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Retrofitting of RCC Beams using FRP and Ferrocement Laminates

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Abstract: ***Presently most of structural components are unable to render their services for full service life, which is due to deterioration of concrete and reinforcements caused by aggressive environment. This results in requirement of rehabilitation of the members. Retrofitting can be used as cost effective alternative to the replacement of such members which is often the only solution. The main objective of this investigation is to find a feasible and most efficient strengthening alternative. In search of such solution, the structural behaviour of reinforced concrete beams strengthened with Carbon Fibre Reinforce Polymer (CFRP), Glass Fibre Reinforced Polymer (GFRP) and Ferrocement laminates have been studied. In this program, 24 beams of 1500 x 200 x150 mm were cast. These beams were load tested for flexural and shear modes of failure. For each mode of failure, there were four sets of beams (where each set consists of three beams), i.e. control beams, CFRP and GFRP strengthened beams and ferrocement strengthened beams. CFRP and GFRP strengthened beams along with ferrocement strengthened beams have enhanced first crack load by 17.3%, 33.1% and 9.4% respectively while ultimate load carrying capacity was enhanced by 19%, 31% and 10.4% respectively for CFRP strengthened, GFRP strengthened and ferrocement strengthened beams.***

Keywords: Control beams, CFRP strengthened beams, GFRP strengthened beams, ferrocement strengthened beams, first crack load, ultimate load, flexure and shear modes of failure

1. Introduction

The maintenance and up-gradation of structural members is one of the most crucial problem in civil engineering structures. A large number of structures constructed in the past using older design codes in different parts of the world are sometimes structurally unsafe according to new code provisions. Since, replacement of such deficient elements of structures incur a huge amount of public money and time, strengthening has become the acceptable way of improving their load carrying capacity and extending their service lives. Environmental decay caused by premature deterioration of buildings and structures has lead to the several processes of repairing and strengthening. One of the challenges in strengthening of concrete structures is selection of strengthening method that will enhance the strength and serviceability of the structure while addressing limitations such as constructability, building operations and budget. Structural strengthening may be required due to any one or more of the following situations:

- Additional strength may be required due to deficiency in structures ability to carry the original design loads. This deficiency may be result of deterioration (due to corrosion of steel reinforcement and loss of concrete section), structural damage (due to vehicular impact, excessive wear, excessive loading and fire), or due to errors in the original design or construction (due to misplaced or missing of reinforcing steel and inadequate concrete strength).
- Additional strength may be needed to allow for higher loads to be placed on the structure. This is often required when the use of structure change and a higher load carrying capacity is needed. This can also occur if additional mechanical equipments, filing systems, planters or other items are being added to the structure.
- Strengthening may be needed to allow the structure to resist loads that were not anticipated in the original design. This may be encountered due to change in location of site and strengthening is required for loads, resulting from wind and seismic forces or to improve blast loading resistance.

When dealing with such circumstance, each project has its own set of restrictions and demands. Whether addressing space restrictions, constructability restrictions, durability demands or any number of other issues, each project requires a great deal of creativity in arriving at a strengthening solution. The majority of structural strengthening involves improvement in ability of the structural element to safely resist one or more of the following internal forces cause by loading: flexure, shear, axial and torsion. Typical strengthening techniques such as section enlargement, externally bonded reinforcement; post-tensioning and supplementary supports may be used to achieve improved strength and serviceability.

Strengthening system can improve the resistance of the existing structure to internal forces in either a passive or active manner. Passive strengthening systems are typically engaged only when additional loads, beyond those existing at the time of installation are applied to the structure. Bonding steel plates or fibre reinforced polymer (FRP) composites on the structural members are examples of passive strengthening systems. Active strengthening systems typically engage the structure instantaneously and may be accomplished by introducing external forces to the member that counteract the effects of internal forces. Examples of this include the use of external post-tensioning systems or by jacking the member to relieve or transfer existing load. Whether passive or active, the main challenge is to achieve composite behaviour between existing structure and the new strengthening elements.

The selection of most suitable method for strengthening requires careful consideration of many factors including the following engineering issues: 1. evaluation of existing load carrying capacity, 2. magnitude of increase in strength required, 3. effect of change in relative member stiffness, 4. environmental conditions, 5. in-place concrete strength and substrate integrity, 6.dimensional/ clearance constraints, 7. accessibility, 8. availability of materials, equipments, qualified and skilled manpower, 9.evaluation/effectiveness of new techniques and materials and 10. Service life and its cost.

FRP as structural reinforcement in combination with other construction materials like steel and concrete has proven its ability. FRP exhibit several improved properties like high strength/weight ratio, high stiffness/weight ratio, flexibility in design, non-corrosiveness, high fatigue strength and its ease of application.

Ferrocement is a type of thin walled reinforced concrete commonly constructed of hydraulic cement mortar reinforced with closed spaced layer of continuous and relatively smaller diameter meshes. The mesh may be of metallic or other suitable materials. Ferrocement possesses a high degree of toughness, ductility, durability, strength and crack resistance which is considerably greater than that found in other forms of concrete construction.

2. Literature Review

Ahmed and Antonio [1] studied the shear performance of Reinforced Concrete (RC) beams with T-section. Different configurations of externally bonded Carbon Fibre Reinforced Polymer (CFRP) sheets were used to strengthen the specimens in shear. The experimental program consisted of six full scale simply supported beams. One beam was used as a bench mark and five beams were strengthened using different configurations of CFRP. The parameters investigated were wrapping schemes, CFRP amount, $90^0/0^0$ ply combination and CFRP end anchorage. Test results indicated that externally bonded CFRP reinforcement can be used to enhance shear capacity of the beams and increase in shear strength of 35 – 145% was achieved. Results show that externally bonded CFRP can increase shear capacity of the beam significantly. The results also indicated that the most effective configuration was U-wrap with end anchorage.

Al-Sulaimani et. al. [2] studied beahaviour of box beams under transverse shear by conducting flexural tests on 15 specimens. The parameters studied were amount of wire mesh reinforcement in web and in flanges of the beams, shear span to depth ratio. Test results revealed that cracking and ultimate shear force increases as wire mesh in web is increases. Placing wire mesh in flanges and in web also increases the shear resistance through arresting tension cracks and causing them to be finer. Shear behaviour studied was in relation to total volume of wire mesh reinforcement in webs and flanges. Cracking and ultimate shear strength also increases as shear span to depth ratio is decreases. They found that ferrocement is less ductile in shear than flexure. They also found that cracking and ultimate shear stresses for ferrocement increases with increasing mortar strength and wire mesh reinforcement.

Benjeddou et. al.[3] studied the damaged RC beams repaired by external bonding of CFRP composite laminates to the tensile face of the beam. Two sets of beams were of control and repaired beams. Various parameters like damage degree, CFRP laminate width and concrete strength were considered. They concluded that mechanical performance of the repaired RC beams is improved and the technique is effective. They also reported that laminate width affects failure mode which changes from interfacial de-bonding to peeling off when width of CFRP was increased from 50mm to 100mm.

Nassif and Najm [4] tested 24 beams, two point loading system under simply supported conditions. Beam specimens with square mesh exhibited better cracking load carrying capacity than the control beam as well as beam with hexagonal mesh. However, change in ultimate load carrying capacity was not significant.

Li et. al. [5] performed experimental and numerical analysis to determine load carrying capacity of RC beams strengthened with carbon fibre reinforced plastic (CFRP) composites. It was concluded that CFRP can effectively increase initial cracking loads, ultimate loads, stiffness and ductility of concrete beams and improve crack pattern. De-bonding failure of concrete beams strengthened with CFRP occurs before the normal ultimate load and high strength of CFRP cannot be fully utilized. It influences the performance of strengthened concrete beams and should be considered sufficiently during the design process.

Koji et. al. [6] studied flexural behaviour of RC beams strengthened with CFRP sheets and bonded with epoxy resin adhesive. The results indicated that flexural rigidity and flexural strength of RC strengthened beams were increased by 1.9 to 2.4 times than that of virgin beam.

Bank and Arora [7] conducted experimental work in which FRP strips reinforced with a combination of carbon and E-glass uni-direction fibres and continuous strand mats, were fastened to concrete beams with steel powder activated fasteners and expansion anchors. They were tested for different failure modes. Tests demonstrated that strengthened beams failed in ductile manner as intended and demonstrated an increase in yield and ultimate moments up to 25% and 58% respectively over virgin beam.

Silva and Biscaia [8] studied the degradation of bond between FRP and RC beams. The effect of cycles of salt fog, temperature and moisture as well as immersion in salt water on bending response of beams externally reinforced with GFRP and CFRP especially on bond between FRP reinforcement and concrete was considered. Temperature cycles (-10^0C to 10^0C) and moisture cycles were associated with failure in concrete substrate, while fog salt cycles originated failure at the interface of concrete-adhesive. Immersion in salt water and salt fog caused considerable degradation of bond between GFRP strips and concrete. Immersion did not lower the load carrying capacity of beams, unlike temperature cycles that cause considerable loss. No significant difference was detected on the behaviour of strengthened beams with GFRP and CFRP.

Shahawy et. al. [9] studied effect of CFRP laminates bonded with epoxy on RC rectangular beams. The number of laminates was varied and it was noted that cracking moment for laminated beams was significantly higher than that of control beam. The percentage increase in the measured cracking moment was 12%, 61% and 105% higher for one, two and three laminate layers, while ultimate capacity increased by 13%, 66% and 92% respectively.

Mansur and Ong [10] found that shear strength of ferrocement beam depends on the strength of mortar, volume fraction and strength of wire mesh. Shear strength of beams reinforced with welded wire mesh was found more than the beam reinforced with woven or hexagonal wire mesh. The beams were reinforced with only welded wire mesh with various layers of mesh lumped together in layers at top and bottom. Test results showed that diagonal cracking strength of ferrocement increases as the span to depth ratio decreased and volume fraction of reinforcement, strength of mortar and amount of reinforcement near compression face is increased. Ferrocemnt beams are susceptible to shear failure at small span to depth ratio when volume fraction of reinforcement and strength of mortar are relatively high.

Al-Kubaisy and Nedwell [11] presented the study on behaviour and strength of ferrocement beams under shear. The results of 30 simply supported beams tested under single concentrated loads are presented.The influence of shear span to depth ratio (a/h), volume fraction of reinforcement (V_f) and strength of mortar ($f_{c'}$) on crack pattern, modes of failure and cracking strength were examined. They concluded that mode of shear failure can only be predicted on the basis of a/h and V_f alone. Shear force at failure cannot be relied upon exceeding cracking shear. Shear force at critical cracking must be considered as the useful shear capacity of beam.

3. Experimental Investigation

Materials

Cement, fine aggregate, coarse aggregate, reinforcing bars are used in casting of beams and mild steel wire mesh, GFRP and CFRP and cement slurry are used for retrofitting of the beams. Primer is used for preparing base and saturant is used for fixing fibres with beams.

Cement

Ordinary Portland cement of 43 grade from a single lot was taken for study. The physical properties of cement as obtained from tests are listed in Table 1 as per IS: 269-2015 [12].

Table 1: Properties of cement

Characteristics	Values Obtained	Values as per IS: 269-2015
Standard consistency	32.5	-
Fineness of cement as retained on 90 µ sieve (%)	4 %	≤ 10 %
Setting time 1. Initial (minutes) 2. Final (minutes)	55 275	≥ 30 ≤ 600
Specific gravity	3.14	-
Compressive strength 1. 7 days (MPa) 2. 28 days (MPa)	34 44	≥ 33 ≥ 43

Table 2: Sieve analysis of fine aggregates

sieve size (mm)	weight retained (g)	% weight retained	cumulative % of weight retained	% passing
4.75	95.0	9.50	9.50	90.50
2.36	42.5	4.25	13.75	86.25
1.18	110.5	11.05	24.80	75.20
0.60	128.5	12.85	37.65	62.35
0.30	308.0	30.80	68.45	31.55
0.15	281.0	28.10	96.55	3.45
Pan	34.5	3.45	-	-
Fineness modulus (F.M.)= Σ (cumulative % retained)/100			= 250.7 / 100 = 2.507	

Fine Aggregates

The sand used for the experimental work was locally procured. The sand was first sieve through 4.75 mm sieve to remove all particles of greater than 4.75 mm size. Thereafter, its sieve analysis was carried out in the laboratory, test results are given in Table 2 and gradation found is conforming to grade III of IS: 383-2016 [13]. Its specific gravity and water absorption were determined as 2.65 and 1.02%.

Coarse Aggregates

Crushed stone aggregate (locally available) of 20 mm down was used in throughout the experimental study. Its specific gravity and water absorption were found as 2.61 and 2.37%, while sieve analysis test results are given in Table 3.

Table 3: Sieve analysis of coarse aggregates

sieve size (mm)	weight retained (g)	% weight retained	cumulative % of weight retained	% passing
20	0.0	0.00	0.00	100.00
12.5	2186.5	72.883	72.883^{+}	27.117
10	674.5	22.483	95.366	4.634
4.75	130.0	4.33	99.696	0.304
2.36	9.0	0.30	100.00	0.00
Pan	0.0	0.00	-	-
Fineness modulus(F.M.) = Σ (cumulative % retained)/100			= 695.062 / 100 = 6.95	

+ Not included in F.M. calculation

Water

Fresh clean water available in the laboratory was used in casting and curing of the specimens.

Reinforcing Steel

Mild steel of grade Fe250 of 12 mm and 8mm diameter bars were used as longitudinal steel. 12mm diameter bars were used as tension reinforcement and 8mm diameter bars as compression/ hanger bars and also as shear stirrups.

Wire mesh

Mild steel wire mesh of 2.4 mm diameter with square grids was used in ferrocement jacket. The grid size of mesh was 40mm.

Fibre Reinforced Polymer (FRP)

The Tyfo SEH 51(GFRP) and Tyfo SCH 11 (CFRP) high strength fabric consisted of glass and carbon fibres respectively in the primary direction and Kevlar fibres at 90 degree to the primary fibre direction. Standard rolls of fabric are available. The structural properties of two materials as supplied by the manufacturer are given in Table 4.

Saturant epoxy

The Tyfo S Epoxy is a two component epoxy material for bonding between FRP reinforcement and RC specimen in order to have a composite material. Tyfo component ‘A’ and ‘B’ were mixed in 1:0.42 proportions by volume to have Tyfo epoxy material. Properties of epoxy components were supplied by the manufactured, which are given in Table 5.

Table 4: Composite gross laminate properties tested as per ASTM D-3039

Properties	Tyfo SCH 11		Tyfo SEH 51	
	test value	design value	test value	design value
Ultimate tensile strength in primary fibre direction (MPa)	827	690	575	460
Elongation at break (%)	1.0	0.5	2.2	1.76
Tensile modulus (GPa)	82.7	74.5	26.1	20.9
Ultimate tensile strength 90^0 to primary fibre (MPa)	0	0	43	34.4
Laminate thickness (mm)	0.6	0.6	1.3	1.3

Table 5: Properties of epoxy components

Curing schedule 72 hours post cure at 60^0C	
property	test value
Colour	Component A is clear to pale yellow Component B is clear
Viscosity	Component A at 25^0C is 11000-13000 cps Component B at 25^0C is 11cps
Pot life	3 – 6 hours at 20^0C
Viscosity of mixed product	600 – 700 cps
Density at 20^0C kg/litre	Component A = 1.16, Component B = 0.95 Mixed product = 1.11

Concrete mix

M20 grade design mix concrete was used in preparing the specimens. Water/cement ratio used in the design was 0.5. The mix proportions determined for the design mix were 1:1.72:2.86 (cement: fine aggregate (i.e. sand): coarse aggregate). The average compressive strength of concrete was 29 N/mm^2.

Table 6: Details of reinforcement in beam specimens

type of strength to be determined	longitudinal reinforcement	transverse/ shear reinforcement
Flexural	2 bars of 8 mm diameter (top) 2 bars of 12 mm diameter (bottom)	8mm diameter @ 130 mm centre to centre.
Shear	2 bars of 8 mm diameter (top) 2 bars of 12 mm diameter (bottom)	8mm diameter @ 190 mm centre to centre.

Mortar mix

The proportion of cement sand mortar used for ferrocement was 1: 2 (cement: sand) and water/cement ratio for the mortar was taken as 0.40.

Test specimens

A total of 24 RCC beams of 1500 x 200 x 150 mm were designed using M20 grade concrete and Fe250 steel. The beams were designed as under reinforced section. The details of reinforcement in the specimens are given below in Table 6.

Casting of Beam Specimens

Casting of all specimens was done in one stage. Spacers of size 25 mm were used to provide uniform clear cover to the reinforcement. First reinforcement cages were placed in position, concrete mix was poured in the mould, which was already coated with mould release oil. Vibrations were given with the help of needle vibrator, so that concrete mix gets compacted. The vibrations were given until the mould was filled completely and there was no gap left. The beams were then covered with moist jute bags for 24 hours, thereafter de-moulded and cured in water for 28 days.

Application of FRP Composites

FRP composite comprised of woven fibre mat namely Tyfo SEH 51 (GFRP) and SCH 11 (CFRP) respectively which were saturated in epoxy resin. The specimens surfaces were saturated with epoxy first and woven fibre mat was applied next to surface of the member manually, by exerting a uniform pressure that was distributed across the entire width of fabric surface, so that all air bubbles/ pockets could come out to ensure a uniform and smooth final surface. The FRP composite materials require air curing for 72 hours. All specimens were carefully staggered without any contact with each other and without any contact with floor or any object to avoid any sticking for air curing.

Application of Ferrocement

First of all, surface of 6 beams were cleaned thereafter cement slurry was applied on the beams for proper bonding between ferrocement laminate and the beam. These beams for shear strengthening were retrofitted with wire mesh at an orientation of 45^0. Thereafter, 20mm cement mortar (1:2 with w/c = 0.4) plaster was applied on three faces of the beams. Finally beams were cured for 7days. Thereafter, these beams were tested in similar manner to control beam under two point loading to determine ultimate load and corresponding deflections.

4. Experimental Setup

Flexure mode of failure

The beam specimens were tested under two point loading for simply support conditions keeping a distance of 200 mm between loading points symmetrical to mid span and 1200 mm distance between supports. The load was applied through a 1000kN hydraulic jack and monotonically increased at constant rate up to failure. The load versus deflection values were recorded at regular intervals. The crack load, ultimate load and their corresponding increase for strengthened beams with respect to control beam are given in Table 7.

Table 7: Test results of beam specimens under flexure mode of failure

specimen designation	1st crack load (kN)	Av. 1st crack load (kN)	ultimate load (kN)	average ultimate load (kN)	remarks
F1	45	42.33	98.4	93.67	Control
F2	42		89.2		
F3	40		93.4		
F4C	50	49.67	112.8	112.6	CFRP
F5C	48		108.4		
F6C	51		116.6		
F7G	54	56.33	125.4	125.4	GFRP
F8G	58		130.8		
F9G	57		120.0		
F10F	45	46.33	108.6	103.4	Ferro-cement
F11F	48		103.2		
F12F	46		98.5		

Table 8: Test results of beam specimens under shear mode of failure

specimen designation	1st crack load (kN)	Av. 1st crack load (kN)	ultimate load (kN)	average ultimate load (kN)	remarks
S1	60	62.67	125.0	130.63	Control
S2	62		135.5		
S3	66		131.4		
S4C	75	78.00	160.5	155.43	CFRP
S5C	78		150.0		
S6C	81		155.8		
S7G	90	92.33	175.7	171.1	GFRP
S8G	95		172.4		
S9G	92		165.2		
S10F	69	70.00	150.6	149.63	Ferro-cement
S11F	71		152.5		
S12F	70		145.8		

Shear mode of failure

The beam specimens were tested under two point loading for simply support conditions keeping a distance of 400 mm between loading points symmetrical to mid span and 1200 mm distance between supports. The load was applied through a 1000kN hydraulic jack and monotonically increased at constant rate up to failure. The load versus deflection values were recorded at regular intervals. The crack load, ultimate load and their corresponding increase for strengthened beams with respect to control beam are given in Table 8.

5. Discussion of Test Results

Flexure mode of failure

The values of first crack load and ultimate load for strengthened beam using one layer of Tyfo SCH 11 (CFRP) and Tyfo SEH 51 (GFRP) laminate and also with ferrocement laminate at soffit along with un-strengthened beam are given in Table 7. It was observed that average values of first crack load are increased by about 17.3%, 33.1% and 9.5 % for CFRP, GFRP and ferrocement strengthened beams respectively, compared to first crack load of control beam. The GFRP strengthened beam increased first crack load significantly as compared to CFRP and ferrocement strengthened beams.

Similarly, ultimate load values for strengthened beam using Tyfo SCH 11 (CFRP) and Tyfo SEH 51 (GFRP) laminate and also with ferrocement laminate at soffit along with un-strengthened beam are given in Table 7. It was observed that average values of ultimate load are increased by about 20.2%, 33.9% and 10.4 % for CFRP, GFRP and ferrocement strengthened beams respectively, compared to ultimate load of control beam. The GFRP strengthened beam increased ultimate load significantly as compared to CFRP and ferrocement strengthened beams.

The load deformation behaviour at mid span of control beams, FRP and ferrocement strengthened beams is shown in Fig. 1. The specimens strengthened with GFRP, showed first crack within the region of constant moment of the beams. Therefore, a large linear phase was recorded, with the development of numerous flexural cracks later. In later phase, the deflection in the GFRP sheet increased considerably and the specimens demonstrated de-bonding failure at both ends. It is concluded that this system is considerably effective. The specimens strengthened with CFRP showed de-bonding, which was started at one of the flexural cracks in the constant moment region and propagated towards the support until total de-lamination occurred and resulted in rupture of the fibre system. This sheet may be considered as a relatively brittle material, which can be used for strengthening of light and secondary beams only. In ferrocement strengthened beams, a marginal increase in load was observed.

Flexural cracks were initiated randomly in the constant moment region, but as the load was increased, cracked zone spread towards supports and inside the section. The specimen retrofitted with GFRP at soffit exhibited a gradual failure though the final mode of failure was due to de-bonding. Due to de-bonding, total strength of laminates could not be utilised. Hence, the strength of retrofitted beam can be further enhanced by taking proper care of de-bonding. The beams retrofitted with ferrocement, initial cracks started at a higher load than for control beams. Further with the increase in loading, propagation of cracks took place towards inside of the section and also towards supports and finally beams failed in flexure on crushing of concrete at mid span region.

Shear mode of failure

The values of first crack load and ultimate load for strengthened beams by CFRP, GFRP and ferrocement along with control beams (i.e. un-strengthened beam) are given in Table 8. It is observed that average first crack load is increased by about 24.5%, 47.3% and 11.7% for strengthened beams by CFRP, GFRP and ferrocement respectively compared to first crack load of control beams. Similarly, ultimate load is increases by about 19%, 31% and 14.5% respectively for CFRP, GFRP and ferrocement strengthened beams respectively, compared to ultimate load of control beams. The overall performance of the beams retrofitted by GFRP is found the best as compared to CFRP and ferrocement strengthened beams.

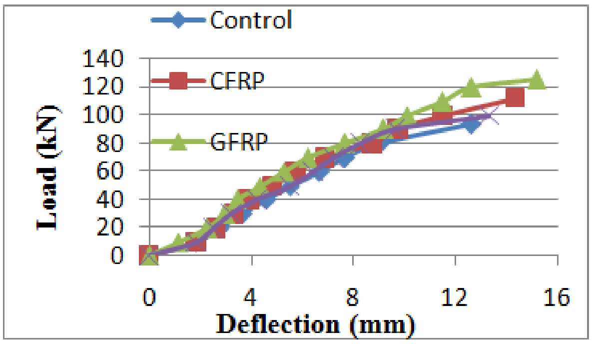

Figure 1: Load versus mid span deflection for flexure mode of failure

Load deformation behaviour of all beams was recorded. Load versus mid span deflection for all four types of beams is shown in Fig. 2. It has been observed that all the beam specimens experienced brittle shear failure mode by developing diagonal tension cracks in the constant shear spans. The diagonal cracking was followed by de-bonding of fibre wrapping system. The GFRP system with full wrap is found more effective compared to CFRP system and ferrocement laminate. The ultimate deformation found more for GFRP system than the others. It is concluded that GFRP system is more effective in enhancing ultimate load carrying capacity of the beam in shear failure mode also.

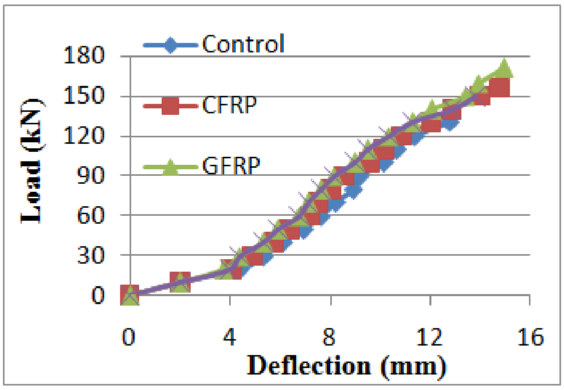

Figure 2: Load versus mid span deflection for shear mode of failure

Shear failure mode of control beam specimen demonstrated that the diagonal cracks were uniformly distributed between loading points and supports. Shear failure of RC beams strengthened with FRP is found similar to those of un-strengthened beams by diagonal failure with main inclined shear cracks along with large number of cracks in fibre wrap and de-lamination started simultaneously.

6. Conclusions

1. First crack load are found about 17.3%, 33.1% and 9.5% higher in CFRP, GFRP and ferrocement strengthened beams respectively as compared to control beams.
2. The ultimate load carrying capacity of retrofitted beam specimens is enhanced by about 19%, 31% and 10.4% for CFRP, GFRP and ferrocement strengthened beams respectively.
3. The cracks at ultimate load in strengthened beams are more in number compared to few wide cracks of virgin beams indicating clearly a composite action in retrofitted beams.
4. The use of FRP delays initial cracks and further developments of cracks in the beam. Also ductile behaviour of FRP gives us enough warning before ultimate failure.
5. GFRP laminates has been found superior to CFRP laminates and ferrocement in enhancing the overall performance of strengthened beams.

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