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Flexural strengthening of RC Beams with low-strength concrete using GFRP and CFRP

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Abstract. The Turkish Earthquake Code was revised in 1998 and 2007. Before these Codes, especially 1998, reinforced concrete (RC) beams with low flexural and shear strength were widely used in the building. In this study, the RC specimens have been produced by taking into consideration the RC beams with insufficient shear and tensile reinforcement having been manufactured with the use of concrete with low strength. The performance of the RC specimens strengthened with different wrapping methods by using of Carbon Fibre Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP) composites have been examined in terms of flexural strength, ductility and energy absorption capacity. In the strengthening of the RC elements, the use of GFRP composites instead of CFRP composites has also been examined. For this purpose, the experimental results of the RC specimens strengthened by wrapping with CFRP and GFRP are presented and discussed. It has been concluded that although the flexural and shear strengths of the RC beams strengthened with GFRP composites are lower than those of beams reinforced with CFRP, their ductility and energy absorption capacities are very high. Moreover, the RC beams strengthened with CFRP fracture are more brittle when compared to GFRP.

Keywords: low-strength concrete; poor reinforcement; carbon fiber; glass fiber; flexural strengthening; ductility

1. Introduction

Turkey is located on one of the most active earthquake zone which has earthquake periods quite often with shortest return periods. During the last century, more than twelve major earthquakes with minimum magnitudes 7 (Mw) caused significant casualties, severe damages to a lot of structures and lifelines in Turkey. This result has revealed that most of the current structures do not have sufficient stiffness and strength to resist possible earthquakes. In the examinations performed after the earthquakes, it has been observed that concrete with poor-reinforcement has been used in most of the structures and the longitudinal and transverse reinforcements are insufficient (Arslan and Korkmaz 2007, Celebi *et al*. 2012, Doğangün 2004, Sarıbıyık *et al*. 2003, Sezen *et al*. 2003). The structures not having sufficient safety for the prevention of great loss of lives should be strengthened with the use of proper materials to increase the strength of these

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buildings. This need for strengthening may occur due to reasons such as the damage caused by the earthquake and the loss of the strength of the building over time, insufficiency of reinforcement, use of concrete with poor reinforcement, mistakes in project design and implementation etc. Along with this, the need for the reinforcement of existent structures may also occur due to modifications in relevant standards and codes.

Various methods are used in the repair and strengthening of reinforced concrete (RC) structure elements. The strengthening of the bearing elements of the existent RC structures with the use of RC jacket or the addition of new bearing elements to the system is widely used. However, it is known that such kind of strengthening significantly increase the structure weight, additional arrangements in the foundation system and not allow the use of the structure during the strengthening and causing extra cost. For these reasons, Fiber Reinforced Polymer (FRP) composites, which do not increase the structure weight, can be applied easily and rapidly by significantly increasing the bearing capacities of the elements and enabling the use of the structure during strengthening. As FRP composites are also easy to be applied in a short period of time they have become quite effective as alternative strengthening elements.

The reinforcement of the structural elements of FRP composites with the use of strip, plate and fabric have been examined by many researchers (Abdel-Kareem 2014, Saadatmanesh and Ehsani 1991, Norris *et al*. 1997, Triantafillou 1998, Khalifa *et al*. 1998, Yoshimura *et al*. 2000, Tâljsten and Elfgren 2000, Rahimi and Hutchinson 2001, Khalifa *et al*. 2002, Adhikary 2004, Zhang and Hsu 2005, Almusallam 2006, Esfahani *et al*. 2007, Sundarraja and Rajamohan 2009). However, in these studies, although the longitudinal and transverse insufficiency of reinforcement has been examined, the use of concrete with poor reinforcement has not been taken into considerationin detail. The experiment beams have been manufactured with the use of concrete with strengths of 25 MPa or above (Saadatmanesh and Ehsani 1991, Norris *et al*. 1997, Triantafillou 1998, Khalifa *et al*. 1998,Yoshimura *et al*. 2000, Tâljsten and Elfgren 2000, Rahimi and Hutchinson 2001, Adhikary 2004, Zhang and Hsu 2005, Almusallam 2006, Sundarraja and Rajamohan 2009, Diagana *et al*. 2003, Obaidat *et al*. 2011, Baggio *et al*. 2014). In addition, the studies of reinforcement with Glass Fibre Reinforced Polymer (GFRP) composites have been limited level (Almusallam 2006, Sen and Jagannatha 2013, Baggio *et al*. 2014).

Almusallam (2006) carried out a study to examine the strength of strengthened RC beams with GFRP plates. Concrete with the compressive strength of 36.4 MPa has been used in the beams. The results of the conducted experiment have proven the activeness of the GFRP plates in increasing the strengths of the RC beams. The beams strengthened with GFRP have shown that generally GFRP plates significantly increase the flexural strength and ductility of the beams.

Esfahani *et al*. (2007) strengthened beams with the Carbon Fibre Reinforced Polymer (CFRP) composites against the flexure with the use of concrete having 25 MPa compressive strength on average. They used different tensile reinforcement in the beams and tested the beams by changing the width, length and layer numbers of the CFRP composites. In their experimental study, they stated that the flexural capacities and strengths of the reinforced beams had increased when compared to the control beams. In this study, they found that the US codes (ACI Committee 440F, 2002) and the design manual for the Canadian codes (SIS Canada, 2001) has stated that the reinforcement increases and capacity increases are high in the beams strengthened with CFRP composites. They have emphasized that the equations suggested in these codes are more suitable for the beams with high tensile reinforcement.

Sen and Jagannatha (2013) used natural jute fiber in the strengthening of RC beams against flexure. RC beams have been compared in various figures by strengthening with CFRP and GFRP.

They have figured out that JFRP, CFRP and GFRP, strengthening improved the ultimate flexural strength of the RC beams by 62.5%, 150% and 125%, respectively, with full wrapping technique and by 25%, 50% and 37.5%, respectively with strip wrapping technique. JFRP strengthening displayed highest deformability index and proved that jute textile FRP material has huge potential as a structural strengthening material.

Camata *et al*. (2007) examined the effects of strengthening by bonding CFRP and GFRP to the bottom surfaces of beams in the strengthening of RC beams. Concrete having the compressive strength of 25 MPa has been used in the beams. An increase by approximately 35% and 72% has been attained in the beam strengthenings when compared to the non-strengthened beams. Although these two plates are the same thickness, this difference stems from a bigger contact area between the binding material and the concrete. Wide plate expands to a wider area and the adjacent concrete tensions decrease as a result of the load. These results are very important because the wide bonding area increases the ductility of the strengthened beams. Test results have shown that the energy absorption capacities of the beams strengthened with GFRP are very similar to those of non- strengthened beams. The energy absorption capacities of the beams strengthened with CFRP are equal to 33% of GFRP.

In this study, the beams have been produced taking into consideration the RC beams with insufficient shearing and flexural strength manufactured with the use of concrete with low strength in the existent structure stock of Turkey. The RC beams strengthened with different wrapping methods used CFRP and GFRP have been examined. The strengthening impacts of the beams have been investigated in the flexural strength, ductility and energy absorption capacities. In addition, it also examined whether GFRP - being more economical and having higher elongation capacity- could be used efficiently instead of CFRP in the strengthening of RC elements. For this purpose, the results attained from the RC beam experiments strengthened by wrapping with CFRP and GFRP are presented and assessed in graphics and tables.

2. Experimental study

In this study, the testing beams have been manufactured by taking into consideration the RC beams with low shearing and flexural strength commonly seen in the existent RC structure stock in Turkey. All of the RC beams have the dimensions of 150/250 mm and 2000 mm length. C16/20 concrete has been used in the RC beams, stirrup spacings has not been made in the wrapping zones and 20 experiments have been manufactured with the scale of 1/2. Ø8/150 has been used in all of the experiment as the transversal reinforcement, longitudinal reinforcement ratio has been selected as 0.5 % and 2Ø10 has been used in the lower and upper zone of the beam. RC beams have been strengthened with GFRP and CFRP, and the performance changes have been examined in the flexural and shear strengths, ductility and energy absorption capacities (Fig. 1).

2.1 Materials

2.1.1 Concrete and steel

C16/20 concrete and S420 steel have been used in all of the RC beams. The concrete has been attained from the ready mixed concrete company at one time and concrete pressure experiment of the standard cylinder specimens taken from the concrete has been conducted. Compressive strength for 28 days has been found as 17 MPa, strain capacities have been found as 0.0025 and

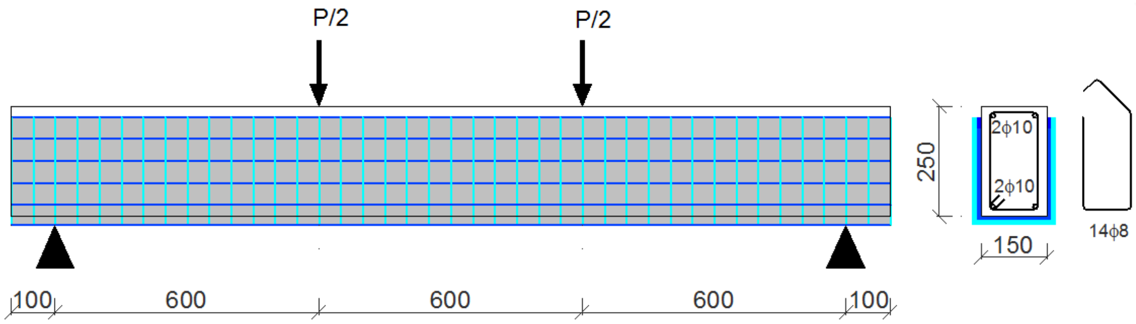


Fig. 1 Reinforcement scheme and loading system of RC beams (units in mm)

Table 1 Typical properties of carbon fiber, glass fiber and resin (http://tur.sika.com)

Material properties	Carbon fiber (Sika Wrap-300 C/60)	Glass fiber (Sika Wrap-430 G/25)	Epoxy resin (Sikadur 330)
Density (g/cm^3)	1.79	2.56	1.31
Tensile strength (MPa)	3900	2300	30
Elastic modulus (MPa)	230000	76000	4500
Strain at failure (%)	1.5	2.8	0.9
Design thickness (mm)	0.17	0.17	-

the elasticity module has been found as 27450 MPa. As a result of the conducted standard experiments, the yield strength of steel reinforcement with Ø 8 has been calculated as 368 and the tensile strength as 525 MPa; the yield strength of steel reinforcement with Ø 10 has been calculated as 480 and the tensile strength as 600 MPa.

2.1.2 Carbon and glass fibres

In the strengthening of the RC beams, the product “Sika Wrap-300 C/60” has been used as uni-directional carbon fiber textile and “Sika Wrap-430 G/25” has been used as uni-directional alkali resistant glass fiber textile. The thickness of the carbon and glass woven textile has been taken as the same. The characteristic-based properties of carbon and glass fiber are given in Table 1. Typical properties of carbon fiber, glass fiber and resin are taken from producer's catalogue. The detailed information can be found at web page of http://tur.sika.com.

2.1.3 Epoxy resin

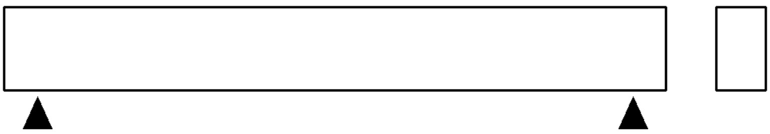
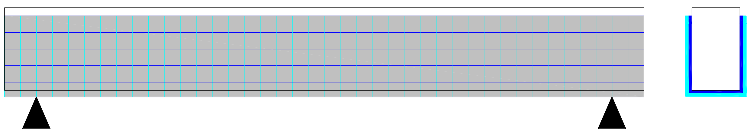
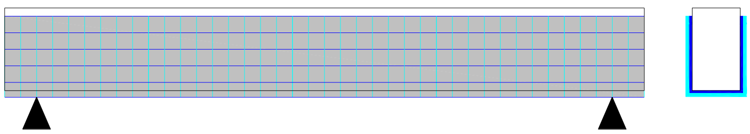
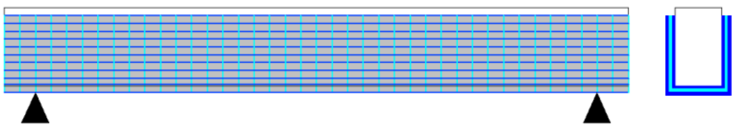
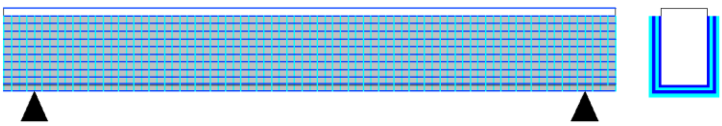
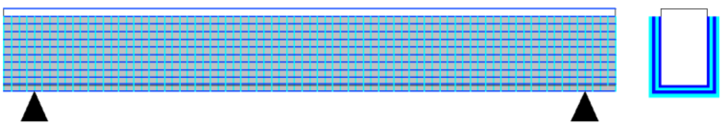
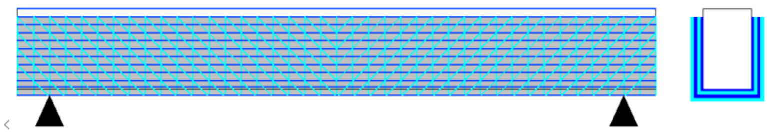
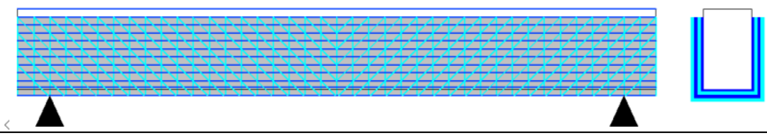
Sikadur 330 double component epoxy-based impregnation resin has been used in the bonding of the glass and carbon fiber on the surfaces of the RC beams. Sikadur 330, which is easy to apply, is a binding material suitable for concrete, stone, metal, wood and structure materials. Sikadur 330 epoxy resin packaged as ready sets of 4 kg of A component (resin) and 1 kg of B component (stiffener) is mixed in the ratio of 4/1 and can easily be applied with the help of trowel, brush and roller to the concrete surfaces with the application surface temperature of +10°C and +35°C. The characteristic-based properties of epoxy are given in Table 1.

2.2 Test beams

Test experiments have been collected as three main headlines. The reference RC beam to which no strengthening process is applied has been selected as the control beam. The RC beams strengthened by wrapping with carbon fiber have been coded with C and the RC beams strengthened by wrapping with glass fiber have been coded with G (see Table 2). The codings and strengthening types belonging to the prepared beams are given in Table 2.

Surfaces on which the FRP composites in the RC beams gaining sufficient strength would be bonded have been cleaned and the pores have been revealed. The surfaces have been roughened for better bonding and the beam corners corresponding to the bonding surfaces have been beveled with the diameter of 2 cm and rounded. Dust and riders have been cleaned with compressor and

Table 2 RC Beams Strengthening schemes

Code		Properties of beams	items
Control		Control beam	3
C11		CFRP Wrap 1 Layers $0^o$and 1 Layers 90^o U Shape	3
G11		GFRP Wrap 1 Layers $0^o$and 1 Layers 90^o U Shape	3
G21		GFRP Wrap 2 Layers $0^o$and 1 Layers 90^o U Shape	3
C22		CFRP Wrap 2 Layers $0^o$and 2 Layers 90^o U Shape	2
G22		GFRP Wrap 2 Layers $0^o$and 2 Layers 90^o U Shape	2
C21-1		CFRP Wrap 2 Layers 0^o, 1 Layers $90^o$and 1 Layers 45^o U Shape	2
G21-1		GFRP Wrap 2 Layers 0^o, 1 Layers $90^o$and 1 Layers 45^o U Shape	2

cloth. Uni-directional FRP composites manufactured with the width of 600 mm have been cut with the length of 2000 mm for longitudinal wrapping and with the length of 650 mm for transversal wrapping with the angle of 90°. In addition, they have been cut at an angle of 45° to the fiber direction and have been prepared as ready for bonding vertical to the shear fracture.

Sikadur 330 epoxy resin has been applied for one fold with the help of roller and brush in a way that there shall not be any space in the side surfaces of the concrete. The prepared uni-directional textiles have been bonded to the beam surfaces. The textiles have applied pressure in the direction of the fibers and have been impregnated to epoxy with the help of a roller. The textiles on which one fold of resin shall be applied again for a better bonding and protection against external effects have been completely left in the resin (Fig. 2). The beams whose bonding process has been completed have been kept under suitable conditions.

2.3 Experimental apparatus and instruments

The control beam and the beam strengthened with FRP fabrics have been subjected to a four-point bending test. Beams have been conducted with the loading frame branded HI-TECH MAGNUS with the capacity of 400 kN taking place in Sakarya University, Civil Engineering material lab. The beams have been simply supported with a clear span of 1800 mm with 600 mm spacing between the two loading points and a shear span of 600 mm. The supports and loading points consisted of a pin and roller connection. The beam has been separated into three zones with 600 mm distance. 1st and 3rd zones are the ones having low flexural moment and high shear load, 2nd zone is the one for which only the flexural moment is efficient. The load distribution beam with full body has been placed on the experiment beams for the purpose of distributing the loads equally. Potentiometric rulers is mounted at the midspan to measure deflection of the specimens. At the beginning of the each test, small loading (i.e., about 5-10 kN) is applied to specimens in order to dispose of any slack in the measuring devices and test setup. Afterwards, the load was applied gradually at a rate of 25 kN per minute until the failure of the specimen.

Jointed apparatus has been placed between the load-giving piston and the load distributor with full body for the purpose of preventing possible additional impacts occurring due to the friction between them. Fixed and sliding supports have been assembled to the box profiles placed and fixed on the lower head of the flexural frame. In the event of loading, the load changes have been

(a) (b)

Fig. 2 (a) Drying and surface preparation of beam (b) Applying the epoxy resin to the beam surface (c) Bonding of glass fibers to beam surface (d) Bonding of carbon fiber to beam surface (e) Applying the epoxy resin to the beam surface (f) epoxy impregnation, (g) Bonding of carbon fiber to beam surface with the 45^{o} angle

(c)

(d)

(e)

(f)

(g)

Fig. 2 Continued

(a) Load gauges and load distributor joint apparatus

(b) Potentiometric rulers

(c) Data collection devices

Fig. 3 Experimental devices

Fig. 4 Control beam

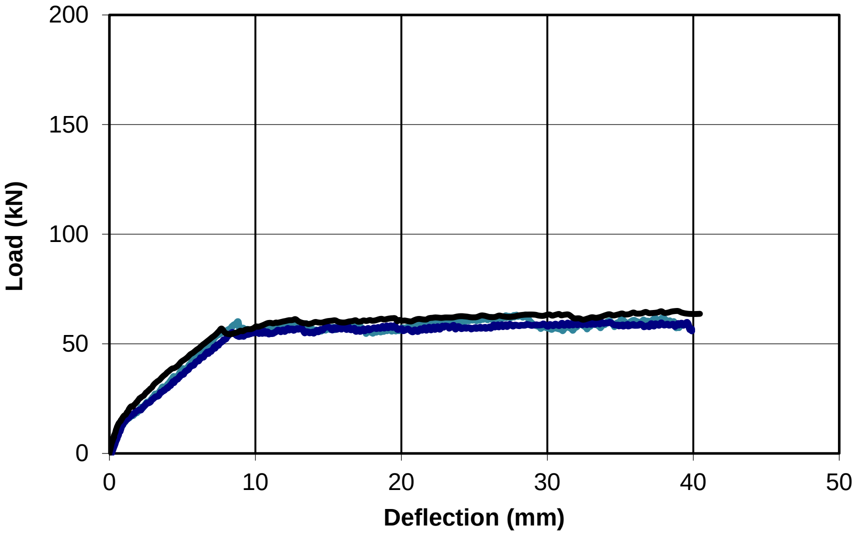


Fig. 5 Load-deflection graphs for the control beams

measured with the coulometer inserted to the end of the load-giving piston (Fig. 3(a)). Potentiometric rulers (model of LPS 100-B-5K Opkon Linfar Resistive Position Transducer) have been used to measure the vertical displacement (Fig. 3(b)). The values coming from the displacement meter and load giver during the experiment have been transferred to the computer by means of the data collection system and for this purpose, the data logger with the channel of Di4b 4 and with the channel of Ai8b 8 has been used (Fig. 3(c)).

3. Experimental results

All of the eight groups of beams have been subjected to a four-point bending tests and have been loaded until their final strength (Fig. 4). The conducted beam test results have been assessed, the load-deflection graphics belonging to the beams have been drawn and the average load-deflection values have been found (Figs. 5-12).

When the load applied to the control beam reached 14.20 kN, a deflection of 0.88 mm occurred in the middle of the beam and the first flexural cracks occurred at the 2nd lower zone of the beam. When the applied load reached 57.40kN, a deflection of 8.30 mm occurred and as the loading continued, the load increase stayed as limited but the deflection continued to increase. When the applied load reached 62.70kN, the experiment beams made the deflection of 33.70 mm (Fig. 5).

Three RC beams coded C11 have been strengthened by wrapping one fold of longitudinal and one fold of transversal carbon fiber to their lower and side surfaces and have been tested. When the load reached 25kN on average in C11 beams, a deflection of 1.70 mm occurred in the middle of the beam, the reinforcement started to yield and deflection corresponding to this load has been measured as 11.70 mm. When the applied load reached 160.60 kN, the beam made a deflection of 28.30, lost its bearing power and collapsed (Fig. 6-Table 3).

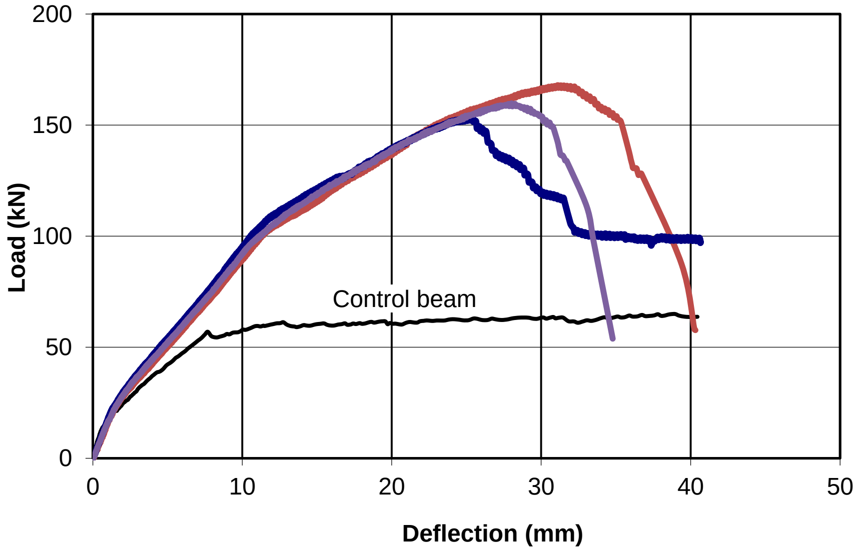


Fig. 6 Load-deflection graphs for the C11 beams

Table 3 Experimental average results of tested beams

Beams	at first crack		at yield		at failure	
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
Control Beams	14.2	0.9	57.4	8.3	62.7	33.7
C11	25.0	1.7	106.0	11.7	160.6	28.3
G11	24.9	1.5	87.2	10.2	119.0	32.3
G21	24.2	1.4	102.7	12.1	148.1	30.9
C22	23.0	1.4	130.3	13.8	180.7	24.0
G22	23.1	1.4	101.9	11.5	153.7	32.6
C21-1	26.6	1.9	111.3	12.0	168.3	24.2
G21-1	23.9	1.4	102.7	12.3	156.6	31.7

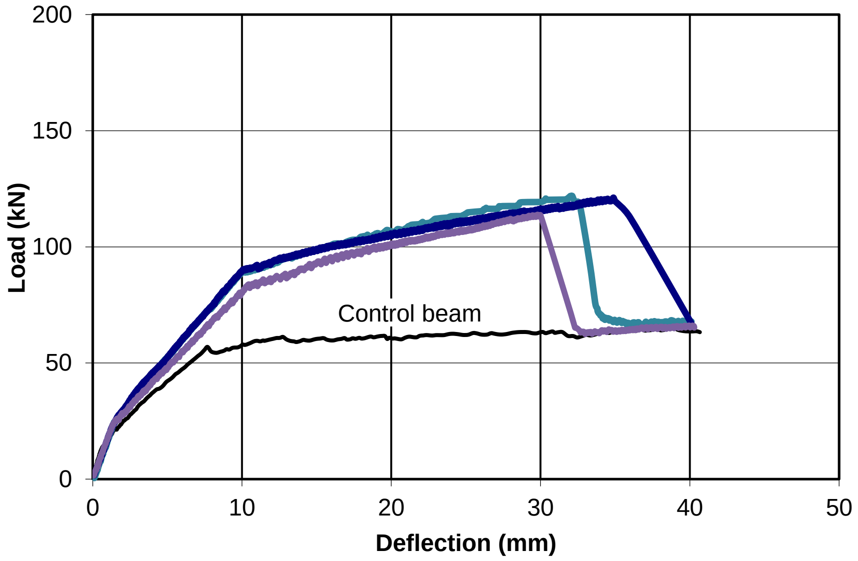


Fig. 7 Load-deflection graphs for the G11 beams

There have been significant increases in the load bearing capacities of the C11 beams when compared to the control beams. The load corresponding to the occurrence of the first crack increased as much as 1.76 times and the deflection value in the middle of the beam increased as much as 1.93 times. The load corresponding to the yielding of the reinforcement increased as much as 1.85 times and the deflection value in the middle of the beam increased as much as 1.41 times. The shear load of the C11 beam increased as much as 2.56 times, but the deflection corresponding to the shear load decreased by 16%.

Three RC beams coded G11 have been strengthened by wrapping one fold of longitudinal and one fold of transversal carbon fiber to their lower and side surfaces and have been tested. When the load reached 25.90 kN on average in G11 beams, a deflection of 1.50 mm occurred in the middle of the beam and the first flexural cracks occurred in the 2nd lower zone of the beam. When the applied load reached 87.20 kN, the reinforcement started to yield and deflection corresponding to this load has been measured as around 10.20 mm. When the applied load reached 119 kN, the beam made a deflection of 32.3, lost its bearing power and collapsed (Fig. 7-Table 3).

There have been significant increases in the load bearing capacities of the G11 beams when compared to the control beams. The load corresponding to the occurrence of the first crack increased as much as 1.75 times and the deflection value in the middle of the beam increased as much as 1.68 times. The load corresponding to the yielding of the reinforcement increased as much as 1.52 times and the deflection value in the middle of the beam increased as much as 1.23 times. The shear load of the G11 beam increased as much as 1.90 times, but the deflection corresponding to the shear load decreased by 4%.

G11 beams strengthened by wrapping one fold of longitudinal and one fold of transversal glass fiber collapsed with flexural fracture. Three RC beams coded G21 have been strengthened by wrapping two folds of longitudinal and one fold of transversal carbon fiber to their lower and side surfaces for the purpose of enhancing the flexural strength and have been tested. When the load

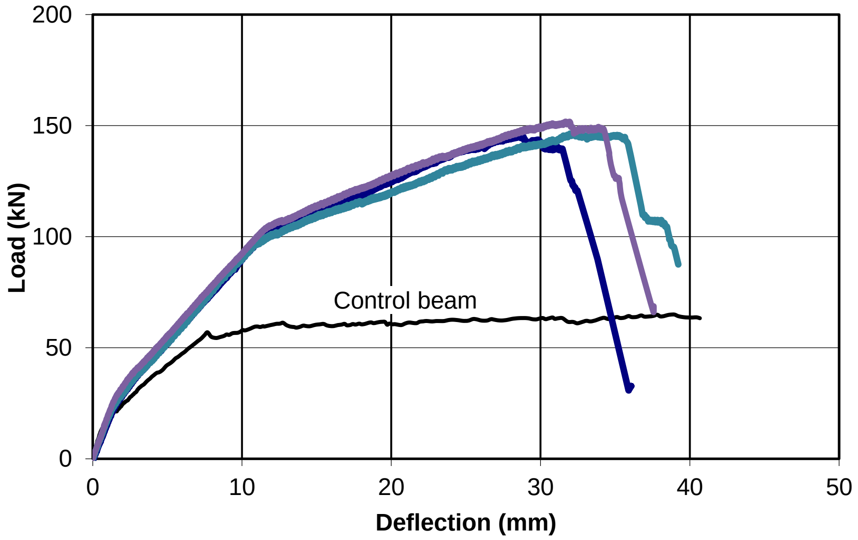


Fig. 8 Load-deflection graphs for the G21 beams

reached 24.20 kN on average in G21 beams, a deflection of 1.40 mm occurred in the middle of the beam and the first flexural cracks occurred in the 2nd lower zone of the beam. When the applied load reached 102.70 kN, the reinforcement started to yield and deflection corresponding to this load has been measured as around 12.10 mm. When the applied load reached 148 kN, the beam made a deflection of 30.90 mm, lost its bearing power and collapsed (Fig. 8-Table 3).

There have been significant increases in the load bearing capacities of the G21 beams when compared to the control beams. The load corresponding to the occurrence of the first crack increased as much as 1.71 times and the deflection value in the middle of the beam increased as much as 1.61 times. The load corresponding to the yielding of the reinforcement increased as much as 1.79 times and the deflection value in the middle of the beam increased as much as 1.45 times. The shear load of the G21 beam increased as much as 2.36 times, but the deflection corresponding to the shear load decreased by 8%.

Two RC beams coded C22 have been strengthened by wrapping two folds of longitudinal and two folds of transversal carbon fiber to their lower and side surfaces for the purpose of searching for the impacts of carbon fiber wrapping amount on the load bearing capacities and have been tested. When the load reached 23 kN on average in C22 beams, a deflection of 1.40 mm occurred in the middle of the beam and the first flexural cracks occurred in the 2nd lower zone of the beam. When the applied load reached 130.30 kN, the reinforcement started to yield and deflection corresponding to this load has been measured as around 13.80 mm. When the applied load reached 180.70 kN, the beam made a deflection of 24 mm, lost its bearing power and collapsed (Fig. 9-Table 3).

There have been significant increases in the load bearing capacities of the C22 beams when compared to the control beams. The load corresponding to the occurrence of the first crack and the deflection amount in the middle of the beam increased as much as 1.60 times. The load corresponding to the yielding of the reinforcement increased as much as 2.27 times and the

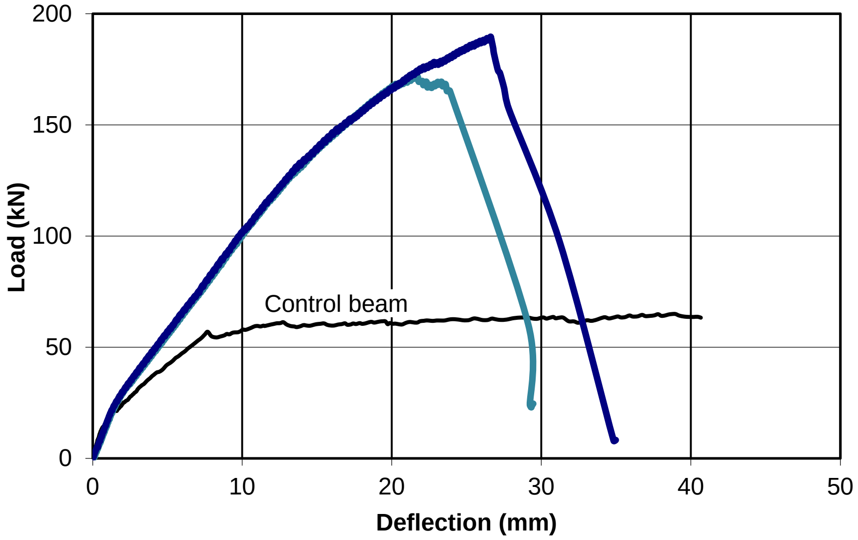


Fig. 9 Load-deflection graphs for the C22 beams

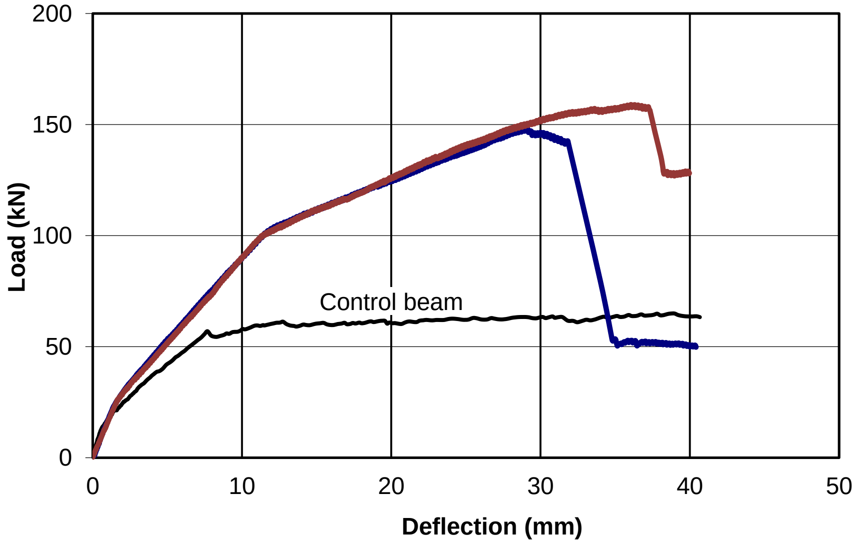


Fig. 10 Load-deflection graphs for the G22 beams

deflection value in the middle of the beam increased as much as 1.66 times. The shear load of the C22 beam increased as much as 2.88 times, but the deflection corresponding to the shear load decreased by 29%.

G22 beams strengthened by wrapping two folds of longitudinal and one fold of transversal glass fiber to the lower and side surfaces have collapsed with flexural fracture. Two RC beams coded G22 have been strengthened by wrapping two folds of longitudinal and two folds of transversal glass fiber to their lower and side surfaces for the purpose of increasing the shear load bearing capacity and have been tested. When the load reached 23.10 kN on average in G22 beams, a deflection of 1.40 mm occurred in the middle of the beam and the first flexural cracks occurred in the 2nd lower zone of the beam. When the applied load reached 101.90 kN, the reinforcement started to yield and deflection corresponding to this load has been measured as around 11.50 mm. When the applied load reached 153.70 kN, the beam made a deflection of 32.60 mm, lost its bearing power and collapsed (Fig. 10-Table 3).

There have been significant increases in the load bearing capacities of the G22 beams when compared to the control beams. The load corresponding to the occurrence of the first crack and the deflection value in the middle of the beam increased as much as 1.63 times. The load corresponding to the yielding of the reinforcement increased as much as 1.76 times and the deflection value in the middle of the beam increased as much as 1.38 times. The shear load of the G22 beam increased as much as 2.45 times, but the deflection corresponding to the shear load decreased by 3%.

After C22 and G22 beams resulted in shear fracture, the similar beams (C21-1 and G21-1) have been strengthened as two folds of longitudinal and one fold of transversal in a way that shall be vertical to the shear fracture and their impact on the load bearing capacities has been examined. When the load reached 26.60 kN on average in C21-1 beams, a deflection of 1.90 mm occurred in the middle of the beam and the first flexural cracks occurred in the 2nd lower zone of the beam. When the applied load reached 111.30 kN, the reinforcement started to yield and deflection corresponding to this load has been measured as around 12.00 mm. When the applied load reached 168.30 kN, the beam made a deflection of 24.20 mm, lost its bearing power and collapsed (Fig. 11-Table 3).

There have been significant increases in the load bearing capacities of the C21-1 beams when compared to the control beams. The load corresponding to the occurrence of the first crack

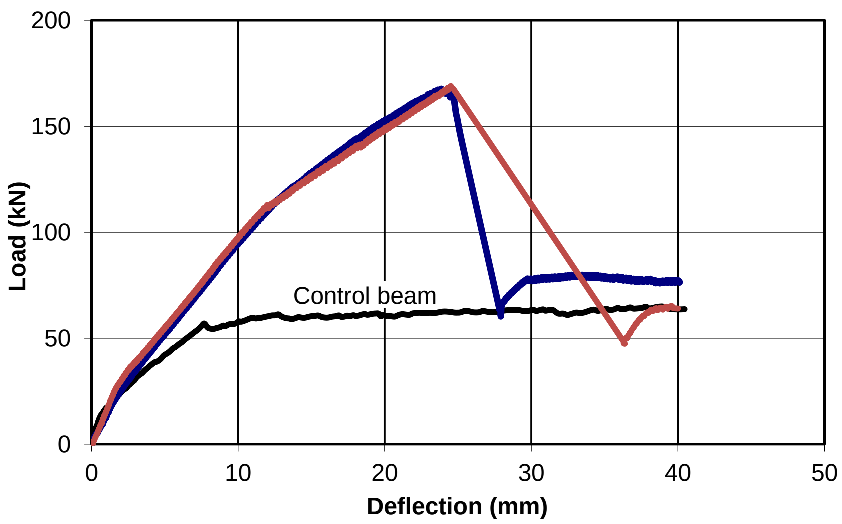


Fig. 11 Load-deflection graphs for the C21-1 beams

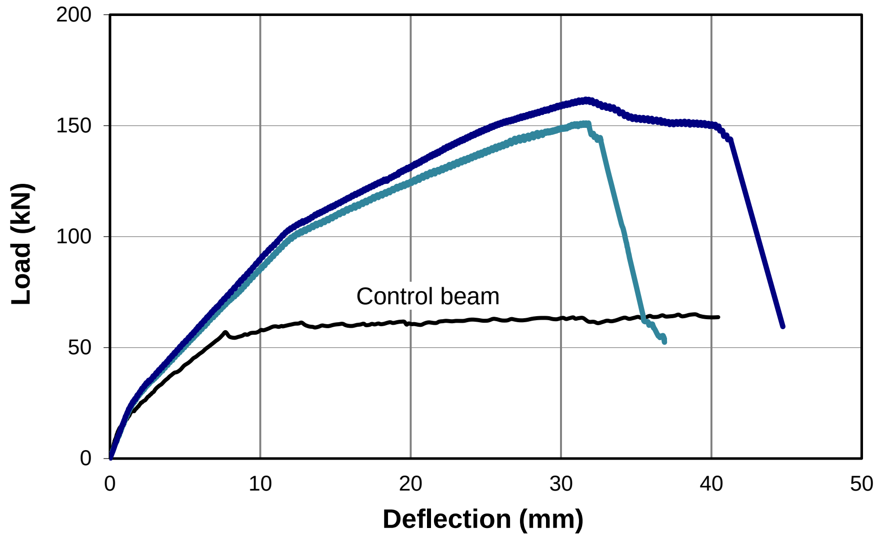


Fig. 12 Load-deflection graphs for the G21-1 beams

increased as much as 1.87 times and the deflection value in the middle of the beam increased as much as 2.13 times. The load corresponding to the yielding of the reinforcement increased as much as 1.94 times and the deflection value in the middle of the beam increased as much as 1.44 times. The shear load of the C21-1 beams increased as much as 2.68 times, but the deflection corresponding to the shear load decreased by 28%.

When the load reached 23.94 kN on average in G21-1 beams, a deflection of 1.43 mm occurred in the middle of the beam and the first flexural cracks occurred in the 2nd lower zone of the beam. When the applied load reached 102.70 kN, the reinforcement started to yield and deflection corresponding to this load has been measured as around 12.30 mm. When the applied load reached 156.60 kN, the beam made a deflection of 31.70 mm, lost its bearing power and collapsed (Fig. 12-Table 3).

There have been significant increases in the load bearing capacities of the G21-1 beams when compared to the control beams. The load corresponding to the occurrence of the first crack increased as much as 1.69 times and the deflection value in the middle of the beam increased as much as 1.62 times The load corresponding to the yielding of the reinforcement increased as much as 1.79 times and the deflection value in the middle of the beam increased as much as 1.48 times. The shear load of the C21-1 beams increased as much as 2.50 times, but the deflection corresponding to the shear load decreased by 6%.

4. Discussions

All of the eight groups of beams have been subjected to four-point flexural experiment and they have been loaded until their final strength. The beams strengthened by wrapping with CFRP and GFRP composites have been compared with the control beam in terms of bearing power, strain

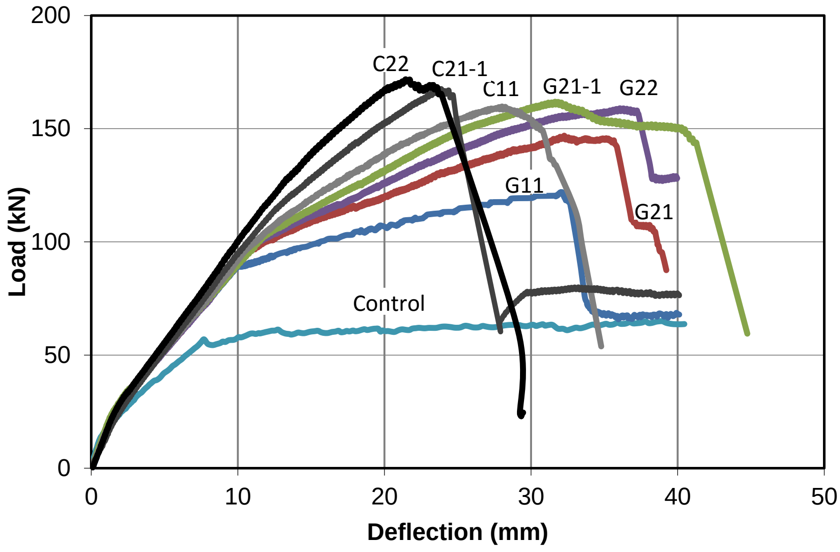


Fig. 13 The load-deflection graphics belonging to the control beam and the beams reinforced with FRP composites

ability, energy absorption capacities, ductility ratios and the results have been examined in detail. Ductility can be defined as energy absorption capacities without losing its load capacity. Energy absorption capacity is determined from the area under the load-displacement curve. The ultimate displacement is taken from the load-displacement curve corresponding to the 85% maximum load.

4.1 Load and strain capacity

As can clearly be seen in Fig. 13, significant increases have been attained in terms of the bearing power and energy absorption capacities in all of the RC beams reinforced with the use of FRP composites when compared to the control beam. The strength of the beam in all strengthening shapes more than doubled. As the wrapping layer increases, its strength has also increased, but this increase has not been in the same ratio.

The yielding load has been 34% lower and its deflection corresponding to the yielding load has been 18% lower in G11 beam when compared to C11 beam. The maximum load has been 69% lower, but the deflection has been 12% higher when compared to C11 beam. Although the load bearing capacity of G11 beam is low in terms of the fracture load, it is understood that it has a higher capacity for making strain. G21 beam has been manufactured within the direction of these results. The yielding load and the deflection of the yielding load have been similar in G21 and C11 beam. The fracture load has been 8% lower, but the deflection has been 9% higher when compared to C11 beam. It has been close to C11 beam in terms of load bearing capacity, but it is understood that it has a higher capacity for making a strain when compared to C11 beam.

The first crack load and deflection of G21 and G11 beam have been similar. The yielding load has been 18% higher and its deflection corresponding to the yielding load has been 18% higher in G21 beam when compared to G11 beam. The fracture load has been 25% higher, but the deflection corresponding to the fracture load has been close to the values of each other. As the wrapping increases in the beam element, the load bearing capacity increases, but the capacity for making deflection decreases.

Significant increases have been attained in the flexural and shear bearing power capacities of the beams strengthened with CFRP composites as two folds of longitudinal and transversal (C22) and strengthened with GFRP composites as two folds of longitudinal and transversal (G22) when compared to the control beam. When G22 beam is compared to C22 beam, the yielding load has been 22% lower and its deflection corresponding to the yielding load has been 17% lower. The fracture load has been 15% lower, but despite this, the deflection has been 36% higher when compared to C22 beam. Although the load bearing capacity of G22 beam is low in terms of the fracture load, it is understood that it has a higher capacity for making a strain.

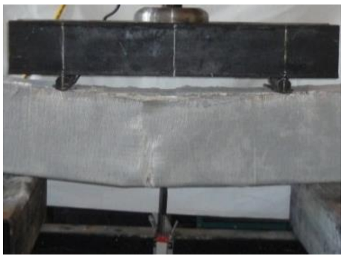
The flexural strength and energy absorption capacities of the beams strengthened as C21-1 and G21-1 with FRP composites have significantly increased when compared to the control beam. When C21-1 beam is compared to the control beam, the yielding load has increased by 94% and the deflection corresponding to the yielding load has increased by 44%. The fracture load of C21-1 beam has increased as much as 2.68 times, but the deflection corresponding to the fracture load has been 28% lower. Similarly, the yielding load of G21-1 beam has increased by 79% and the deflection corresponding to the yielding load has increased by 48%. The fracture load has increased as much as 2.5 times, but the deflection corresponding to the fracture load has decreased by 6%. The yielding load of G21-1 beam has been 8% lower than that of C21-1 beam but the deflection corresponding to the yielding load has been close to the values of each other. The fracture load has been 7% lower, but the deflection has been 31% higher when compared to C21-1. Although the load bearing capacity of G21-1 beam has been partly lower in terms of fracture load, it is understood that it has a higher capacity for making a strain.

4.2 Fracture types

The first cracks in the control beams have occurred under the beam in the flexure zone and the cracks have continued to occur towards the upper zone of the beam as loading has continued. When the beam has reached its final strength, it has been detected that shear cracks have also occurred in the shear zone (Fig. 14(a)). In all strengthenings conducted, significant increases have been attained in terms of the load bearing capacities when compared to the control beam. The shear fracture has immediately been broken when the C11, G21, C22, G22 and G21-1 beams have reached the collapsing load. These beams have been separated by breaking the FRP concrete parts under the loading point (Fig. 14(b), (d), (e), (f), (g), (h)). The longitudinal fibers have started to break off in the 2nd zone (flexural zone) of the beam when G11 beam has approached its final strength; and the beam has been broken from the flexural zone and the load value has continued at a level close to that of the control beam (Fig. 14(c)). When C21-1 beam has reached its final strength, it has been broken from the beam flexural zone and it has stayed at a level close to that of the control beam when the loading has continued (Fig. 14(g)). The breaking has been sudden in the strengthenings made with CFRP composites and it has been detected that the beam concrete has scattered in the fracture zone. In all strengthenings made with GFRP composites, the fractures have been softer when compared to CFRP composites. After the beam experiment of G21 subjected to experiment has been finalized, GFRP composite has been removed from the side surface of the beam and it has been detected that there have been significant flexural and shear fractures in the beam. FRP composites in the side surfaces of the beam has been opened by hand for the purpose of detecting the strains occurring along the beam and it has been detected that there have been crushes in the loading points and shear and flexural fractures of beam have also occurred except for the zone in which collapse has occurred (Fig. 14(d)). When C22 has reached its final strength, the beam has suddenly collapsed with the shear fracture. It has acted so brittlely although its load bearing capacity increases when compared to C11 beam. The concrete in the fracture zone has shattered together with the shear fracture and the C22 beams have not carried any load after the fracture. The load-deflection behavior has been similar until G22 beams have reached their final strength and sudden collapse has occurred with the shear fracture in the beam (Fig. 5). Although the bearing capacity has decreased after the shear fracture of G22 beams, it has continued to bear load at the level of the control beam. Differently from the strengthenings made with G22 and C22, the beam has continued to bear load even after the occurrence of the shear fracture. The collapse of C22 and G22 beams with shear fracture has been taken into consideration and it has been aimed to increase the beam bearing capacity with wrapping at an angle. For this purpose, two RC beams have been strengthened by wrapping two folds of longitudinal and one fold of transversal glass fiber with the angle of 90° and one fold of transversal glass fiber with the angle of 45° to the lower and side surfaces of the beam (C21-1, G21-1) and they have been tested. Shear fracture has occurred in both of the G21-1 beams. Flexural fracture has occurred in one of

(a) Control beams

(b) C11



(c) G11

(d) G21

Fig. 14 After the experiment the beam deformation (cont)

(e) C22 (f) G22

(g) C21-1 (h) G21-1

Fig. 14 Continued

the C21-1 beams and shear fracture has occurred in the other. The beam has continued to bear load as a result of the flexural fracture. When the beam has been examined after the experiment, it has been observed that FRP composites wrapped on the surface of the concrete has not been scraped out of the concrete surface but it has been separated by breaking off the concrete layer.

4.3 Ductility and the energy absorption capacity

The components of the structure elements and their ductility as well as the materials forming them have a special importance in the design of the structures. It is known that the structure elements are exposed to plastic behavior in different amounts before they collapse. Ductility is not only a reason for warning before reaching the final strength, but also decreases the dynamic load request with the increasing energy distribution and damage. Ductility has a vital importance in the structures made in earthquake zones. The ductility of the RC structures is a property desired to provide the structural integrity during flexure against the brittle collapse.

Ductility could be measured in terms of the impregnation of an element, strain ability or energy absorption capacity. Within this context, not only the strength of the structural elements, but also their ductility should be paid attention to in the strengthening works because a decrease occurs in the ductility while the strength of the structural elements significantly increases especially in the strengthenings made with FRP composites. All of the beams have been kept within the limits given in the regulations for the purpose of being able to see the changes in the ductility and energy absorption capacities as well as the strength and all of the beams have been equipped in a way that they shall meet the condition of ductility. The ductility levels of all of the beams have been found and compared using the load-deflection curve. The control beam has provided sufficient ductility and the ductilities of the RC beams strengthened with FRP composites have decreased as expected (Table 4). Together with this, significant increases have occurred in the flexural load bearing capacities of the beams strengthened with CFRP and GFRP composites.

An average decrease of 43% in C11 beam, 32% in G11 beam and 41% in G21 beam occurred

Table 4 Average ductility and the energy absorption capacity of tested beams

Specimens	at Yield Deflection (mm)	at Ultimate load Deflection (mm)	Ductility	The energy absorption capacity
Control beams	8.31	40	4.81	2145.23
C11	11.73	31.97	2.73	3229.51
G11	10.20	33.16	3.25	3032.54
G21	12.06	34.24	2.84	3598.14
C22	13.80	25.71	1.86	2923.33
G22	11.48	35.25	3.07	3804.19
C21-1	11.98	24.98	2.09	2579.96
G21-1	12.30	37.20	3.03	4138.37

in the ductility values of the strengthened beams. C22 beam has lost 61% of its ductility ratio when compared to the control beam. G22 beam has lost 36% of its ductility ratio. Therefore, it has been detected that G22 beam was 65% more ductile when compared to C22 beam. Also, there has been a decrease in the ductility ratios of the C21-1 and G21-1 beams when compared to the control beam. C21-1 beam has lost 57% of its ductility ratio and G21-1 beam has lost 37% of its ductility ratio when compared to the control beam. G21-1 beam was 45% more ductile when compared to C21-1 beam.

Significant changes have occurred in the energy absorption capacities of C11, G11 and G21 beams strengthened in similar ways (Table 4). There has been an increase in the absorbed energy amounts of all strengthened beams. G21 beam has given the best result with the ratio of 68% on average in terms of the absorbed energy amount. When the energy absorption percentages of C22 and G22 beams are examined between each other and when compared to the control beam, it has been detected that the beams strengthened as C22 and G22 have increased the energy absorption capacities significantly. The energy amount absorbed by C22 beam has been 36% higher than that of the control beam. G22 beam has been higher with the value of 77% as the absorbed energy amounts when compared to the control beam and C22 beams. The energy amount absorbed by C21-1 beam has been 20% higher than the energy amount absorbed by the control beam. G21-1 beam has absorbed 93% more energy when compared to the control beam. G21-1 beam has absorbed 60% more energy when compared to C21-1 beam.

5. Conclusions

In this study, rectangular RC beams have been manufactured on one-half scale in the laboratory environment by taking into consideration beams in RC structures not damaged during an earthquake but in need of strengthening. The RC beams strengthened with CFRP and GFRP composites have been examined through the impacts of the beams on flexural and shear strength, energy absorption capacities and ductility ratios. The experimental results of the strengthened RC beams have been compared to investigate the usability of GFRP instead of CFRP composites. In the study, significant increases have been attained in the load bearing and energy absorption capacities of the RC beams strengthened with CFRP and GFRP composites. According to the results:

When FRP wrapping layer has been increased, load bearing capacities of the beams have also increased; but it has been detected that the increase in the load bearing capacities is not at the same ratio with the increase in the wrapping layer. When the experiment results of C11, C22 and C21-1 beams are taken into consideration, it is clear that the strengthening as C22 shall provide more advantage by wrapping two folds longitudinally and two folds transversally with the angle of 90° with CFRP.

When the results of G11, G21, G22 and G21-1 beams are examined, it has been detected that the strengthening as G21-1 and G22 is more suitable. G22 shall be more suitable for strengthening due to the hardness of the wrapping of G21-1 beam.

It has been detected in all of the beams strengthened with GFRP composites that as the amount of wrapping increases, the energy absorption capacities of the beam also increase. G22 and G21-1 have given the most effective results in the beams strengthened with GFRP composites in various shapes.

Although the amount of wrapping increases in the strengthenings made with CFRP composites, the energy absorption capacities of the beam decrease. The best result has been attained from the beams strengthened as C11 in terms of energy absorption capacity.

- Although the strength of the strengthenings made with GFRP composites, lower when compared to the ones made with CFRP composites, their ductility and energy absorption capacities are higher.
- Although the strength decreases while the amount of wrapping increases in the beams strengthened with FRP composites, the ductility ratios of the beams decrease. However, the ductility loss of beams strengthened with GFRP composites has been less than that of CFRP composites.
- The fracture of the beams has been more sudden in the strengthenings made with CFRP composites. Most of the beams have not borne any load after fracture. However, the fractures have been softer in the strengthenings made with GFRP composites and it has been seen that the beam has protected a part of the load bearing capacity after fracture.
- It has been seen in the strengthening works conducted related to the beams that as FRP wrapping layer increases, FRP composites concrete breaks off and gets separated from the side surfaces of the beam. The separation of FRP could be prevented by making an anchorage application to the side surfaces of the beam. Together with this, the beams manufactured with concrete with lower strength under the existent conditions could also be tried.

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