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Experimental study on strengthening of R.C beam using glass fibre reinforced composite

K.M. Mini*, Rini John Alapatt, Anjana Elizabeth David, Aswathy Radhakrishnan, Minu Maria Cyriac and R. Ramakrishnan

Department of Civil Engineering, Amrita School of Engineering, Amrita Vishwa Vidyapeetham, Amrita Nagar, Coimbatore, Tamil Nadu, India

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Abstract. This paper reports the influence of number of layers and length of GFRP sheets wrapped onto RCC beams for strengthening. Twelve beams of size 700mm × 150mm × 150mm were cast and tested. Two beams without GFRP and ten beams wrapped in different lay-up patterns with one and two layers of GFRP sheets was subjected to three point loading test and ultrasonic pulse velocity test. Initial crack load, ultimate failure load and types of failure have been observed and noted. Experimental results indicate a significant increase in initial and ultimate load carrying capacity of GFRP wrapped beams compared to unwrapped beams. The failed control specimen was retrofitted using U wrap scheme and tested under three point loading.

Keywords: GFRP; wrapping schemes; strengthening; R C beam; flexure loading; retrofitting

1. Introduction

Many civil structures are no longer considered safe due to changes in load, inferior building material used, increased load specification in the design codes or natural calamities. Hence, structural strengthening and retrofitting of existing structures are currently the major activities in the construction industry. Nowadays, strengthening using FRP composites is gaining popularity due to its high strength to weight ratio, minimal change in structural geometry, easy and rapid installation and corrosion and fatigue resistance.

A lot of research works have been done on strengthening of RC beams using externally bonded FRP laminates/sheets (Chiew *et al*. 2007, Rai and Indolia 2011, Sheela and Anugeetha 2010). The technique of bonding FRP sheets using epoxy adhesives is recognized as an effective and convenient method for repair and rehabilitation of RC structures (Alagusundaramoorthy 2003). The concrete member to be strengthened is dried, chipped, cleaned and marked prior to epoxy application and wrapping (Al-Saidy 2010). The FRP sheets are wrapped on the tension face and shear face of beams to provide confinement and crack prevention which contribute to strengthening of the beams (Barros *et al*. 2007). Ferrier *et al*. (2003) conducted a comparative study on flexural strength of wrapped and unwrapped beams and found a higher ultimate load

*Corresponding author, Professor, E-mail: k_mini@cb.amrita.edu

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carrying capacity and initial crack load for wrapped beams compared to unwrapped beams. Subramanian and Kalpana (2011) concluded in their study that the RC beams strengthened externally are expected to fail under any one of the following modes: fabric rupture, tension failure, shear failure, de-bonding failure and compression failure. A large increase in stiffness and strength as well as the occurrence of brittle failure due to concrete rupture as a result of stress concentration near the ends of the CFRP was observed by Norris *et al*. (1997).

Various works are being done on wrapping schemes and wrap thickness to find out the optimum amount of FRP required for strengthening the beam efficiently and economically. Swain and Nayak (2010) carried out an experimental study on strengthening of RC beams in different lay-up patterns with one, two, three, and four layers of GFRP sheets. The flexural strength of retrofitted beams was found to increase with increase in number of layers in all lay-up patterns. However, the failure pattern gradually changes from ductile to brittle behaviour with increase in number of layers. Panda *et al*. (2010) and El-Amoury *et al*. (2002) performed tests on different lay-up patterns and found that U wrapped beams (bottom portion and half of both sides are wrapped) showed superior performance with reference to increase in flexural strength, failure pattern and economy. To increase concrete confinement and thus strength and ductility of columns, columns are wrapped with FRP sheets (Sundarraja and Rajamohan 2009). The performance of concrete columns externally wrapped with FRP sheets has been studied by Kumutha (2007) and Mathai (2010) and found that effective confinement with GFRP composite sheets resulted in improving the compressive strength. Teng *et al*. (2001) conducted an experimental study on the feasibility of strengthening of RC cantilever slabs by bonding glass FRP (GFRP) strips/sheets on the top surface (the tension side).

Numerous studies carried out on strengthening of RC beams showed that U-wrapping gave better results than all the other types of wrapping schemes. Previous researchers conducted studies on the effect of different wrapping schemes and number of layers of GFRP for strengthening of RC beams. In addition, the present work also reported the effect of U-wrap of varying length for the same, as not many studies were carried out on this area. Apart from the conventional test methods, Ultrasonic Pulse Velocity (UPV) test was carried out to study the widening of cracks under various stages of loading.

2. Materials and methods

In order to study the structural performance of strengthened RC beams with GFRP, 12 beams were cast, out of which 2 beams were taken as control beams, and tested.

2.1 Casting of specimens

Two sets of concrete beam specimens of size 700 mm×150 mm×150 mm were cast. A nominal mix of 1:1.5:3 was used. Three cubes of size 150 mm×150 mm×150 mm were cast along with the casting of each set of beams. The beams and cubes were allowed for 28 days of curing in water. The beam dimensions and reinforcement detailing is shown in Fig. 1.

2.2 Wrapping of GFRP

GFRP sheets used in present investigation are fabric type E-glass of grade 400 GSM. The

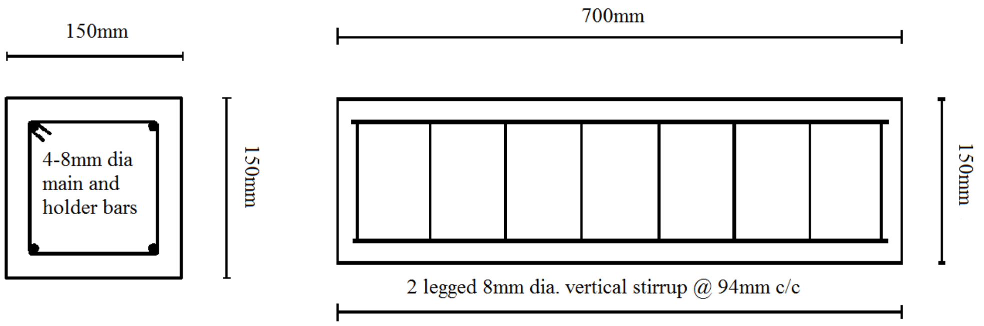
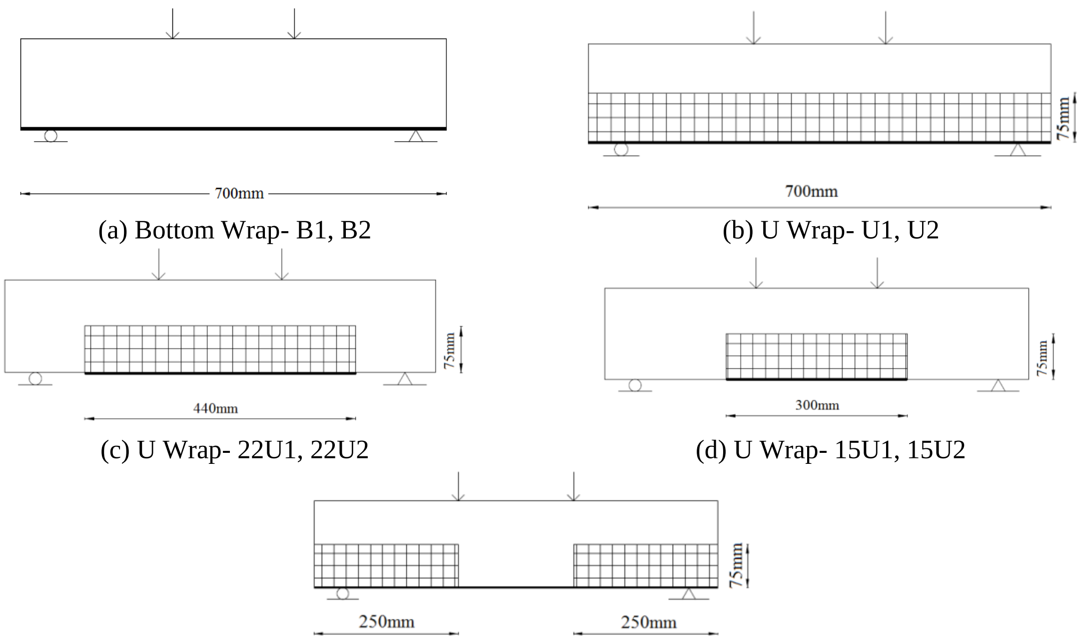


Fig. 1 Cross sectional and longitudinal section of beam



(a) Bottom Wrap- B1, B2

(b) U Wrap- U1, U2

(c) U Wrap- 22U1, 22U2

(d) U Wrap- 15U1, 15U2

(e) Special Wrap- S1, S2

Fig. 2 Lay-up schemes used for the study

sheets used were of bidirectional fibre orientation with tensile strength of 3450 N/mm^2. Two sets of six beams were cast. One beam of each set is considered as control specimen and is designated as the beam type C1 and C2. The remaining set I beams were wrapped with one layer of GFRP and set II with two layers of GFRP. The present study is restricted to one and two layers of GFRP as previous researchers [1, 10] suggested that the optimum result was obtained with two layers of GFRP as brittle behaviour increased with increase in number of layers. Following are the five lay-up schemes used to wrap the remaining ten beams:

• **Bottom Wrap**- The underside of the beam wrapped with one and two layers of GFRP throughout the length and designated as B1 and B2 respectively (Fig. 2(a)).

• **U Wrap** -The following are the different types of U wraps: The beam wrapped with one and two layers on the underside and bottom half depth, throughout the length and designated as U1 and

U2 respectively (Fig. 2(b)); the beam wrapped with one and two layers on the underside and bottom half depth, along a length of 22cm to either side from the centre of the beam and designated as 22U1 and 22U2 respectively (Fig. 2(c)); the beam wrapped with one and two layers on the underside and bottom half depth, along a length of 15cm to either side from the centre of the beam and designated as 15U1 and 15U2 respectively (Fig. 2(d)).

• **Special Wrap-** The beam wrapped with one and two layers on the underside and bottom half depth, along a length of 25cm from either ends of the beam and the remaining unwrapped portion of the beam was wrapped on the underside alone and designated as S1 and S2 respectively. In this case, beam was wrapped at regions of maximum shear force and bending moment (Fig. 2(e)).

The resin (ARALDITE LY556) and hardner (ARADUR HY951) comprising the matrix in a composite material was mixed in accordance with the manufacturer's instructions (in the ratio 1: 0.175) inorder to provide bond between concrete surface and GFRP sheets. Prior to strengthening with GFRP, the portion of the beam where the GFRP was to be wrapped was marked, chipped and then cleaned. The portion to be wrapped by GFRP sheets was given a coating of the epoxy, using a brush, onto which the sheet was placed. Then a second coating of the epoxy was provided on the GFRP sheet. The wrapped portions were rolled over with a roller to squeeze out excess epoxy resin and to remove air voids. The specimen was kept for air curing for 7 days.

3. Test results and discussion

3.1 Compression test

The cubes casted were tested under compression and the result obtained is shown in Table 1.

3.2 Flexural test

The beams were loaded up to failure using three point loading. The load was applied using universal testing machine (UTM) of capacity 400kN. Three dial gauges were used for recording the deflection of beams. One dial gauge was placed just below the centre of the beam and the remaining two dial gauges were placed at one-third distance from either roller support. The experimental set up and a schematic representation of the test setup is shown in Figs. 3 and 4. The load at initial crack and the ultimate load carrying capacity of the beams were noted. For each beam, deflections were recorded at every 2kN load increment and load-deflection graph was plotted. The crack pattern and the failure mode of each beam were also studied.

3.2.1 Initial crack load and failure load

The load at initial crack was noted by visual inspection. It was observed from the Figs. 5(a)-(b) that the load at initial visible crack of the GFRP wrapped beams was higher than the control beam.

Table 1 Cube compressive strength for different sets of beams.

Set of Beams	28 Day Average Compressive Strength (N/mm^2)
Set I	41.14
Set II	35.26

Fig. 3 Experimental set up

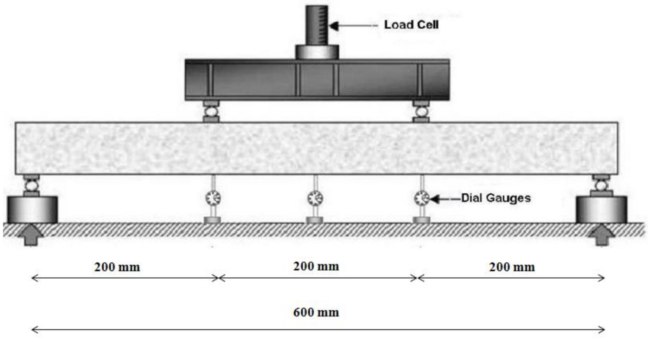
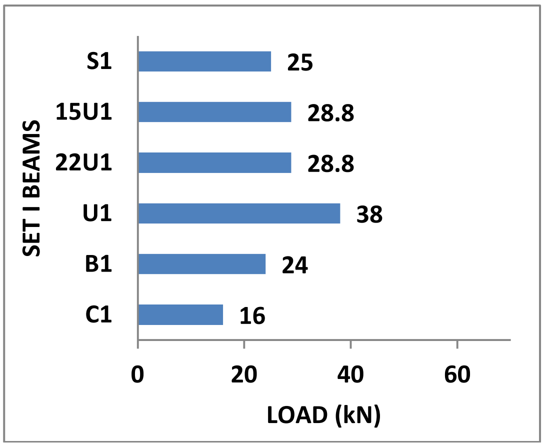
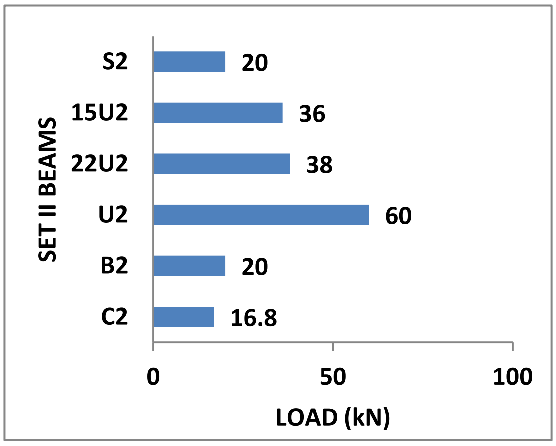


Fig. 4 Schematic representation of test set up.



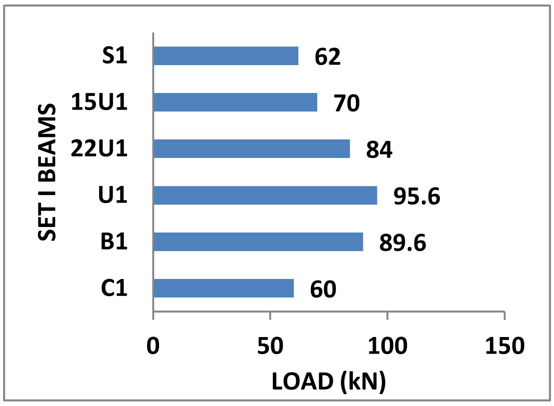
(a) Load at initial visible crack for set I



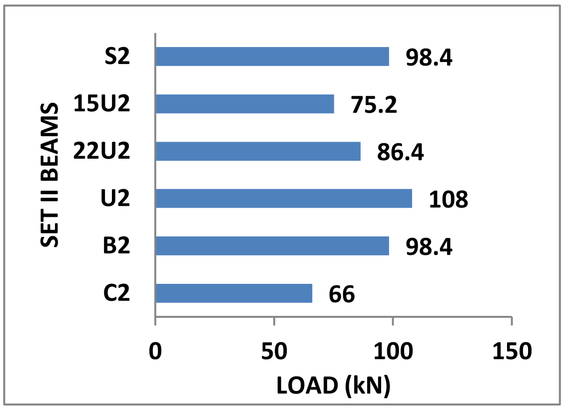
(b) Load at initial visible crack for set II

Fig. 5 Load at initial visible for set I and set II beams

This implies that the presence of GFRP wrap delayed the crack formation. Wrapping of beams with the GFRP also enhanced the load carrying capacity of the beams (Figs. 6(a)-(b)). The initial cracking load and failure load of beam U1 and U2 was higher than all the other beams of the corresponding set as these configurations had a better resistance to crack initiation and

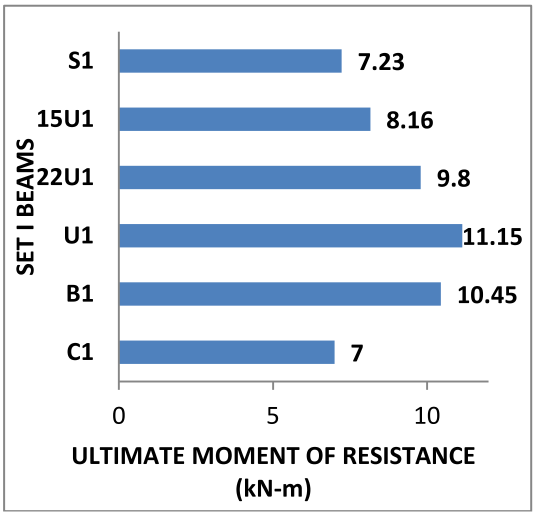


(a) Failure load for set I

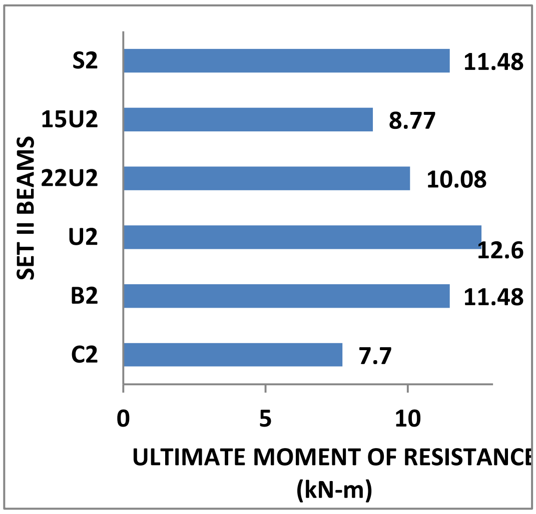


(b) Failure load for set II

Fig. 6 Failure load for set I and set II beams



(a)Moment of resistance for set I



(b)Moment of resistance for set II

Fig. 7 Moment of resistance for set I and set II beams

propagation. It was observed that the initial cracking load and failure load increased with the number of GFRP layers for the beams having U wrap configuration. However, the initial cracking load of beams B1 and S1 was found to be higher than that of beams B2 and S2. The capacity of beams U1, 22U1,15U1 U2, 22U2 and 15U2 were 59.33%, 40% ,16% 63.63%, 30.9% and 13% more than the control beam of corresponding set respectively. This indicates that the longer GFRP wrap enhances the load carrying capacity. The load carrying capacity of B1 is closer to that of U1 as the bottom wrap configuration resists the crack initiation from the underside of the beam.

From the ultimate load carrying capacity (P), the ultimate moment of resistance of the beam was calculated using the formula $M_u = Pl/6$ where, l is the length of the beam (700 mm).

It was observed that the moment carrying capacity of beams increased due to GFRP wrapping

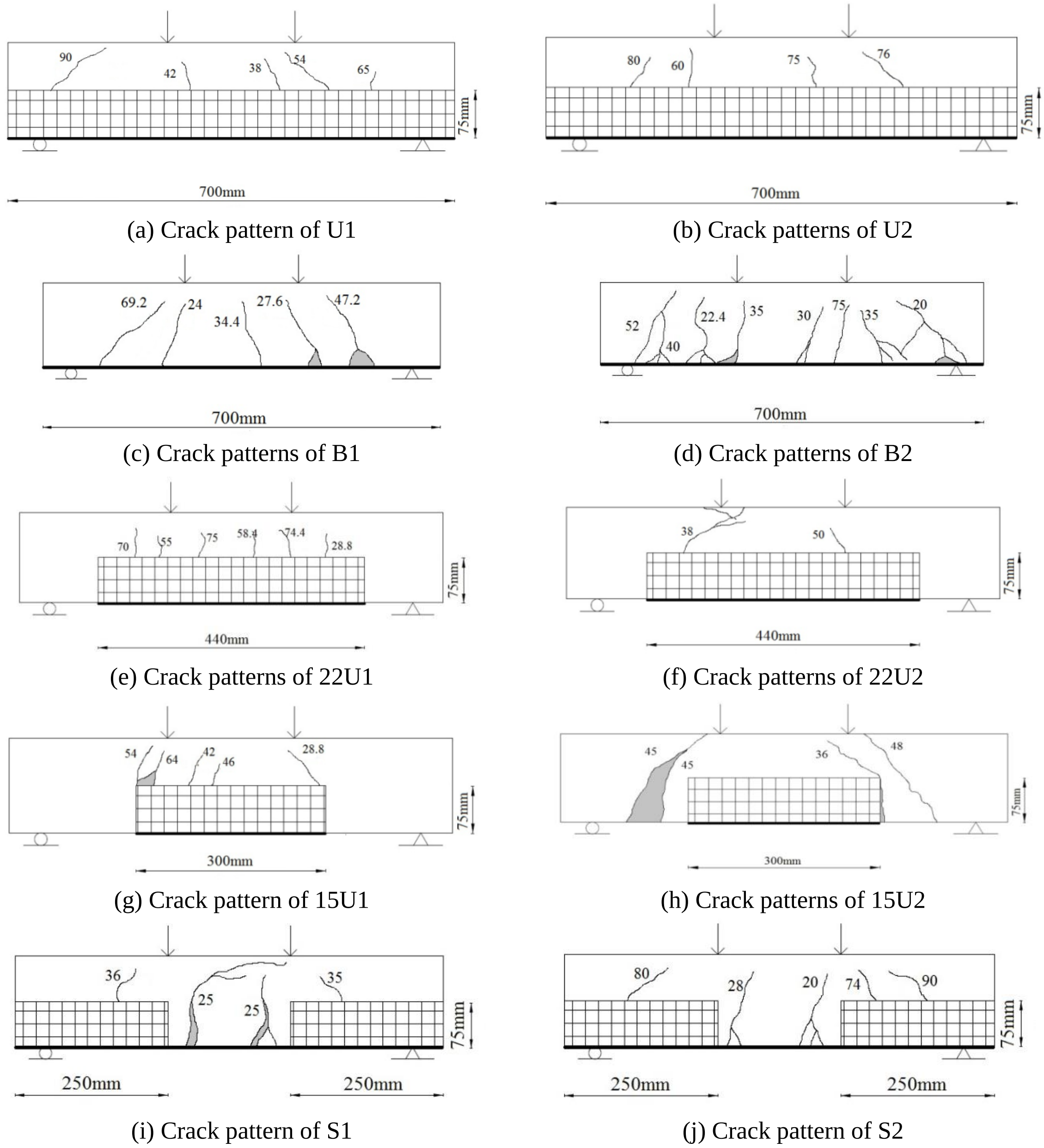
(Figs. 7(a)-(b)). In set I, U1 had maximum moment carrying capacity followed by B1, 22U1 and 15U1. A similar observation was found for set II specimens also. The moment carrying capacity was found to increase as the length and number of layers of GFRP increased.

3.2.2 Crack pattern and failure modes

The crack patterns at collapse were observed and studied. The cracks in vertical direction are flexural cracks and those inclined to 45° are shear cracks. Those cracks which initiate in vertical direction and moves in inclined direction as the load increases have combined effects of shear and flexure. The control beams which had less number of widely spaced cracks were flexural in nature. Both the beams U1 and U2 had widely spaced cracks with less crack width (Figs. 8(a)-(b)). The beam U1 had more number of cracks than U2 which points to the more ductile behaviour of beam U1. In both beams, flexural cracks were found in middle zone while shear cracks were developed in shear zone. Both the beams B1 and B2 had large number of widely spaced cracks with less crack width (Figs. 8(c)-(d)). B2 had more number of cracks and more branched cracks compared to B1. Cracks having shear and flexural behaviour was found at the middle zone and shear cracks were found at the shear spans. The beam 22U1 had large number of closely spaced cracks (Fig. 8(e)). All the cracks were flexural and were confined in the middle zone. The beam 22U2 had only two cracks out of which one was a shear crack in the shear zone (Fig. 8(f)). The crack width in 22U2 is more compared to 22U1. The beam 15U1 had large number of closely spaced cracks confined in middle zone (Fig. 8(g)). Shear cracks of more width were observed, which started from the shear zone and propagated to the middle zone. Flexural cracks were also found near the centre of the beam. The beam 15U2 had only shear cracks which were of more width (Fig.8(h)). These cracks started from the shear zone and propagated to the middle zone. Both the beams S1 and S2 had less number of widely spaced cracks (Figs. 8(i)-(j)). Flexural cracks were found in the middle zone which had more width. The numbers in the Figs. 8(a)-(j) represents the corresponding load at which the cracks are developed. The failure modes of the different set of beams are reported in Table 2. More widely spaced cracks were found as length of GFRP increased. The failure mode was found to be in accordance with the location/zone where the GFRP was provided.

Table 2 Failure modes

Beam Designation	Nature of failure
C1	Flexural failure + Crushing of concrete
C2	Flexural failure + Crushing of concrete
U1	Flexure-shear failure + GFRP rupture + Debonding
U2	Flexure-shear failure + GFRP rupture+ Debonding
B1	Flexure-shear failure + GFRP rupture+ Debonding
B2	Flexure-shear failure + GFRP rupture+ Debonding
22U1	Flexure failure + GFRP rupture+ Debonding
22U2	Shear failure + Debonding
15U1	Shear failure + Cushing of concrete
15U2	Shear failure + Crushing of concrete
S1	Flexural failure + Crushing of concrete+ GFRP rupture
S2	Flexural-shear failure + GFRP rupture



(a) Crack pattern of U1 (b) Crack patterns of U2

(c) Crack patterns of B1 (d) Crack patterns of B2

(e) Crack patterns of 22U1 (f) Crack patterns of 22U2

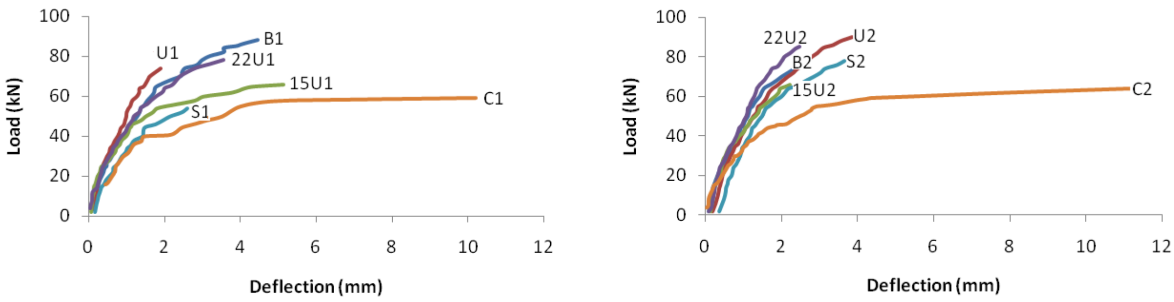
(g) Crack pattern of 15U1 (h) Crack patterns of 15U2

(i) Crack pattern of S1 (j) Crack pattern of S2

Fig. 8 Crack pattern of beams

3.2.3 Load-deflection behaviour

Three dial gauges were used for recording the deflection of beams. One dial gauge was placed just below the centre of the beam and the remaining two dial gauges were placed at 200mm from the supports. Dial 1, dial 2 and dial 3 were placed at distances l/3, l/2 and 2l/3 respectively from the left support. Deflection was noted for every 2kN load increment and load deflection graph was plotted for the centre point of the beam (Figs. 9(a)-(b)).



(a) Load deflection graph at centre of set I beams (b)Load deflection graph at centre of set II beams

Fig. 9 Load deflection graph at centre of set I beams and set II beams

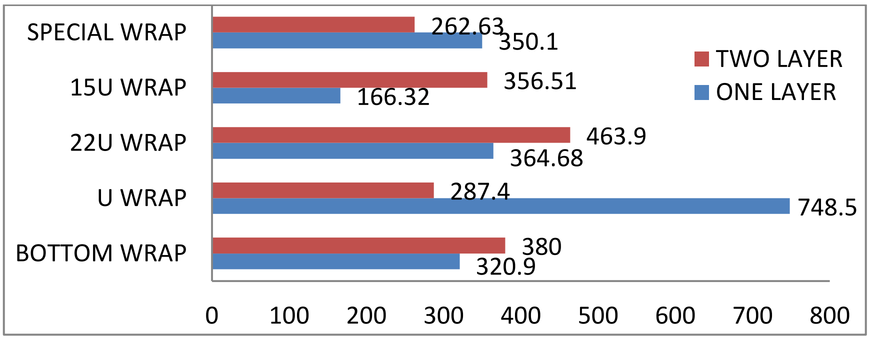


Fig. 10 Percentage increase in stiffness for set I and set II

The control beam underwent the maximum deflection at the mid-span than all the strengthened beams. The GFRP wrapping has reduced the beam deflection and hence, increased brittle behaviour of the beams. The beam U2 showed more ductile behaviour than beam U1. But for remaining beams, compared to set I, set II showed more brittle behaviour. Hence, it can be concluded that as the number of layers of GFRP increases ductile behaviour decreases.

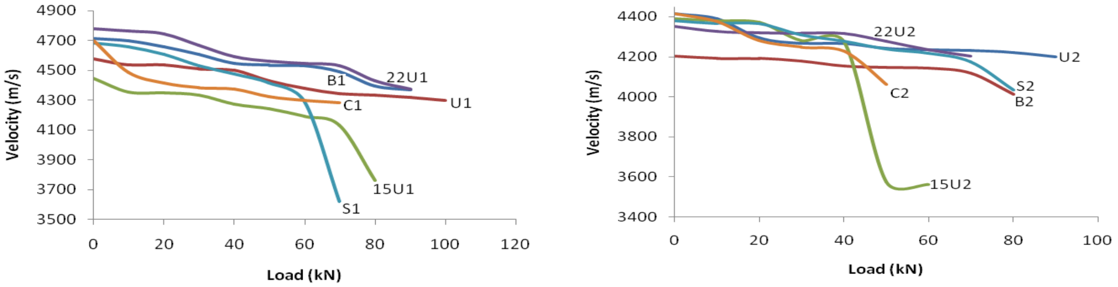
3.2.4 Stiffness

The slope of the load deflection graph was determined to obtain stiffness. The percentage increase in stiffness (with respect to corresponding control beams) for the two sets of the beams is given in Fig. 10.

From the figure it is observed that as the number of layers (except for U1 and S1) and length of GFRP increases, the stiffness is found to increase.

3.3 Ultrasonic pulse velocity test

The direct transmission method was adopted to study the propagation of cracks in the beams at different stages of loading. The transducers were placed at the longitudinal ends of the beam at a height of 5cm from the bottom centre, so as to avoid any reinforcement on the path of the wave propagation. The travel path was set to 0.7 m and time frame to 0.1 ms. The wave propagation was then initiated and the pulse travels through the concrete and is received by a similar transducer on



(a) Velocity load graph for set I beams (b) Velocity load graph for set II beams

Fig. 11Velocity load graph for set I beams and set II beams

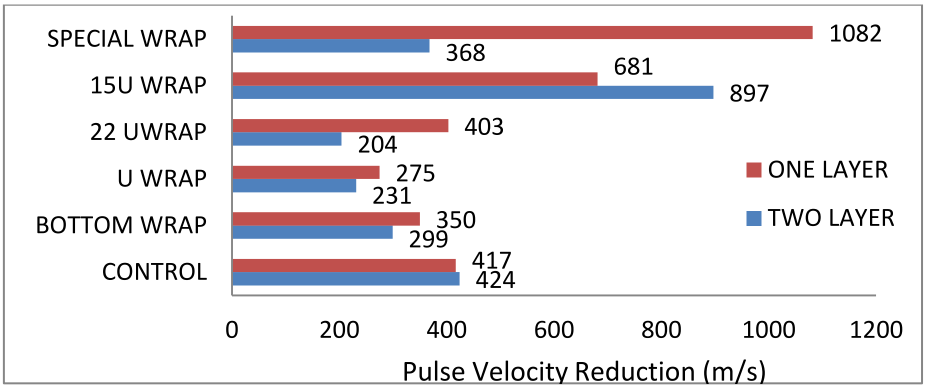


Fig. 12 Pulse velocity reduction of GFRP wrapped beams

the opposite surface. The pulse velocity and travel time was then obtained. The same was repeated for time frame of 0.2 ms.

The velocity-load graph of set I and set II beams are shown in Figs. 11(a)-(b). In 15U1 and 15U2 beams, a sudden decrease in velocity was observed towards failure showing that large number of cracks or widening of cracks occurred at a fast pace, implying brittle failure. For the remaining U-wrapped beams the variation in velocity was gradual. Therefore it can be concluded that as length of wrap increases failure becomes more ductile.

In set I, the maximum reduction in pulse velocity (difference between initial and final pulse velocity) at failure was found in SI followed by 15U1, 22U1, B1 and U1, whereas in set II it was in the order 15U2, S2, B2, U2 and 22U2 (Fig. 12). Reduction in pulse velocity depends on the number of internal cracks as well as the width of cracks developed. It can be concluded from the observations that for set I beams, unlike set II beams, as the length of the wrap increases the width of the cracks developed decreases (narrow). Except 15U1, the crack width of all the beams decreased as the number of layers of GFRP sheets increased.

3.4 Retrofitting of control beams

From the experimental investigations U wrapped beam with two layers of GFRP sheets was found to provide better strength. To check the efficiency of the obtained lay-up scheme in

Table 3 Test results after retrofitting

Beam Designation	Ultimate Load (kN)	Load carried after retrofitting (kN)	Percentage of ultimate load carried after retrofitting (%)
C1	60.0	55.2	92.00
C2	66.0	59.0	89.39
C3	79.6	73.6	92.46

strengthening of failed specimens, three control beams (C1, C2, C3) was first loaded to failure and then retrofitted with two layers of GFRP sheets wrapped in *U* wrap lay-up scheme. Table 3 shows the results obtained after retrofitting. From the results it is observed that the proposed scheme is very efficient even for retrofitting of RC beams.

4. Conclusions

In the present experimental investigation, the mechanical behaviour of RC beams wrapped with GFRP sheets is studied. Two sets of beams each with one and two layers of GFRP were cast and tested.

From the test results and the calculated strength values it is found that GFRP wrapping strengthened the beams by delaying the crack initiation and propagation and increasing the ultimate load carrying capacity. GFRP wrapping also led to greater moment of resistance and stiffness compared to the control beam. However the GFRP wrapping was found to reduce the deflection of the beams making them less ductile. The failure pattern gradually changes from ductile to brittle with increase in number of layers of GFRP sheets. Also, as length of wrap increases failure was found to become more ductile. With the increase in number of layers and length of GFRP wrap, the initial cracking load, ultimate load carrying capacity, moment of resistance and stiffness was found to increase.

Crack patterns and mode of failure of beams with same pattern of GFRP wrap showed similar behaviour (except 22U1 and S1). This indicates that number of layers does not have much influence in the mode of failure. The cracks found in control beams were purely flexural in nature. While GFRP wrapped beams had shear cracks as well as flexure-shear cracks. The failure mode of control beams were flexural along with crushing of concrete while rest of the beams had shear failure or GFRP rupture or debonding along with flexural failure or shear failure. The cracks at collapse was found to become closer and confined to the middle zone as the length of GFRP reduces.

Ultrasonic Pulse Velocity test was also conducted to study the crack propagation in beams. Variation in velocity of the pulse in UPV test was found to decrease as the length of the wrap increases. This indicates that the width of crack is reduced as the length of the GFRP wrap increases.

Further, failed control specimens were retrofitted with GFRP sheets and it was found that almost 90% of the ultimate load was carried by all the retrofitted beams and they were found to fail due to the rupture of GFRP sheets.

Compared to all layup patterns, the beam fully U wrapped with two layers of GFRP sheets showed better performance with more than 50 % increase in initial cracking load, ultimate load carrying capacity, moment of resistance and stiffness.

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