attained the envelope curve. This was done by monitoring the incremental load up to yield and incremental deflection after yield in each cycle. An incremental load of 10 kN up to yield and an incremental deflection of about 2.0-5.0 mm after yield point in each cycle was found to be appropriate for the loading curve to attain the envelop curve and to obtain number of common points for all the beams. The load-deflection curve so obtained possessed a locus of common points. A common point is defined as the point at which the reloading curve of any cycle crosses the unloading curve of the previous cycle e.g: point 'A' in Fig 6. Load above this limit will lead to additional strains and deflections. The load below this will lead the load-deflection curve into a closed hysteresis loop, giving no additional deflection and no additional strains. Lower bound points are termed as stability points (Shrivastava et al, 2013b), which is beyond the scope of present study.

TABLE 1
Load Capacity of Beams Under Cyclic Loading for Common Points

Beam	1	2	3	4	5	6	7	8	9	10	11	12
Group	Group 'A' Beams				Group 'B' Beams				Group 'C' Beams			
Beam Designation	A-0-C	A-1-C	A-2-C	A-3-C	B-0-C	B-1-C	B-2-C	B-3-C	C-0-C	C-1-C	C-2-C	C-3-C
Load at 1st Crack P_{fc} (kN)	7.12	9.36	10.40	9.30	8.90	9.07	9.37	9.09	10.60	15.91	19.00	13.60
Load at Yield P_y (kN)	25.60	32.70	30.60	29.93	39.00	41.40	41.40	44.80	44.20	50.90	57.10	48.20
Maximum Load P_m (kN)	32.00	39.00	39.14	38.00	46.00	52.70	53.12	50.91	57.00	61.21	64.12	57.95
Ultimate Load P_u (kN)	31.80	39.00	39.14	38.00	43.80	52.70	53.12	50.91	57.00	61.21	64.12	57.95

IV. TEST RESULTS AND DISCUSSION

4.1. Load capacity of beams

Load-deflection curves under cyclic loading for common points are plotted for all the twelve test specimens and Load capacity of beams under cyclic loading at four different stages of loading is given in Table 1. Due to limited space, Load-deflection curves for only two specimens are presented here for example in Figs. 6 and 7. The beams tested here were all under reinforced, and in their load-deflection curves four significant stages are observed. At all the four stages FRP strengthened beams show increased load carrying capacity as compared to unstrengthened beams. Details are discussed below.

The first stage 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.

The second significant stage was the yield point, 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).

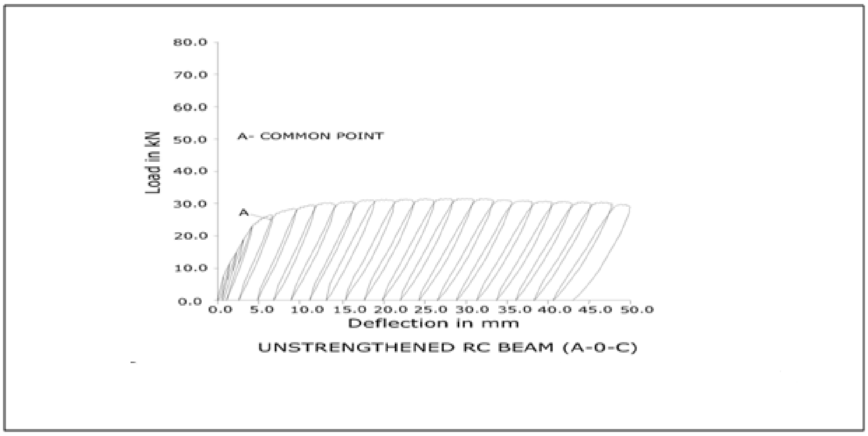


FIG.6. CYCLIC LOADING TEST TO OBTAIN COMMON POINTS (SPECIMEN A-0-C)

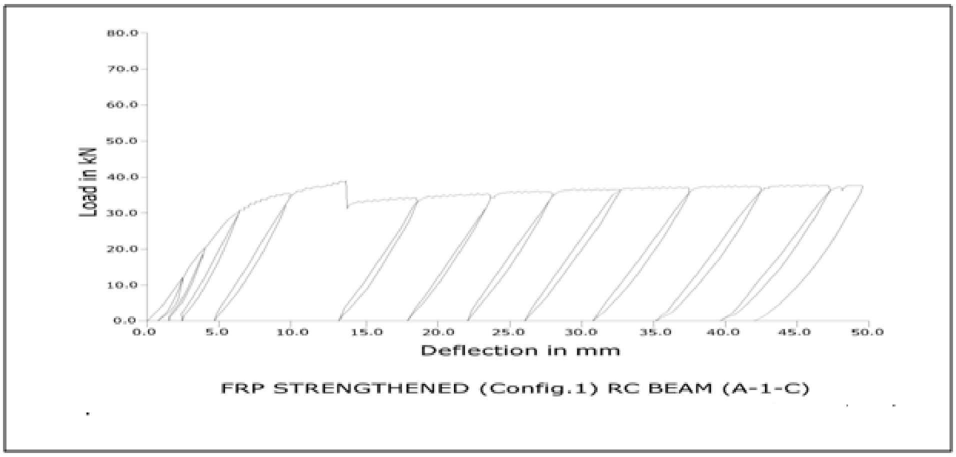


FIG.7. CYCLIC LOADING TEST TO OBTAIN COMMON POINTS (SPECIMEN A-1-C)

The third stage corresponds to maximum load on the load deflection curve (P_m). The load-deflection curve became almost horizontal at this stage 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 corresponding to ultimate load (P_u), which corresponds to failure of the beam. Failure is defined here as when load cannot 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.

Accordingly, failure modes for all unstrengthened and FRP strengthened beams were observed and failures of only a few beams are shown in Fig. 8. As all beams tested in this program were under reinforced, failure of unstrengthened beams was ductile failure, with large deflection in the order of 40-50 mm at ultimate load.

Fig. 8 Failure of beams A-0-C, A-1-C, B-1-C, C-1-C

4.2. Effect of strengthening with FRP

As per the load-deflection curves and the Table 1 (obtained from the load-deflection curves), effect of strengthening with FRP is given below-

1. In general, failure of the FRP strengthened beams begins with yielding of steel followed by sudden FRP rupture with sound. Concrete crushing at top of beam was also noticed at the same time in all the cases. It is to be noted here that each FRP strengthened beams were strengthened with very little amount of FRP (only 0.00053 percentage).

2. End-span de-bonding has not been observed in any case. Extending FRP to the supports i.e. zero moment regions (where it is actually not needed for the purpose of flexural strengthening) effectively mitigated the concrete cover delamination. Concrete cover delamination due to end-span de-bonding involves full depth of concrete cover, while with mid-span de-bonding (observed in some parts of the vast experiment which is beyond the scope of present experiment) only thin layer of concrete is peeled off with FRP.

3. It is observed that flexural strengthening of RC Beams using FRP provides extra strength but with brittle mode of failure. Applying higher percentage of FRP may result in higher increase in strength but it will be with reduced ductility and will demonstrate extremely brittle behaviour with catastrophic failure.

4. As failure begins with yielding of steel followed by sudden FRP rupture or debonding in case of FRP strengthened under reinforced RC beams 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, behaviour of strengthened beams is just like as of unstrengthened beams with yielded steel.

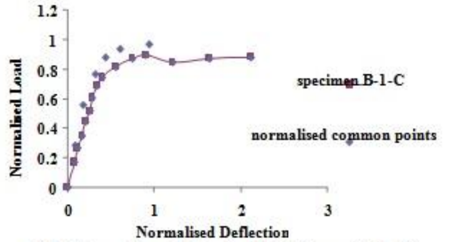
5. Deflection at maximum load of FRP strengthened RC beams is very less as compared to unstrengthened RC beams. Decrease in deflection due to FRP strengthening can be very useful to mitigate excessive deflection problem of under reinforced RC beams having very small amount of tensile steel.

6. In case of strengthened beams of group A (with lower amount of tensile steel), higher extra strength provided by the same amount of FRP and better deformation capacity has been noticed as compared to strengthened beams of the other two groups viz.- B and C (which were reinforced with higher amount of internal tensile steel). This observation indicates that strengthening using FRP is more effective and far better in case of under reinforced RC beams having lower amount of steel.

7. In general higher value of first crack load, more number of thinner cracks and higher ultimate load however not that significant, and better deformation capacity were noticed in case of FRP configuration no. 2 (in which FRP is distributed over the tension face) - where two symmetrically placed FRP strips were used in single layer as compared to other two configurations of the same group of beams (in which FRP is concentrated at centre). In configuration no. 1 - single FRP strip was placed at centre and in configuration no. 3 – two FRP strips were placed in double layer at centre. Amount of FRP was the same in all the three configurations. This is noticed for all the three groups of beams viz. - A, B and C, having different amount of steel. Distributing FRP over the tension face gives more effective and far better configuration.

4.3. Common point curves

Common point curves are plotted on normalized load-deflection co-ordinate system. In this system the load co-ordinates are normalized with respect to P_m-maximum load, of each specimen; and deflection coordinates are normalized with respect to δm-the deflection corresponding to maximum load. Common point curves are plotted using the common points obtained from the cyclic test. A comparison of common point curves also is drawn for each group of beams. Due to space limitations only one common point curve is shown in Fig.9 from the beams of group B. Comparison of common point curves is shown in Fig.10 for instance for the beams of the same group B. Here also the common point curves for FRP strengthened beams lay above that of unstrengthened beam, and that the curve for beam with FRP strengthening configuration 2(in which FRP is distributed over the tension face), supersedes other two configurations 1 and 3. This is observed for all the three groups of the beams -A, B and C.



FRP Strengthened (Config. 1) RC Beam (B-1-C)
Fig. 9 Common Point Curve (Group B)

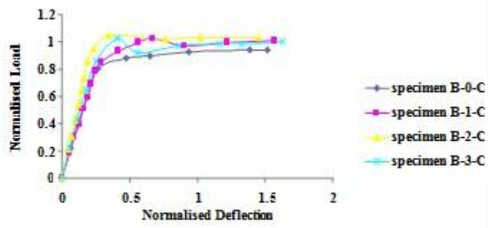


Fig. 10 Comparision of Common Point Curves (Group B)

4.4. Permissible load capacity of FRP strengthened beams under cyclic loading

The common points and consequently common point curve fall below the envelop curve (the curve following peaks of the load deflection curve of each cycle). This envelop curve for cyclic loading coincides with the envelop curve obtained under monotonic loading reported elsewhere (Shrivastava et al, 2013a). This shows that the permissible load level for FRP strengthened RC beams under cyclic loading is lower than that for monotonic loading. Permissible load levels were obtained using stability point approach (which is time intensive) reported elsewhere (Shrivastava et al, 2013b). Hence it is suggested that due consideration be given to cyclic behaviour of beams, as live loads are of cyclic nature for the majority of the structures, and maximum load may be reduced for cyclic loading.

V. CONCLUSIONS

i. Extra strength but extremely brittle behavior with reduced ductility leading to catastrophic failure is obtained by flexural strengthening of RC Beams with FRP.
ii. Failure begins with yielding of steel followed by sudden FRP rupture or debonding in case of FRP strengthened under reinforced RC beams.
iii. After sudden FRP rupture or debonding, FRP strengthened under reinforced RC beams show behaviour of unstrengthened beams with yielded steel.
iv. Problem of concrete cover delamination or end-span debonding, can be overcome effectively by applying FRP up to the supports.
v. In case of under reinforced RC beams having lower amount of steel, strengthening with FRP is far effective and better.
vi. Distributing FRP over the tension face is better and far effective than applying FRP as a single strip.
vii. The permissible load for FRP strengthened RC beams under cyclic loading is lower than that for monotonic loading. It is suggested that maximum load must be reduced for cyclic loading.

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