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Retrofitting of RC girders using pre-stressed CFRP sheets

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Abstract. Pre-stressing of existing structures using steel cables, FRP cables or FRP laminates has been successfully tried in the past. Retrofitting of beams using pre-stressed laminates does not utilize the full strength of the FRP due to de-bonding of the laminates before the fibre fracture. In the present study attempt has been made to overcome this problem by replacing the FRP laminates by the FRP sheets. In the present paper the effect of initial damage level and pre-stress level on strength, stiffness, cracking behaviour and failure mode of girders retrofitted using pre-stressed CFRP sheets has been studied. The results indicate that rehabilitation of initially damaged girders by bonding pre-stressed CFRP sheets improves the flexural behaviour of beams appreciably. However, it has been observed that with increase in pre-stressing force the load carrying capacity of the girders increases up to a particular level up to which the mode of failure is fibre fracture. Thereafter, the mode of failure shifts from fibre fracture to de-bonding and there is no appreciable increase in load carrying capacity with further increase in pre-stressing force.

Keywords: retrofitting; pre-stressed FRP sheets; girders; initial damage level; pre-stressing force level

1. Introduction

Many existing structures now-a-days are unable to give their service effectively and get deteriorated or get damaged much before the time for which they are designed for. The damage to the structure can be assessed using different non-destructive techniques. After assessing the initial damage level of the structures the next step is to decide an appropriate retrofitting technique. Apart from conventional methods, there are various methods of retrofitting of structures such as jacketing using steel, FRP or ferrocement plates, external pre-stressing using pre-stressing steel or FRP cable or FRP composites, providing shear or infill wall etc.

The use of fiber reinforced polymers (FRP) to retrofit and rehabilitate concrete structures is rapidly becoming popular. The advantages of using composite materials for retrofitting, as, opposed to steel plate bonding or jacketing, are that FRP is light weight, has a high tensile strength, and possesses a high resistance to acids and bases making them essentially non-corrosive. The use of externally bonded carbon fiber reinforced polymer sheets for flexure and shear strengthening of reinforced concrete structures has been extensively investigated (Priestley and Seible 1993, Saadatmanesh *et al.* 1994, Xiao 1998, Chaallal *et al.* 1998, Hutchinson *et al.* 1998, Pellegrio and

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Modena 1998, and Bank 2006) and concluded that FRP's are very effective in enhancing the seismic performance of the structures. Kim *et al*. (2015) strengthened the RC (Reinforced concrete) beams with four layers of CFRP sheets and each layer of the CFRP is prepared to have different length. Experimental results show that tapered CFRPs have better strengthening effect than non-tapered CFRP sheets. The maximum loads of the beams with tapered CFRPs are governed by the length of first CFRP layer rather than the total length of CFRP layers. Panjehpour *et al*. (2014) concluded that the CFRP-strengthened deep beams exhibit an energy absorption capacity which is 45% to 80% higher than those of ordinary RC deep beams. The trend shows that energy absorption increases approximately linearly with shear span to effective depth ratio. Similar types of results are also observed in the flexural and compression steel members strengthened with carbon fiber reinforced polymers (CFRP) sheets. Park and Yoo (2015) reported 11.3% and 57% increase in load carrying capacity of steel flexural and compression members, respectively, on strengthening with CFRP sheets. Based on past studies, ACI report 440-02 (2002) has given guidelines for strengthening of concrete structures, for strengthening of concrete structures. But this process does not fully utilize the strength of FRP due to lower concrete strength and bond strength at interface of concrete and FRP.

Pre-stressing of concrete is one of the effective methods of utilizing the high compressive strength of concrete. This technique is well established for new structures, but pre-stressing of existing structures is relatively a new area. Pre-stressing of existing structures help in recovering permanent deformations in the structure. Pre-stressing of existing structures using steel cables, FRP cables or FRP laminates has been successfully tried in the past. Yoo *et al*. (2005) performed flexural experiments on RC beams with various pre-stressing levels of 0%, 20%, 40%, 60% and 70% of the tensile strength of CFRP plates. They reported that pre-stressing CFRP reinforcement method increased the cracking stress, yielding stress, and ultimate strength based on the pre-stressing level, while it reduced the displacement of the member during final failure. Park *et al*. (2005) performed flexural experiments on bonded and non-bonded pre-stressed CFRP plate strengthened RC members to evaluate improved member flexural capacity and ductility. However, their research did not consider the various types of parameters that can affect flexural capacity, but mainly focused on pre-stressing levels. Only focusing on the pre-stressing level is insufficient in evaluating the overall capacity improvement because the behaviour of pre-stressed CFRP plate strengthened flexural members also depend on other structural parameters such as concrete strength and member stiffness. A laboratory study was carried out by Soudki *et al*. (2000, 2017), and El Maaddawy *et al*. (2007) in which the overall program included 16 small-scale reinforced concrete beams (100×150×1200 mm) and 20 large-scale beams (152×254×3200 mm). The specimens were exposed to different corrosion levels (minor at 5%, moderate at 10% and severe at a 15% mass loss) by means of a constant impressed current. The strengthening scheme used in the small-scale beams consisted of first layer of CFRP flexural laminate bonded to the tension face, with the fiber orientation in the longitudinal direction followed by second layer of transverse laminates bonded to the tension face and up each side of the beam, with the fiber orientation in the transverse direction. In the large-scale beams, FRP sheets were applied using two repair schemes. The first scheme involved wrapping the specimen intermittently with U-shaped glass (GFRP) strips around the tension face and the sides. The second scheme involved flexural strengthening of the corroded specimen by externally bonding carbon (CFRP) sheet to the tension face of the specimen and then wrapping the specimen with U-shaped GFRP sheets. All strengthened beams exhibited increased stiffness over un-strengthened specimens and marked an increase in the yield and ultimate strength.

Bonacci and Maalej (2000) carried out an experimental program to provide a realistic assessment of the potential of using FRP materials in the repair and strengthening of reinforced concrete flexural members exposed to a corrosive environment. A total of seven specimens (270×400×4350 mm) was tested. Four of the seven RC beams were reinforced externally with one or two layers of CFRP composite. Some specimens were tested under monotonic loading and other specimens were tested under sustained loading. CFRP external reinforcement increased beam load carrying capacities from 10-35% and reduced deflection by 10-32% with respect to the control specimen. The results showed that the use of FRP sheets for strengthening corroded reinforced concrete beams is an efficient technique that can not only maintain structural integrity but also enhance the behaviour of such beams. Mukherjee and Gopal (2009) investigated the flexural behaviour of reinforced concrete (RC) beams that have reached their ultimate bearing capacities and were then retrofitted with externally pre-stressed carbon fiber reinforced composite (CFRC) laminates. The effect of variation in pre-stressing force on CFRC laminates bonded to the RC beam is investigated in terms of the flexural strength, deflections, cracking behaviour and failure modes. The results indicate that rehabilitation of significantly cracked beams by bonding CFRC laminates is structurally efficient. Bansal *et al*. (2011) studied the effect of initial stress on the beams retrofitted with ferrocement jacketing and it was concluded that with the increase in the initial stress level the load carrying capacity of the beams decreases.

Diab *et al*. (2009) studied the short and long-term behavior of the anchorage zones of externally bonded prestressed fiber reinforced polymer (FRP) sheets. The effective bonding length was found to increase to 50% due to creep of the adhesive layer. The anchored end of the FRP sheets using steel plates and anchor bolts is an effective solution to enhance the bond capacity of FRP-concrete interface for short and long-term loading. Michels *et al*. (2014) used innovative gradient anchorage instead of conventional mechanical fasteners for strengthening of RC beams using externally bonded prestressed CFRP strip. It was concluded that structural behavior is very satisfying, exhibiting ductile deformation up to failure. Flexural cracks are not developed in the present case in the gradient anchorage zone, thus not creating any premature debonding in this region.

Mukherjee *et al*. (2009) modeled the process of degradation of RC beams until failure and its recovery through externally prestressed CFRP and proposed a model for the load-deflection behavior of the fresh and rehabilitated beams. The main import of the model is that it incorporates the effect of confinement of concrete. The model shows very good agreement with the experimental results.

The key issues in retrofitting of RC girders using pre-stressed laminates are initial damage level of beams, levels of pre-stress, anchorage system, bonding of laminates/transfer of pre-stressing force to beam, application methods, durability and modelling and design methods.

From the past studied, it is found that on the retrofitting of beams using pre-stressed laminates full strength of the FRP cannot be utilized due to debonding of the laminates. In the present study attempt has been made to overcome this problem by replacing the FRP laminates by the FRP sheets, leading to increase in the surface area for the transfer of the forces.

To meet the objectives of the proposed study, prototype reinforced concrete girders have been cast and then damaged to predefined stress level. The damaged beams have then been retrofitted using pre-stressed CFRP sheets. The effect of initial damage level and different pre-stressing force level on strength, ductility, stiffness of the retrofitted girders has been studied and reported in the paper.

2. Material characterization

The details of the materials used for casting of reinforced concrete girders and retrofitting of the girders using pre-stressed CFRP sheets along with their properties are presented in the subsequent sections. Relevant tests in accordance with Indian standard codes of practice were conducted to determine the physical properties of the materials used in the study.

2.1 Cement

Portland Pozzolana Cement confirming to IS:1489 (Part 1)-1991 available in the local market was used for the study. The physical properties of cement obtained from various tests conducted in accordance with relevant IS standards are given in Table 1.

2.2 Fine aggregates

IS: 383-1970 defines the fine aggregates as the aggregate most of which pass the 4.75 mm IS sieve. The fine aggregates are often termed as sand size aggregates. Locally available riverbed sand was used in the present study. The properties of the same are given in Tables 2 and 3.

As the percentage of fine aggregates passing 600 micron sieve are 52.3, it indicates that the sand conforms to grading zone-II as per IS: 383-1970.

Table 1 Physical properties of Portland pozzolana cement

Sr. No.	Characteristics	Test values	Values as per IS:1489 (Part 1)
1	Standard consistency	32	-
2	Fineness of cement as retained on 90-micron sieve (%)	0.7	< 10
3	Setting time (mins)		
	1. Initial	105	> 30
	2. Final	255	< 600
4	Specific gravity (Specific gravity bottle)	3.10	-
5	Compressive strength (MPa)		
	1. 7 days	27.0	22.0
	2. 28 days	39.0	33.0
6	Soundness (mm) (by Le-Chatelier’s method)i	2.0	< 10 (Fresh cement) < 5 (Old cement)

Table 2 Physical properties of fine aggregates

S. No.	Characteristics	Value
1.	Specific gravity (oven dry basis)	2.46
2.	Bulk density loose (kN/m3)	1.4
3.	Fineness modulus	2.56
4.	Water absorption (%)	0.85
5.	Grading zone	Zone II

Table 3 Sieve analysis of fine aggregates — Weight of Sample = 1000 gm

Sr. No.	Sieve size (mm)	Weight retained (gm)	Percentage weight retained	Percentage weight passing	Cumulative percentage weight retained
1	4.75	4.0	0.4	99.6	0.4
2	2.36	75.0	7.50	92.1	7.90
3	1.18	178.0	17.8	74.3	25.7
4	0.600	220.0	22.0	52.3	47.7
5	0.300	274.0	27.4	24.9	75.1
6	0.150	246.5	24.65	0.25	99.75
7	Pan	2.5	0.25		
					$\Sigma = 256.55$

Fineness modulus = 256.55/100 = 2.56

2.3 Coarse aggregates

The aggregates retained on 4.75 mm IS sieve are termed as coarse aggregates. Two types of crushed aggregates with different sizes were used in the present study as detailed below:

CA-I Aggregates passing through a 20 mm sieve and retained on 10 mm sieve
CA-II Aggregates passing through a 10 mm sieve and retained on 4.75 mm sieve

The properties of these aggregates are listed in Tables 4 to 6.

2.4 Water

Fresh and clean potable water was used for casting and curing of the specimens in the present study. The water was relatively free from organic matter, silt, oil, sugar, chloride and acidic material as per Indian standard IS:456-2000.

Table 4 Sieve Analysis of Coarse Aggregate CA-I — Weight of Sample = 3 kg

Sr. No.	Sieve size (mm)	Weight retained (kg)	Percentage weight retained	Percent weight passing	Cumulative percentage weight retained
1.	80	-	-	100	-
2.	40	-	-	100	-
3.	20	-	-	100	-
4.	10	2648	88.26	11.74	88.26
5.	4.75	324	10.8	0.94	99.06
6.	Pan	28	0.94		
					$\Sigma = 187.32$

Fineness modulus = (500 + 187.32)/100 = 6.87

Table 5 Sieve analysis of coarse aggregate CA-II Weight of Sample = 3 kg

Sr. No.	Sieve size (mm)	Weight retained (kg)	Percentage weight retained	Percent weight passing	Cumulative percentage weight retained
1.	80	-	-	100	-
2.	40	-	-	100	-
3.	20	-	-	100	-
4	10	122.5	40.83	59.17	40.83
5.	4.75	1624	54.13	5.04	94.96
6.	Pan	151	5.04	-	
					Σ = 135.79

Fineness modulus = (500 + 135.79)/100 = 6.36

Table 6 Physical properties of coarse aggregates

Sr. No.	Characteristics	Value	
		CA-I	CA-II
1.	Type	Crushed	Crushed
2.	Maximum nominal size (mm)	20	10
3.	Specific gravity	2.60	2.66
4.	Total water absorption (%)	1.90	1.81
5	Fineness modulus	6.87	6.36

2.5 Reinforcing steel

The HYSD steel of grade Fe-500 D confirming to IS:1786-1985 was used in the present study. 12 mm diameter bars were used as tension reinforcement and 8mm bars were used as compression steel and shear stirrups in the girders, The properties of these bars are presented in Table 7.

2.6 Concrete mix

Nominal M20 grade concrete mix as per Indian Standard code, using the materials with properties given in Tables 1 to 6 was used in the study. The water-cement ratio used in the proportioned mix was 0.50. The mix proportion of material adopted was 1:1.5:3 by weight (cement: sand: aggregate). The 28 days strength results of 150 mm cubes cast for the proportioned

Table 7 Physical properties of steel bars

Sr. No.	Diameter of bars (mm)	Yield-strength (N/mm^2)	Ultimate strength (N/mm^2)	Elongation (percent)
1.	12	530.00	620.00	23.00
2.	10	532.00	630.0	22.0
3.	8	535.00	626.0	24.0
4.	6	542.42	612.7	26.0

Table 8 Compressive strength of cubes for M20 concrete

S. No.	Age (Days)	Compressive strength (N/mm^2)
1.	28	29

Table 9 Physical properties of CFRP

Sr. No.	Physical property	Value
1	Tensile strength	3800 N/mm^2
2	Modulus of elasticity	240 × 103 N/mm^2
3	Density	1.7 g/cm^3
4	Thickness	0.117 mm

mix are listed in Table 8.

2.7 Carbon Fibre Reinforced Polymer (CFRP) material

Unidirectional CFRP sheets have been used for the retrofitting of the RC girders. The CFRP sheets were obtained from BASF construction chemicals and building systems (Fig. 1). Under stress, fibre utilizes the plastic flow of matrix to transfer the load to the fibre which results in high strength and high modulus composite. Properties of the fibre used have been given in Table 9.

2.8 Adhesives

The adhesive used for bonding CFRP sheets with concrete is a compatible epoxy system provided by the manufacturer. It is blue pigmented epoxy resin for saturation of M-Brace fibre sheet to form in-situ CFRP composite. It has been made by mixing base saturant and hardener in the ratio 100:40. Mixing of saturant and hardener is done for five minutes until components are thoroughly dispersed. The properties of the adhesive saturant are shown in Table 10.

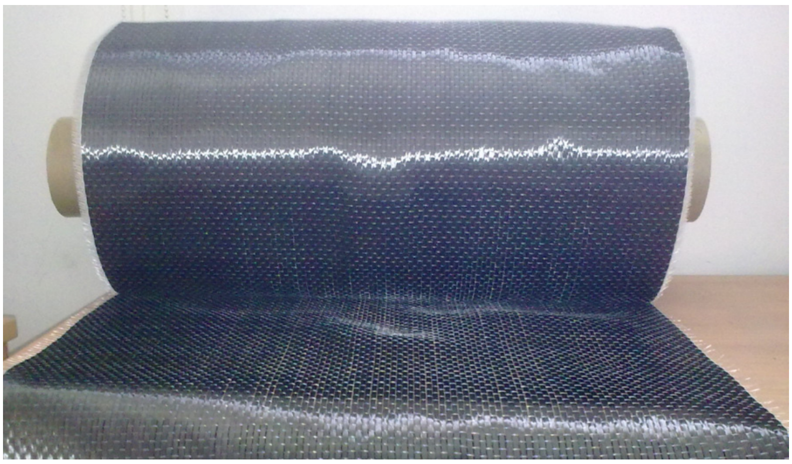

Fig. 1 CFRP sheet used for retrofitting

Table 10 Properties of Mbrace Saturant (as provided by manufacturer)

Aspect	Translucent blue liquid
Volume solids	100%
Mix density	1.13 ± 0.03
Mixing ratio (by weight)	100 to 40
Mixed viscosity (cps at 25°C)	4000 ± 500
Pot life (in minutes)	25 min. at 25°C
Setting time	< 3 hrs. at 25°C
Full cure	7 days at 18°C
Compressive strength	> 40 MPa at 1 day > 60 MPa at 7 days
Tensile strength	> 17 MPa
Flexure strength	> 35 MPa
Density	0.8 to 1.0 kg/m^2

3. Experimental programme

Prototype girders of size 4100×608×304 mm (Ref. Fig. 2) have been cast using M20 grade concrete and Fe-500 D grade steel, designed to behave as under-reinforced section. Girders have been reinforced with 4 bars of 8 mm diameter in the compression zone and 4 bars of 12 mm diameter in the tension zone. 8 mm diameter 4-legged shear stirrups have been provided at a spacing of 75mm center to center to prevent shear failure of girders, as shown in Fig. 2.

Two girders has taken as control girders, are tested after 56 days, to failure and load-deflection curves are plotted. From load-deflection curves obtained, to study the effect of initial stress level, three initial stress levels, first in elastic zone, second in elasto-plastic zone and third in the plastic zone, has been selected. A set of two girders, each has been stressed to these predefined initial stress levels. These have been than retrofitted using pre-stressed CFRP sheets. The test matrix of the experimental programme is shown in Table 9.

Similarly, another set of two girders damaged to predefined level and then retrofitted using three different pre-stress levels, are tested to study the effect of initial pre-stress level. The test matrix of the experimental programme is shown in Table 10.

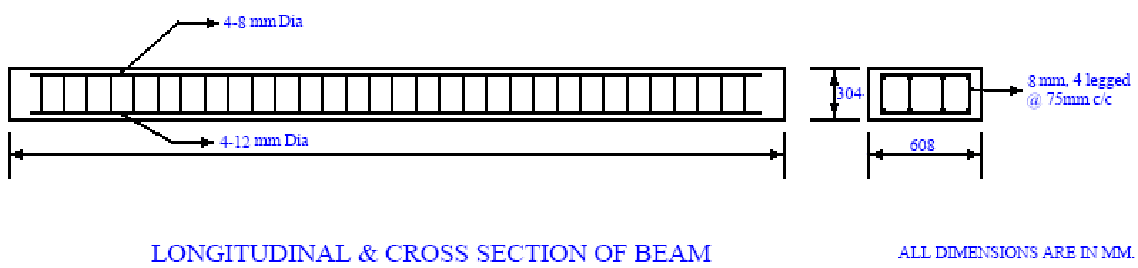

Fig. 2 Structural detailing of girder

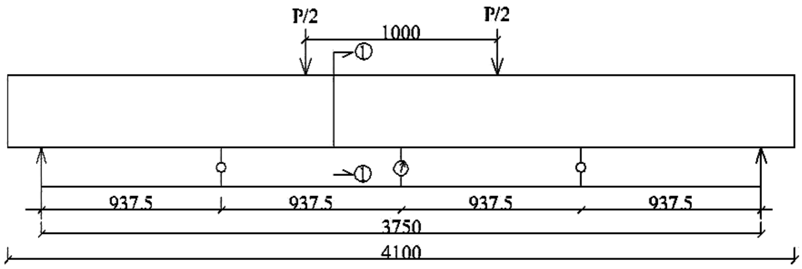

Fig. 3 Loading arrangement for testing of all airder specimens (All dimensions are in mm)

3.1 Testing arrangement

All girders, control as well as retrofitted, have been tested under two point loading system with simply supported end conditions having an effective span of 3750 mm. The point loads have been applied at a distance of 500 mm on either side of the center of the girder (refer Fig. 3). The load has been applied with the help of servo-controlled hydraulic jacks. The deflection corresponding to the loads has been measured with help of LVDT's attached to the data acquisition system. Three LVDT's have been used to measure deflection at quarter spans and at the center of the girder.

3.2 Process of retrofitting using pre-stressed CFRP sheets

The girders have first been stressed to a pre-decided stress level and then these girders are partially de-stressed (due to self-weight only) by putting them upside down on the supports. The surface of stressed girders is then grinded with the help of diamond plate grinder and cleaned to remove all loose particles and dust, to achieve better adhesion of CFRP sheets with the surface of the girder.

The retrofitting of the girders was done with the help of pre-stressed CFRP fabric sheets. The pre-stressing of the sheets was done with the help of specially designed pre-stressing machine. The pre-stressing machine consists of two parts, a fixed end and a moveable end.

Fixed end of the machine consists of MS plate used to fix FRP sheet at one end of the girder. FRP sheet to be fixed is placed between the plate and the girder substrate. The sheet is first bonded to the girder with the help of adhesive and then the plate is fixed with the help of anchor bolts as shown in Figs. 4 and 6. The moveable end further consists of two parts. One part of the moveable end is fixed to the girder with the help of anchor bolts, whereas, the other part, which is moveable arm, is connected to the first part with the help of a pin. A hydraulic jack of capacity 500 kN is fixed between the two parts in such a way that when hydraulic jack opens the moveable arm rotates about the hinge as shown in Fig. 5. The CFRP sheet is fixed to moveable arm, and when jack is opened this causes elongation in the sheet. The elongation in the sheet is measured with the help of LVDT's fixed on both sides of the moveable part as shown in Fig. 7. Using the stress-strain curve of the CFRP sheet, from the elongation, the force in the sheet is calculated. This force will then be transferred to the beam to be retrofitted and act as pre-stressing force. For the purpose, stretched sheet was bonded to the substrate of the girder with the help of adhesive and continuous rolling was done with the roller till the sheet makes bond with the concrete. The sheet is then allowed to cure for the curing period of 7 days (as prescribed by the manufacturer) and during this time the force in the sheet is maintained with the help of the jack. After the curing period, both ends of the pre-stressed CFRP sheet were fixed by wrapping sheet so that there is no slippage/ peeling of the sheet as shown in Fig. 6. The sheet was then detached from the pre-stressing machine and the machine was removed from the girder. The force in CFRP sheet gets transferred to the girder and act as a pre-stressing force in the girder and causes reverse stressing and relives initial deformation in the girder.

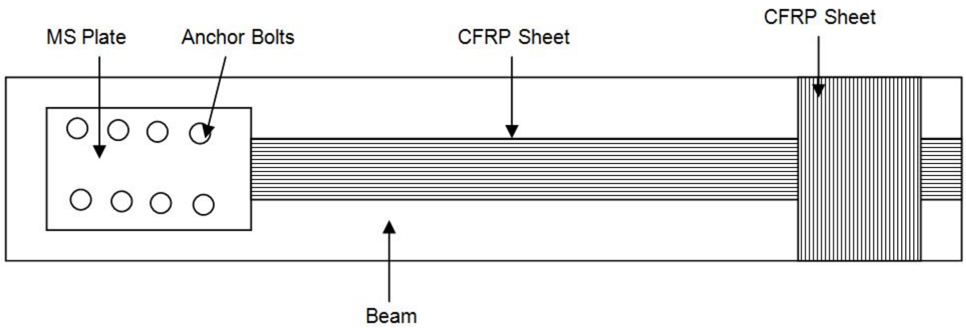

Fig. 4 Anchoring arrangement for pre-stressing

Fig. 5 Pre-stressing machine used for pre-stressing of sheets

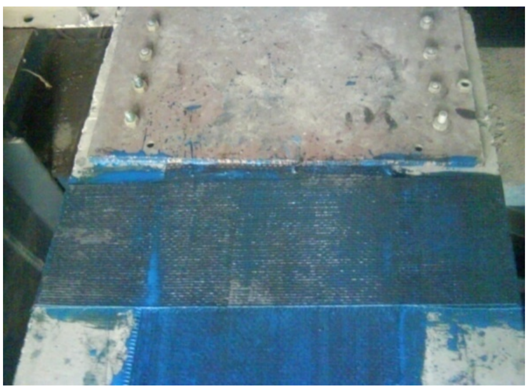

Fig. 6 CFRP sheets anchored on one end

Fig. 7 LVDTs attached to both sides of the machine for measuring the elongation in fibre

4. Result and discussions

Firstly, a set of two control girders (designated as CB01 and CB02) were tested to failure and load and deflection data at center of span and at quarter span was recorded. The average values of results obtained has been taken and plotted and designated as 'RC'. The load deflection curve of 'RC' has been shown in Fig. 8.

During the testing of the girders it has been observed that the damage in the girder started with bending cracks in the central region of the girder. At a load of 75 kN, yielding of the reinforcement started. With further increase in the load the cracks in the girders started increasing rapidly. Major

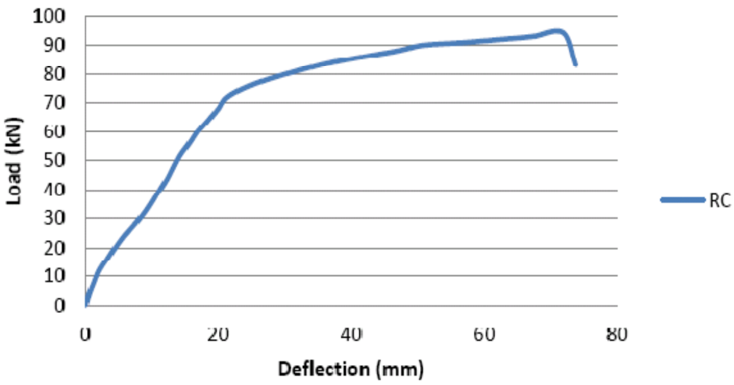

Fig. 8 Load v/s deflection curves of control girder 'RC' at centre of span

Fig. 9 Crack pattern in control girder CB01

cracking has been observed at 87 kN. Girder stopped taking load at 94.35 kN. The cracking pattern shows (as shown in Fig. 9) that the failure in girder is a pure flexural failure as all the cracks are seen near the bottom edge. Maximum deflection recorded at the maximum load was 73.27 mm.

4.1 Effect of initial stress level

To study the effect of initial stress level on girders retrofitted with pre-stressed CFRP sheets, each set of two girders were stressed to three initial damage levels. The initial stress levels were so chosen that first, second and third stress level lies in elastic zone, elasto-plastic and plastic zone, respectively. From the curve the three initial stress levels finalized were corresponding to loads of 50 kN, 84 kN, and 93 kN respectively, which come out to be 53%, 89% and 98% of maximum load carrying capacity of the reference control girder. The designations used for control girder and girders stressed to different stress level is shown in Table 11.

A set of two girders, each was stressed to an initial stress level I, II, and III of maximum load carrying capacity of the control girder. These initially stressed girders were then retrofitted using two layers of pre-stressed CFRP sheets subjected to pre-stressing force of 310 kN, using the setup developed and discussed earlier. The retrofitted girders were again tested to failure and results of each tested girder was recorded. The average values of results obtained has been taken and plotted and designated as RDB1, RDB2, and RDB3 for stress level I, II, and III, respectively. The load

Table 11 Designations of beams used for girders stressed to different levels

Type of girder	Initial stress level	Designation of girder	Designation for average
Control girder	-	CB01	RC
	-	CB02	
Initial stress level I	53% (50 kN)	DB11	RDB1
	53% (50 kN)	DB12	
Initial stress level II	89% (84 kN)	DB21	RDB2
	89% (84 kN)	DB22	
Initial stress level III	98% (93 kN)	DB31	RDB3
	98% (93 kN)	DB32	

Table 12 Designations of girders for girders retrofitted using different pre-stressing force

Type of girder	Pre-Stressing force	Designation of girder	Designation for average
Control Girder	-	CB01	RC
	-	CB02	
Pre-stress level I	80 kN	01 RDB60	RDB60
	80 kN	02 RDB60	
Pre-stress level II	110 kN	01 RDB80	RDB80
	110 kN	02 RDB80	
Pre-stress level III	310 kN	DB31	RDB3
	310 kN	DB32	

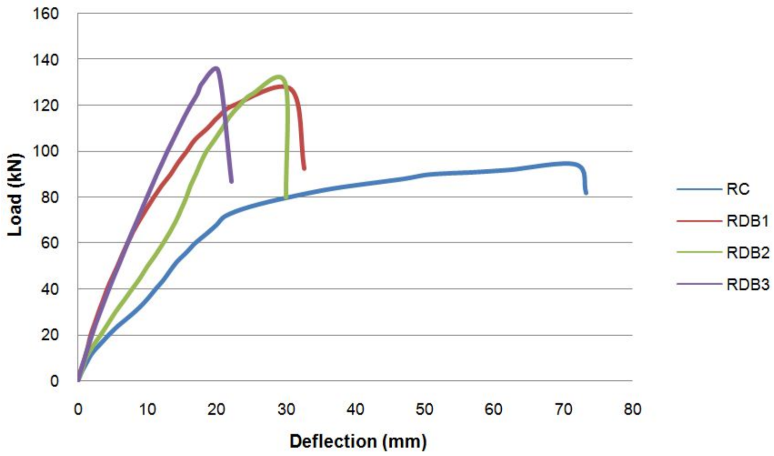

Fig. 10 Load v/s deflection curves of control girder RC and retrofitted girders RDB1, RDB2 and RDB3 at centre of span

Table 13 Maximum load, deflection and stiffness for control and retrofitted girders

Girder	Damage level	Maximum load (kN)	Maximum deflection (mm)	Yield load (kN)
RC	_	94.35	73.27	75
RDB1	50 kN (53%)	127	32.635	120
RDB2	84 kN (89%)	130	30.0	130
RDB3	93 kN (98%)	135.15	22.08	135.15

deflection curves for RDB1, RDB2, and RDB3 and the results obtained are shown in Fig. 10, Table 13, respectively.

It has been observed that after retrofitting the stiffness, yield load and maximum load carrying capacity of the girders increases. However, at maximum load the failure of the girders is observed to be due to debonding of the FRP sheet from the substrate of the girder (as shown in Fig. 11), resulting in a sudden drop in the load.

It has also been observed from Table 13 that after retrofitting average maximum load carrying capacity increased to 127 kN, 130 kN and 135.15 kN for girders RDB1, RDB2, and RDB3 respectively. This projects a 34 to 43 percent increase in maximum load carrying capacity of the girders after retrofitting. Similarly, the average yield load increased to 120 kN, 130 kN and

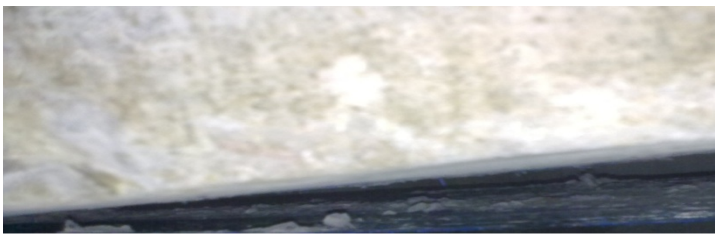

Fig. 11 Debonding of CFRP sheets in girders RDB1, RDB2, and RDB3

135.15 kN for girders RDB1, RDB2, and RDB3 respectively resulting in an average 80 percent increase for retrofitted beams. The stiffness of the retrofitted girder also increased by nearly 140%. The increase in maximum load carrying capacity and yield load of the girders is primarily due to increase in stiffness of the section which can be attributed to the bonding of CFRP sheets at bottom of girders and pre-stressing force applied to the girder. It can be observed from the load deflection curves of retrofitted girders that due to application of CRRP sheets at the substrate of the girders the girders become brittle and yield load is almost equal to the maximum load carrying capacity of the girder. Hence there is an appreciable increase in yield load of the beams. As retrofitted girders reached the maximum load the debonding of CFRP sheets from the substrate of the girders has also been observed due to which there is a sudden transfer of load from CFRP to girder and results a sudden drop in the load. Although due to the limitation of deflection controlled testing in the laboratory it was not possible to observe the behaviour of the girder after it has reached maximum load. However, it is expected that as the failure of the retrofitted girders occurred due to debonding, so after debonding of the CFRP sheets the retrofitted beams will take the path of the control girder thus may result in a further increase in the both ductility and energy absorption capacity of the girders. Moreover, as the mode of failure of the girders is by debonding so no appreciable effect of initial stress level is observed in the retrofitted girders.

4.2 Effect of pre-stress level

To study the effect of pre-stress level on girders, retrofitted with pre-stressed CFRP sheets, a set of two girders, each damaged to 98 percent of maximum load carrying capacity of control beam and then retrofitted with three different pre-stressing forces were considered. The pre-stressing forces selected were 80 kN, 110 kN and 310 kN for the retrofitting of the girders. The designations used for control girder and girders stressed to different stress level is shown in Table 12. The average values of results obtained has been taken and plotted and designated as RDB60, RDB80, and RDB3 for stress level I, II, and III respectively. The load deflection curves for RDB60,

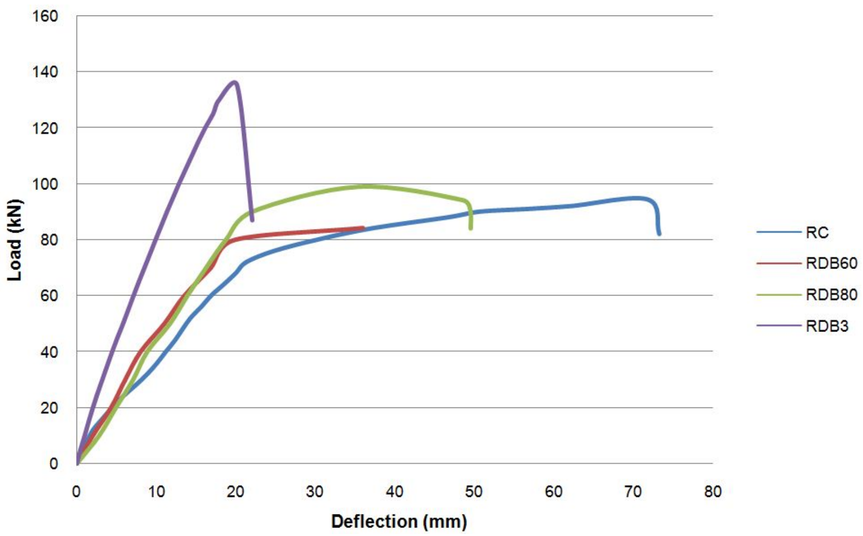

Fig. 12 Load v/s deflection curves of control girder RC and retrofitted girders RDB60, RDB80 and RDB3 at centre of span

Table 14 Maximum load, deflection and stiffness for control and retrofitted girders

Girder	Damage level	Maximum load (kN)	Maximum deflection (mm)	Yield load (kN)
RC	_	94.35	73.27	75
RDB1	80kN	84.235	35.99	80
RDB2	110 kN	98.87	49.464	90
RDB3	310 kN	135.15	22.08	135.15

RDB80, and RDB3, and the results obtained are shown in Fig. 12 and tabulated in Table 14 respectively.

It has been observed from Table 14 that after retrofitting average maximum load carrying capacity of girders increases with increase in initial pre-stress level. Although the maximum load carrying capacity of the girder initially fully damaged and then retrofitted using pre-stressing force of 80 kN decreased by 10.7 percent, but with further increase in pre-stressing force from 80 kN to 110 kN and 310 kN, the maximum load carrying capacity of girders increased to 98.87 kN and 135.15 kN, respectively resulting in a 4.8 percent and 43.2 percent increase in maximum load carrying capacity. Similarly, yield load of retrofitted girders increased to 80 kN, 90 kN, and 135.15 kN for girders RDB60, RDB80 and RDB3, respectively, thereby showing a 17.6, 32.35, 98.76 percent increase in the yield load. Stiffness of the retrofitted girders also increased by 40 to 50 percent. The increase in maximum load carrying capacity and yield load of the girders is due to increase in stiffness of the section due to the addition of CFRP sheets at bottom of girders and pre-stressing force applied to the girder. As the pre-stressing force increased the load carrying capacity of the girders also increased. Retrofitted girders RDB60 and RDB80 failed due fiber fracture, whereas, the girder RDB3 failed due to debonding of the CFRP sheet. From the mode of failure of the girders i.e., by fracture of fibres in RDB60 and RDB80 and debonding in RDB3, it can be concluded that an increase in pre-stressing force beyond a particular value changes the mode of failure and beyond that any further increase in pre-stressing force will not cause any appreciable increase in load carrying capacities of the beam. It can further be observed that in case of debonding failure the failure is brittle in nature and yield load is almost equal to the maximum load carrying capacity of the girder. Hence, there is an appreciable increase in yield load of the girder RDB3. After the fibre fracture in the retrofitted girders it is expected that girders will follow the path of control beam. Hence, both ductility and energy absorption capacity of the girders is expected to increase.

5. Conclusions

An experimental investigation on retrofitting of RC beams with pre-stressed CFRP sheets is reported. In the first phase of the study the girders were initially damaged to three different stress levels and then retrofitted with externally bonded pre-stressed CFRP sheets and in the second phase initially damaged girders have been retrofitted using different pre-stressing force. It is observed that the behavior of retrofitted girders improved appreciably after retrofitting. Keeping these results in mind, this method of retrofitting can be used with far more benefits over the conventional retrofitting measures. On the basis of current study following conclusions can be drawn:

- Pre-stressed CFRP sheet performs well in terms of effective utilization of tensile strength of CFRP.
- Load carrying capacity of the retrofitted beams using the prestressing technique is remarkably improved compared to that of control girder.
- The increase in pre-stressing force appreciably affects the load carrying capacity of the retrofitted beams.
- Increasing pre-stressing force from 80 kN to 110 kN and 310 kN causes an increase in the maximum load carrying capacity of retrofitted girders by 4.8 percent to 43.2 percent.
- With an increase in the pre-stressing force beyond a particular point, where shear stress on the surface between CFRP sheet and girder substrate increases the bond stress, results in a change in the mode of failure from fibre fracture to debonding of the sheet.
- Decrease in the deflection is observed as compared to that of the fresh control girder in all retrofitted girders.
- The stiffness of the retrofitted girders also increased as compared to the control girder.

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