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Textile Types, Number of Layers and Wrapping Types Effect on Shear Strengthening of Reinforced Concrete Beams with Textile-Reinforced Mortar versus Carbon-Fiber-Reinforced Polymer

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Abstract: In the scope of this study, the strengthening of reinforced concrete beams against to shear with different types of composite materials was investigated experimentally. A total of seventeen reinforced concrete beams, one with high shear strength and sixteen with low shear strength, were fabricated. The beam with high shear strength and one of the beams with low shear strength were chosen as reference beams. The remaining fifteen beam specimens were strengthened with textile-reinforced mortar (TRM) and carbon-fiber-reinforced polymer (CFRP). While light and heavy carbon mesh were used for strengthening with TRM, unidirectional carbon textile was used for strengthening with CFRP. Other experimental parameters were the spacing of strips, the number of layers (one or two) and the way of wrapping (strip or full). Simply supported beam specimens were tested under three-point loading. Beam specimens were compared in terms of failure mode, ultimate load capacity, ductility index and energy dissipation capacity.

Keywords: RC beam; strengthening; TRM; CFRP; shear

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1. Introduction

Reinforced concrete structural elements (beam, column, etc.) are strengthened by different types of methods because of aging, environmental effects, changes in the purpose of use, etc. Previously, strengthening was performed by adding a reinforced concrete layer to the existing structural elements [1–10]. Later, because of some disadvantages of strengthening by adding a reinforced concrete layer (jacketing), the use of steel strips, steel plates, etc., has come to the fore for the strengthening of reinforced concrete columns [11–16]. Structural elements were strengthened by bonding steel plates to the tensile and shearing zones with adhesive and bolts.

Fiber-reinforced polymers (FRPs) are another material widely used in strengthening because of their advantages such as high tensile strength, light weight and easy application. FRP material is bonded to surfaces with an organic epoxy material. However, negative effects such as low resistance to fire, inability to be applied on wet or moist surfaces, inability to replace the coating layer and high cost of FRP strengthening techniques were seen in the literature review [17–24]. Considering these disadvantages of FRP, the widespread use of textile-reinforced mortar (TRM), depending on the scientific research on it, has been accepted as remarkable progress in the field of structural strengthening [19–21,25]. Considering that the mortar is produced and applied by traditional methods, it has been understood that TRM has some important advantages over FRP such as low cost, high temperature resistance and is applicable to wet surfaces. Considering these advantages, researchers have increased the number of studies on TRM reinforcement in the last 15 years.

In the literature on strengthening, strengthening with the FRP method, which is older than the TRM method, has been used effectively from the beginning of the 2000s to the

present [26–44]. The study conducted by Triantafillou (1998) [40] is one of the pioneering studies on the strengthening of reinforced concrete beams with FRP against shear. In the study [40], 11 reinforced concrete beams with a cross-section of 70 mm × 100 mm and a length of 1000 mm were strengthened with carbon FRP without anchors, and the bearing capacity increased between 2.44 and 2.76 times. Wrapping scheme (full or strip), strip shape ([ ] or I I) and strip angle (45° or 90°) were selected as variables. In the research done by Adhikari and Mutsuyoshi (2004) [38], a total of eight reinforced concrete beams with dimensions of 150 × 200 × 2600 mm were tested. Effects of different configurations and layouts of carbon fiber polymer sheets on the ultimate shear strength of beams were studied. According to the test results, it was observed that externally bonded carbon fiber polymer sheets were effective in strengthening against to shear. As the number of sheet layers increased, the strength increased. In the study, the most effective strengthening was obtained with U-wrap of sheets. Deifalla and Ghobarah (2010) [29] aimed to investigate the strengthening detail for T beams. Six half-scale beams were tested by subjecting them to combined shear and torsion. From the study, it was observed that the extended U-jacket strengthening technique gave promising results regarding to strength and ductility.

So far, important results of some research [29,38,40] examining strengthening with FRP were mentioned. The obtained results and the parameters in other research [26–44] examining the strengthening of beams with FRP are presented in Table 1. When Table 1 is examined, it is seen that the lowest concrete compressive strength is 13.3 MPa [39] and the highest concrete compressive strength is 47.2 MPa [26]. Researchers have mostly used carbon FRP. Some researchers preferred glass FRP [30,33,42] and rarely aramid [33] FRP. The U shape has often been used as the strip shape. Some of the researchers have examined strengthening details regarding side bonding [30,32,38,39], rarely full [42] and L-shaped [31] strips. For details of strengthening with FRP, researchers generally used strip [26,27,30–33,35,37,39–44] (partial) instead of full wrapping [28–30,33,38,39]. One of the most important parameters in the research presented in Table 1 is the number of FRP layers. Most of the researchers applied FRP with a single layer. In the studies numbered [26,31,38], FRP was applied as both one and two layers, and it was concluded that the increase in the number of layers improves the performance of the specimen. In addition, in the study referred to as [26], four and six were also seen as the numbers of layers examined. As well as the number of layers, the number of strips in the shear zone also differed in the studies. Researchers strengthened the specimens with at least 3 [27,30,32,39] and at most 14 [44] FRP strips, depending on the lengths of the shear zones and width of the strips. In studies examining the number of strips (or strip spacing) as a parameter, it was emphasized that as the number of strips increases, load bearing capacity increases significantly. One of the most important details of the strengthening process is the anchor application. Many of the researchers did not prefer anchorage due to the difficulty of application. In only 6 of the 18 studies presented in Table 1, the researchers suggested an anchor detail. Fan-type anchors were used in three of these six studies, and mechanical anchors were used in the rest. As a result of strengthening against shear with FRP applied with the variables given in Table 1, an increase of at least 101% [39] and at most 276% [40] was obtained in the load bearing capacity.

Strengthening with TRM, as mentioned before, is an innovative strengthening method that has been introduced to the literature as an alternative due to some disadvantages of strengthening with FRP. Escrig et al. (2015) [45] also emphasized that TRM is a composite material that overcomes some of the disadvantages of other strengthening methods against shear. Escrig et al. (2015) [45] strengthened reinforced concrete beams with four different types of TRM. In the study in which the mechanical performances of the beam specimens were compared, it was seen that the different TRM combinations used could increase the load bearing capacity and change the failure modes. In addition, new methodologies were presented that allow the evaluation of the bonding behavior and bending stiffness increase in the TRM. Experiment results were compared with previous analytical formulations derived for FRP and TRM.

Table 1. Summary of previous studies involving RC beams strengthened with FRP.

References	Compressive Strength of Concrete (MPa)	Type of FRP	Strip Shape	Wrapping Type	Number of Layers	Number of FRP Strips	Anchor Type	Pstr./Pref.
Nguyen-Minh et al. (2018) [26]	47.2	C	U	Strip	2–4–6	4–6	-	1.08–1.37
Hussein et al. (2013) [27]	30.0	C	U	Strip	1	3	-	1.25–1.68
Koutas and Triantafillou (2013) [28]	22.5–22.9	C	U	Full	2	-	Fan-type	1.40–2.16
Deifalla and Ghobarah [29]	25.6	C	U	Full	1	-	Mechanical	1.45–1.71
Haddad et al. (2013) [30]	40	C–G	U–I I	Full–Strip	1	3–4	-	1.09–1.65
Dong et al. (2013) [31]	22.8–31.3	C	U–L	Strip	1–2	6	-	1.42–2.24
Mostofinejad and Kashani (2013) [32]	38.0	C	I I	Strip	1	3–4	-	1.09–1.59
Nikopour and Nehdi (2011) [33]	25.1	C–G–A	U	Full–Strip	1	4	-	1.09–1.36
Galal and Mofidi (2010) [34]	41.0–43.0	C	U	Full	1	-	Mechanical	1.27–1.48
El-Ghandour (2011) [35]	39.5	C	U	Strip	1	5	-	1.10–1.30
Ebead and Saeed (2017) [37]	35	C	U	Strip	1	4–6–8	Mechanical	1.73–2.33
Adhikary and Mutsuyoshi (2014) [38]	34	C	U–I I	Full	1–2	-	-	1.29–2.19
Monti and Liotta (2007) [39]	13.3	C	U–I I	Full–Strip	1	3–4	-	1.01–1.86
Triantafillou (1998) [40]	30.0	C	I I	Strip	1	6	-	2.44–2.76
Pellegrino and Modena (2006) [41]	41.4	C	U	Strip	1	-	-	1.02–1.36
Sengun and Arslan (2022) [42]	43.0	C–G	U–full	Strip	1	5–7	-	1.46–2.12
Altın et al. (2011) [43]	24.2–25.8	C	U	Strip	1	8–10–12	Fan-type	1.05–1.29
Altın et al. (2010) [44]	24.2–25.8	C	U	Strip	1	8–13–14	Fan-type	1.65–1.77

C = carbon, G = glass, A = aramid, U = U-shaped strip, and I I = side bonding.

Tetta et al. (2016) [46], presented a study showing the effectiveness of strengthening of reinforced concrete T-beams with TRM jacketing. They used a new end anchor system consisting of fan type anchors. A total of 11 full-scale reinforced concrete T-beams were tested under three-point bending loading. According to the study: the anchors significantly increased the effectiveness of TRM U-jackets. In non-anchored strengthening, increasing the number of layers provided an almost proportional increase in shear capacity and changed the failure mode. Different textile geometries used with the same reinforcement ratio provided practically equal capacity increase in non-anchored strengthened beams. It was observed that TRM jackets can be as effective in increasing the shear capacity of reinforced concrete T-beams as FRP jackets. Guo et al. (2022) [47] carried out an experimental study in which reinforced concrete beams that were previously damaged under the effect of shear were strengthened with TRM. A total of eight reinforced concrete beams were tested under four-point bending loading. Experiment results showed that strengthening with TRM can completely restore the mechanical properties of previously damaged reinforced concrete beams. The shear capacity of previously damaged strengthened beams was measured smaller than that of undamaged strengthened beams with the same strengthening configuration. Yılmaz and Mercimek [48] researched the effect of FRP and TRM strips on shear behavior of RC beams. According to the study, it was concluded that all materials,

especially CFRP, were quite effective in enhancing shear capacity of the RC beams. In the research conducted by Mercimek [49], effects of strengthening material (FRP or TRM) type, anchorage type (mechanical or fan) and strip shapes on RC beam shear behavior were investigated. According to the study, better results were taken with the material FRP in terms of shear capacity. Application of the textile material with a side bonding scheme was more effective by around 8 to 31%. In terms of shear capacity, while the better results for U-shaped strips were taken with mechanical anchors, for the side-bonded strips, better results were obtained with fan-type anchors. Also, it was concluded that the energy dissipation capacities increased 3.6 to 4.1 times by strengthening with FRP and TRM.

Some important results of some research [45–47] examining TRM reinforcement have been mentioned so far. The obtained results and variables in other research [45–47,50–64] examining the reinforcement of beams with TRM are presented in Table 2. When Table 2 is examined, it is seen that the lowest concrete compressive strength is 12.6 MPa [54] and the highest concrete compressive strength is 44.8 MPa [56]. Researchers have mostly used carbon mesh. Some researchers preferred glass [45,46,53,61], rarely basalt [45,57] and Benzobis Oxazole (PBO) textile mesh [45,56]. The U shape has often been used as a strip shape. Some of the researchers examined strengthening orientations regarding side bonding [50,51,57,60] and rarely full-wrapped strips [50,52]. For details of strengthening with TRM, researchers generally used full wrapping [45–47,50–58,60] instead of strip [60,64]. One of the most important parameters in the research presented in Table 1 is the number of TRM layers. Many of the researchers applied TRM as one and more layers. It was emphasized that the second layer [46,47,51–55,58], which is frequently preferred by researchers, significantly increases the strength. The largest number of layers was applied as seven [46,53]. In the studies referred to as [45,50,56,57,61,64], TRM was applied only as a single layer. In addition to the number of layers, the number of strips in the shear zone also showed differences in the studies on strengthening with strip (partial). Researchers strengthened the specimens with at least two [60,61] and at most six [64] TRM strips, depending on the lengths of the shear zones and width of the strips. In studies in which the number of strips (or strip spacing) was taken as a parameter, it was emphasized that as the number of strips increases, load bearing capacity increases significantly. Many of the researchers did not use anchors because of the difficulty of application. In only 6 of the 15 studies presented in Table 2, the researchers suggested an anchor detail. The fan-type anchor was used in three of these six studies and mechanical anchors were used in the remainder. As a result of strengthening against shear with TRM applied with the variables given in Table 2, an increase of at least 103% [61] and at most 295% [50] was obtained in the load bearing capacity.

The parameters used in important studies on the strengthening of reinforced concrete beams against shear with FRP and TRM and the results obtained were examined in detail. Although researchers emphasize that TRM is a more environmentally friendly alternative to FRP, a very limited number of studies [46,49,50] have compared these two reinforcement methods experimentally. Therefore, in this study, it was planned to compare the TRM and FRP strengthening methods. Then, the stages and details of the study were determined by considering the variables in Tables 1 and 2.

So, generally, strengthening with FRP is applied with strips, while strengthening with TRM is applied as a full wrap. In this study, both TRM and FRP strengthening methods were applied with strips and full wraps. The spacing of the strips was selected as one of the parameters. Also, when the literature is examined, it can be seen that FRP strips were generally applied with a single layer, while TRM full wraps were generally applied with more than one layer. In this study, one and two layers were applied for both TRM and FRP strengthening methods. Textile type was taken as a parameter in a limited number of studies including TRM strengthening method [45,46,53,57]. Accordingly, two types of carbon textiles, light and heavy, were used in the proposed TRM strengthening details. In addition, by examining Tables 1 and 2, the strip shape and anchor type were selected as one type (U-shaped and mechanical, respectively). The most preferred U-shaped strip in the

literature was selected in the study. By considering the current number of test specimens and the literature, mechanical anchorage was used in all strengthened test specimens.

Table 2. Summary of previous studies involving RC beams strengthened with TRM.

References	Compressive Strength of Concrete (MPa)	Type of FRP Mesh	Strip Shape	Wrapping Type	Number of Layers	Number of FRP Strips	Anchor Type	Pstr./Pref.
Tetta et al. (2015) [50]	21.6–23.8	C	U–I I–Full	Full	1	-	-	1.09–2.95
Escrig et al. (2015) [45]	33.8–40.9	B–C PBO–G	U	Full	1	-	-	1.00–1.43
Al-Salloum et al. (2012) [51]	20	C	I I	Full	2–4	-	-	1.36–1.88
Triantafillou and Pap. (2006) [52]	30.5	C	Full	Full	1–2	-	-	2.00–2.25
Tetta et al. (2018) [53]	20.0–23.8	C–G	U	Full	1–2–3–4–7	-	-	1.41–2.79
Tzoura and Triantafillou (2016) [54]	12.6–25.1	C	U	Full	1–2	-	Mechanical	1.05–1.97
Tetta et al. (2016) [46]	13.8–15.2	C–G	U	Full	1–2–3–4–7	-	Fan-type	1.38–2.19
Zang et al. (2019 [55]	25.0	C	U	Full	1–2–3	-	Mechanical	1.47–2.26
Guo et al. (2022) [47]	30.6	C	U	Full	2–3	-	-	1.29–2.37
Marcinczak et al. (2019) [56]	44.8	PBO	U	Strip	1	3	Fan-type	1.10–1.28
Yang et al. (2020) [57]	32.7	B–C	I I	Full	1	-	-	1.51–2.15
Brückner et al. (2008) [58]	30.7–41.0	G	U	Full	2–4–6	-	Mechanical	1.16–1.33
Larbi et al. (2010) [60]	33.0	C	U–I I	Full–Strip	3	2–4	-	1.17–1.69
Contamine et al. (2013) [61]	30.0–40.0	G	U–I I	Full–Strip	1	2–3–5	-	1.03–1.38
Trapko et al. (2015) [64]	42.9	PBO	U	Strip	1	3–4–6	Fan	1.07–1.16

B = basalt, C = carbon, G = glass, PBO = poli–pfenilenbenzobisoksazol, U = U-shaped strip, and I I = side bonding.

2. Experimental Study

2.1. Test Specimens and Materials

A total of 17 reinforced concrete (RC) beams were tested under the effect of bending by applying three-point loading. When the beam behavior against shear was investigated experimentally, generally, 4-point or 3-point bending tests were performed in the past studies. For this type of study, shear spans are considered. When 4-point and 3-point bending loading configurations were compared, shear or moment diagrams in shear spans of the beams are closer to each other. Because of that main reason and current laboratory conditions, it was decided to conduct the tests under 3-point bending loading.

Properties of the tested beam specimens are presented in Table 3. One of the beams was fabricated with steel stirrups along its entire length. The other 16 beams were fabricated as they did not include any stirrups in their short shear span, but they included steel stirrups in their long shear span. The beam including steel stirrups along its entire length and one of the beams not having steel stirrups in their short span were considered as reference beams. The other 15 RC beams were strengthened with CFRP or TRM against shear.

Beams were fabricated monolithically (Figure 2). The 150 × 150 × 150 mm concrete cubic samples were taken during construction. Average compression strength of transformed standard cylinder samples was obtained as 25 MPa. The mixture of the concrete was given in Table 4.

Table 3. Properties of specimens.

Specimens	Name of Specimens	Comp. Strength of Concrete	Textile	Wrapping Type	Layer Number	Strip Number
1 *	RBS	25.1		with stirrups		
2 *	RB	24.9		without stirrup		
3 *	CFRP-L1-S2	25.3	CFRP	Strip	1	3
4	CFRP-L1-S1	24.9				4
5	CFRP-L2-S2	25.2			2	3
6	CFRP-L2-S1	25.4				4
7	CFRP-L1-S0	25.1		Full	1	
8 *	TRM170-L1-S2	25.0	Carbon Mesh-170	Strip	1	3
9	TRM170-L1-S1	25.0				4
10	TRM170-L2-S2	24.7			2	3
11	TRM170-L2-S1	25.4				4
12	TRM170-S0	25.3		Full	1	
13 *	TRM350-L1-S2	25.4	Carbon Mesh-350	Strip	1	3
14	TRM350-L1-S1	25.2				4
15	TRM350-L2-S2	24.8			2	3
16	TRM350-L2-S1	24.9				4
17	TRM350-S0	24.9		Full	1	

* These specimens were used in [48,49].

Table 4. Concrete mix design for 1 m^3.

Targeted concrete compressive strength	25 MPa
Consistency	S3
W/C	0.71
Dmax	11 mm
Material	Amount (kg)
0–4 Aggregate	1060
4–11 Aggregate	811
Concrete mixing water	150
Concrete mixing water-back	35
Cement (CEM-I-42,5-R)	350
Plasticiser	3.88
Fly ash	40

RC beam specimens had a length of 2500 mm and a rectangular cross-section of 125 × 250 mm. Two longitudinal reinforcement ribbed steel bars of ϕ16 and of ϕ10 were placed in tension and compression zones of the beams, respectively. Ribbed steel of ϕ10 was used and placed as a stirrup. Mechanical properties of the steel bars are listed in Table 5. The layout of the reinforcement of the reference beam including steel stirrups along its entire length and of the reinforcement of the other 16 beams are shown in Figures 1 and 2, respectively.

Table 5. Mechanical properties of materials.

Reinforcement		
Properties	Diameter of 10 mm	Diameter of 16 mm
Yield Strength (MPa)	400	425
Ultimate Tensile Strength (MPa)	460	562
Modulus of Elasticity	201	203
Type	Ribbed	Ribbed
Textiles using in strengthening *		
Properties	Carbon mesh-350	Carbon mesh-170
Tensile Strength	255 kN/m	240 kN/m
Coated Weight for m^2 (gr)	350	170
Thickness (mm)	1.43	0.048
Modulus of Elasticity (GPa)	235	235
Elongation at Break (%)	1.7	1.8
Mortar using in strengthening *		
Properties	Mortar-300	
Flexural Strength (MPa)	>7	
Concrete adhesion strength (MPa)	>2	
Compressive Strength (MPa)	>60	
Modulus of elasticity (GPa)	>20	
Carbon-Fiber-Reinforced Polymer *		
Properties	Sikawrap 230-C (Unidirectional)	
Weight	230 gr/m^2	
Thickness	0.12 mm	
Tensile Strength	4100 MPa	
Modulus of Elasticity	231 GPa	
Ultimate Strain	1.7%	
Density	1.75–2.00 (g/cm^3)	
Sikadur 330 Epoxy Resin *		
Density	1.31 kg/lt	
Mix Ratio	White/Gray Compound = 4/1	
Application Temperature	Min +10 °C, mac +35 °C	
Tension Strength	30 MPa	
Bending Modulus of Elasticity	3800 MPa	
Density	1.1–1.4 (g/cm^3)	

* Mechanical properties are provided by the manufacturer.

Steel stirrups placed in conventional configuration bear the shear loads by their vertical legs. FRP and TRM were applied in a similar logic with steel stirrups. It can be thought that the sides of the FRP and TRM sticked on the front and back faces of the beams are the legs of them. Related articles in the literature were also considered to specify the configuration of the textile materials. In these strengthening methods, beams can collapse by slipping of the textile materials from concrete surface without any rupture in textile material. Considering this issue, anchorages were used to hinder debonding and to increase the bearing capacity of the beam.



Figure 1. Reinforcement details of references RBS and RB (dimensions in mm).

In the previous studies conducted by researchers, it was seen that the parameters of strip spacing, number of layers and the scheme of wrapping were important factors in strengthening the beams. Due to the changes in these parameters, the behavior of the beams was affected significantly. Because of that, it was decided to select these valuables as test parameters in this study.



Figure 2. *Cont.*



Figure 2. The production process of test specimens.

The strip thickness was 100 mm in all beam specimens strengthened with strips. Two strip spacing values, 167 mm and 250 mm, were used. One or two layers of strip were used for the beams strengthened with strip. On the other hand, only one layer of CFRP or TRM was used in the beam specimens that were strengthened in the scheme of full wrapping. The layout of the strengthened RC beams is shown in Figure 3. As shown in Figure 4, mechanical type of anchorage was used for the strengthening of the beams. The ϕ10-8.8 type of steel rods was used as mechanical anchorage. The bolts must be tightened sufficiently for the anchors to work, but care must be taken not to crush the concrete under the plate under the bolt head while tightening the bolts. In the study, tension load was given to the bolt with a snug-tight condition in such a way to not give any obvious deformation to the plate located under bolt head. Because of the advantages of TRM, it is thought that investigations should have been performed for all available manufactured carbon mesh products. Since it was not seen in any research that investigates the effects of textile materials TRM-170 and TRM-350 in the configurations applied in this study, it was decided to use them as textile material in TRM strengthening method. Textile materials of TRM and CFRP are shown in Figure 5.

Tensile strength of carbon mesh-170 and carbon mesh-350 are 240 kN/m and 255 kN/m, respectively. These materials were bonded to the surface of the RC beams using cement-based mortar (Figure 6). Mechanical properties of the mortar and TRM textile material are given in Table 5. Tensile strength of the CFRP is 4100 MPa. CFRP layer was bonded to the surface of the RC beams by using a type of epoxy adhesive, named Sikadur-330, produced by the Sika company. Mechanical properties of the epoxy adhesive and CFRP material are given in Table 5.

Names of the tested beam specimens are presented in Table 3. The beam specimen named as RBS denotes the reference beam with steel stirrups in shear span, and the specimen named as RB denotes the reference beam without steel stirrups in short shear span. For the notation of the strengthened beam specimens, in summary, first part of the name denotes the material type used for strengthening. The number following the letter L denotes the number of layers applied. The number following the letter S denotes the spacing of the strips; 2 is for 250 mm spacing, 1 is for 167 mm spacing and 0 is for full layer. The description of the beam specimens follows below:

- Specimen RBS is the reference beam with steel stirrups in shear span.
- Specimen RB is the reference beam without steel stirrups in shear span.
- Specimens CFRP-L1-S2 and CFRP-L1-S1 were strengthened with 1 layer of CFRP strips by spacing 250 mm and 167 mm, respectively.
- Specimens CFRP-L2-S2 and CFRP-L2-S1 were strengthened with 2 layers of CFRP strips by spacing 250 mm and 167 mm, respectively.
- Specimens TRM170-L1-S2 and TRM170-L1-S1 were strengthened with 1 layer of TRM-170 strips by spacing 250 mm and 167 mm, respectively.

- Specimens TRM170-L2-S2 and TRM170-L2-S1 were strengthened with 2 layers of TRM-170 strips by spacing 250 mm and 167 mm, respectively.
- Specimens TRM350-L1-S2 and TRM350-L1-S1 were strengthened with 1 layer of TRM-350 strips by spacing 250 mm and 167 mm, respectively.
- Specimens TRM350-L2-S2 and TRM350-L2-S1 were strengthened with 2 layers of TRM-350 strips by spacing 250 mm and 167 mm, respectively.
- Specimens CFRP-L1-S0, TRM170-L1-S0 and TRM350-L1-S0 were strengthened with 1 full-wrapped layer of CFRP, TRM-170 and TRM-350, respectively.

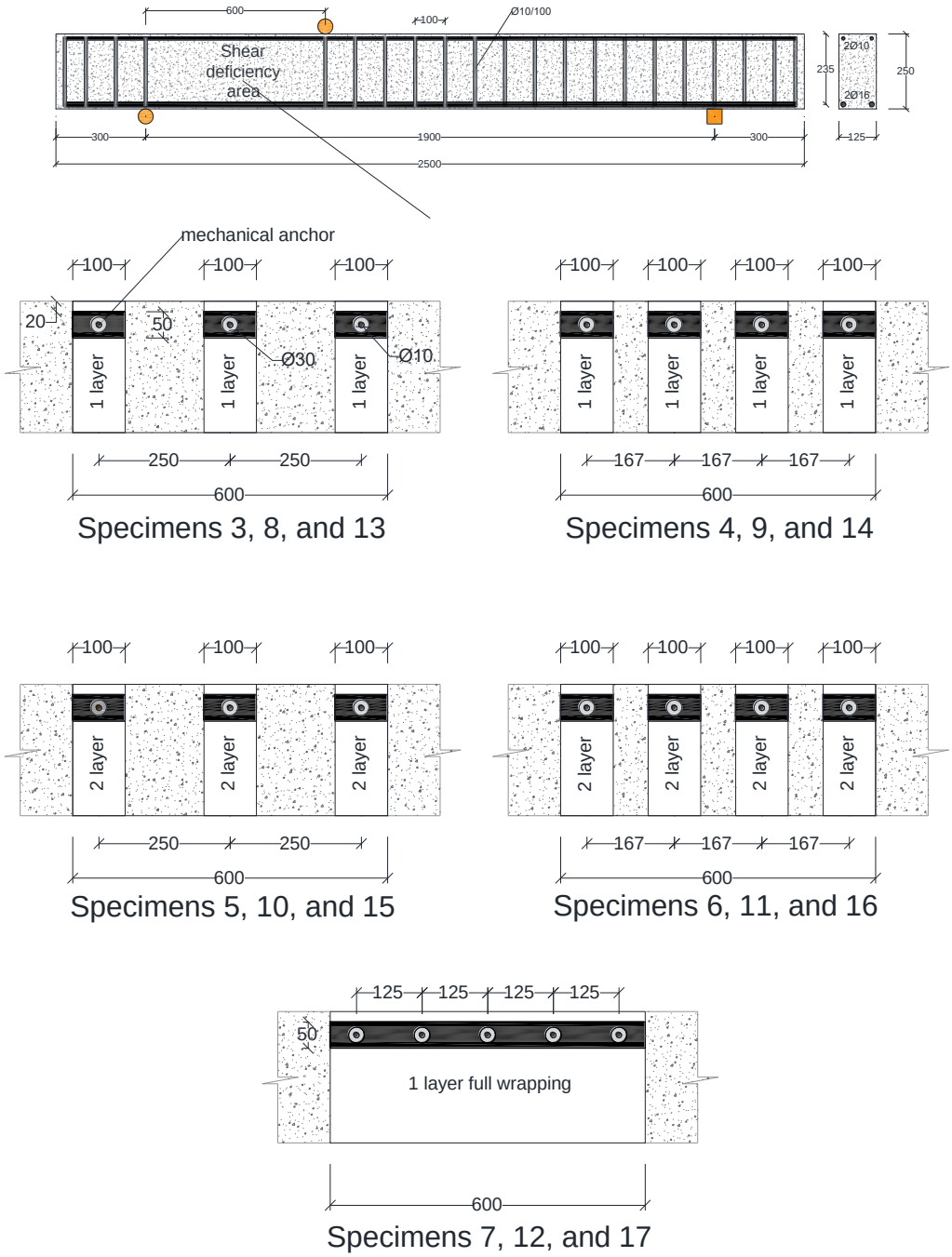


Figure 3. Strengthening details (dimensions in mm).

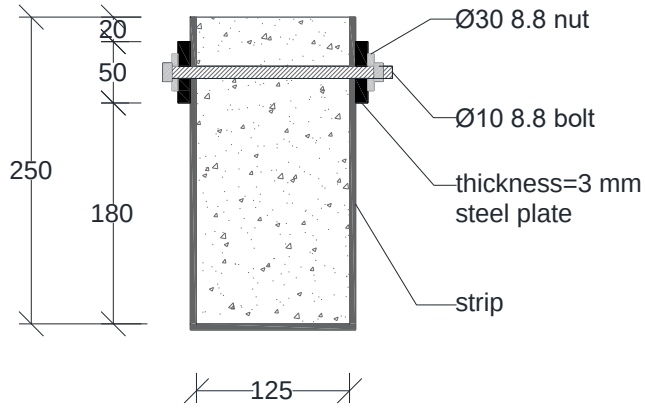


Figure 4. Mechanical anchor details (dimensions in mm).



Figure 5. Strengthening processes with TRM.



Figure 6. *Cont.*



Figure 6. Strengthening processes with CFRP.

2.2. Test Setup and Instrumentations

Simply supported beam specimens were tested under three-point loading. Experiments were carried out in a steel frame having 600 kN load bearing capacity, as shown in Figure 7. Load was applied by a motorized hydraulic system. A load cell with a capacity of 500 kN was used to measure the load values. One vertical displacement measurement was taken from the bottom surface of the beam on the same line of the load application point on each beam specimen. A linear variable differential transformer (LVDT) was used for this measurement. The obtained load and deflection data were transferred to a computer by a data collection system.

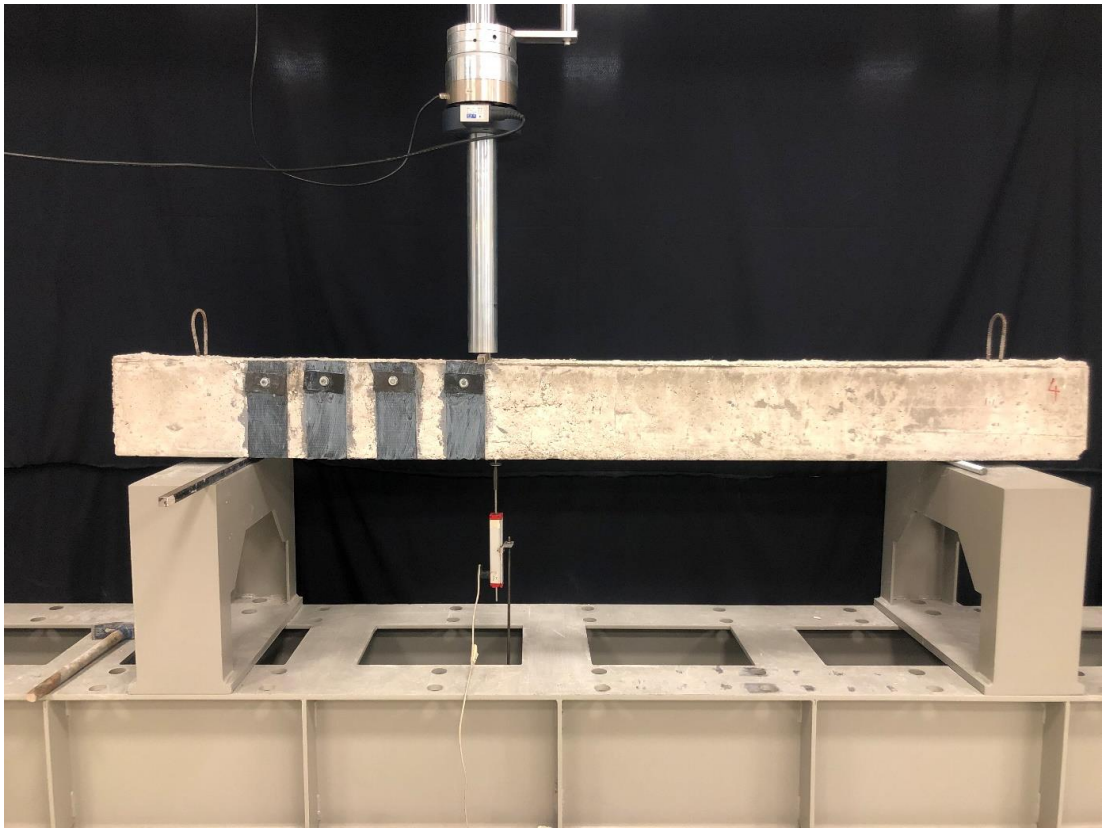


Figure 7. Test setup and instrumentation.

3. Experimental Results and Discussion

Beam specimens RB, CFRP-L1-S2, CFRP-L2-S2, TRM170-L1-S2, TRM170-L1-S1, TRM170-L2-S2, TRM170-L2-S1, TRM170-S0, TRM350-L1-S2, TRM350-L1-S1, TRM350-L2-S2, TRM350-

L2-S1 and TRM350-S0 collapsed in shear failure mode and the other beam specimens RBS, CFRP-L1-S1, CFRP-L2-S1 and CFRP-L1-S0 collapsed in bending failure mode.

For strengthened beams collapsing in bending failure mode, crack propagation was similar with the reference beam RBS. Both types of cracks occurred due to bending or shear. For the other strengthened beams collapsing in shear failure mode, crack propagation was similar with the reference beam RB. Cracks were mainly due to shear and occurred in a short shear span.

Load–displacement curves of the beam specimens obtained from the experiments were given in Figure 8. Beam specimens were assessed in terms of ultimate load, deflection corresponding to the ultimate load, ductility and energy dissipation capacity. The load value after reaching the ultimate load, which is equal to 85% of the ultimate load, was taken as the failure load. Experimental results of the beam specimens are given in Table 6. Failure modes of specimens are given in Figures 9–12. Energy dissipation capacity was determined by computing the area under the load-deflection curve. These assumptions are shown in Figure 13.

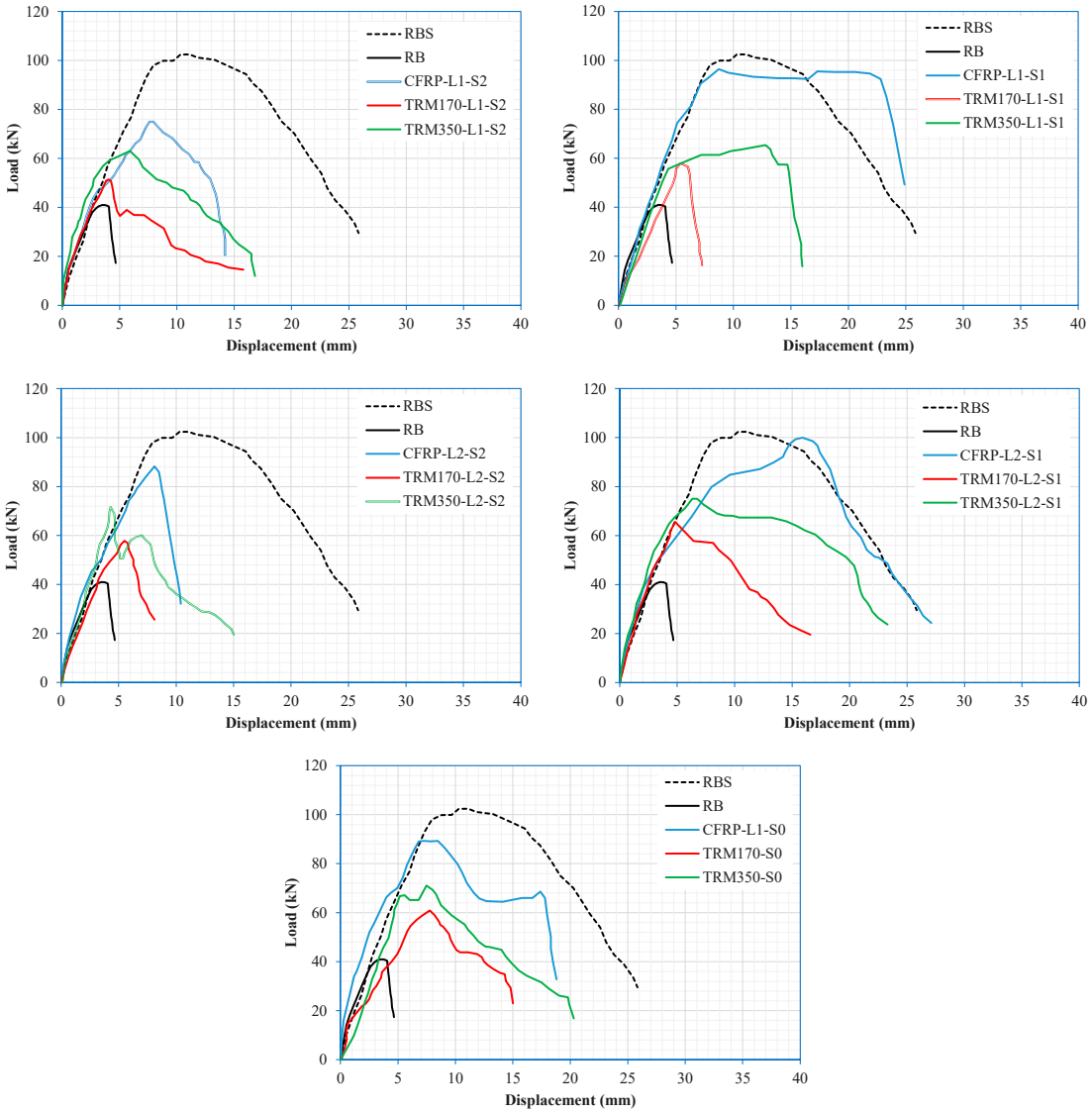


Figure 8. Load–displacement graphs of test specimens.

Table 6. Experimental results.

Spec. #	Ultimate Load (kN)	Disp. at Ultimate Load (mm)	0.85 × Ultimate Load (kN)	Disp. at 0.85 × Ultimate Load (mm)	Initial Stiffness (kN/mm)	Ductility Index, μ	Energy Dissipation Capacity (kN-mm)	Failure Mode
1	103.84	10.86	88.26	16.95	13.45	2.88	1321.30	Flexure
2	40.92	3.78	34.78	4.20	24.25	2.22	131.38	Shear
3	74.79	7.56	63.57	10.14	23.67	2.21	534.87	Shear
4	97.57	8.76	82.93	23.06	14.54	4.07	1841.52	Flexure
5	88.34	8.12	75.09	8.98	18.60	1.96	498.69	Shear
6	99.35	15.35	84.45	18.53	16.68	2.90	1316.90	Flexure
7	89.51	6.85	76.08	10.55	54.14	2.74	688.83	Flexure
8	51.43	3.90	43.72	4.79	26.07	1.72	155.53	Shear
9	58.05	5.43	49.34	6.38	13.85	1.26	211.90	Shear
10	57.99	5.33	49.29	6.52	11.93	1.57	237.19	Shear
11	65.30	4.72	55.51	8.35	16.66	2.17	377.73	Shear
12	60.70	7.40	51.60	9.45	17.62	2.07	365.93	Shear
13	62.58	5.91	53.19	7.67	19.21	3.58	362.35	Shear
14	64.93	12.59	55.19	14.72	12.75	3.42	741.96	Shear
15	71.16	4.35	60.49	6.98	16.40	1.93	302.49	Shear
16	74.60	6.50	63.41	15.35	27.95	3.91	912.03	Shear
17	71.27	7.59	60.58	9.12	11.33	1.67	407.79	Shear

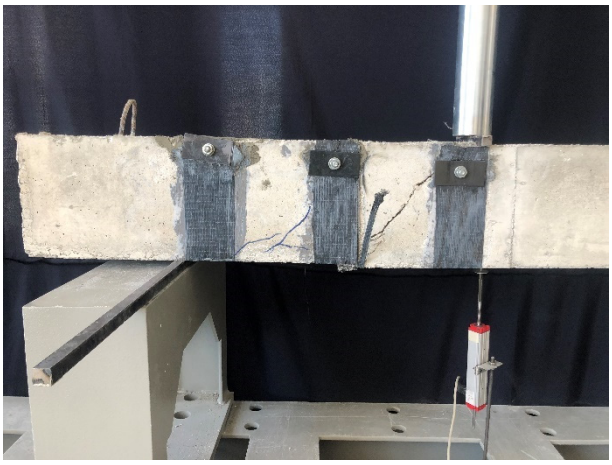


RBS

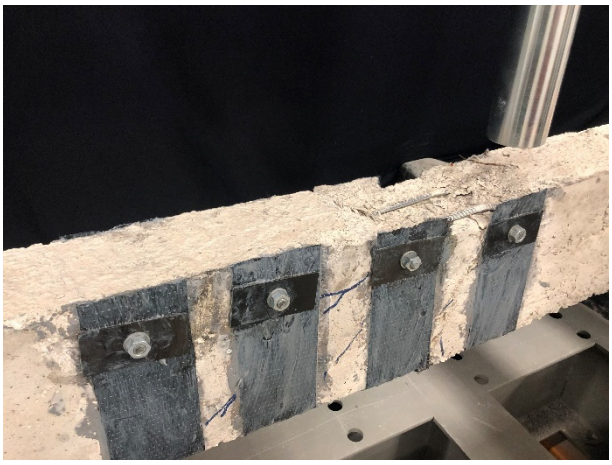


RB

Figure 9. Failure modes and damage distribution of the reference specimens.

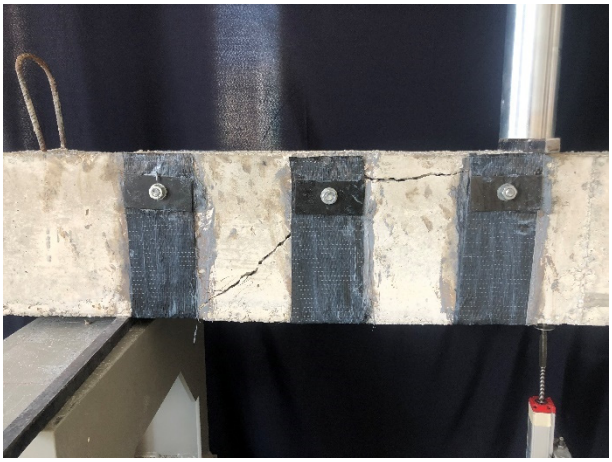


CFRP-L1-S2



CFRP-L1-S1

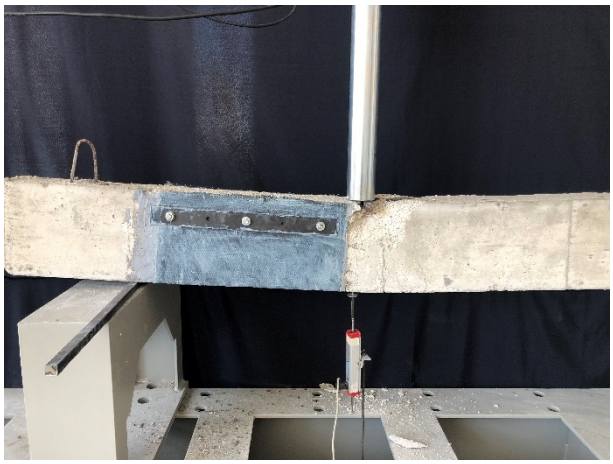
Figure 10. *Cont.*



CFRP-L2-S2

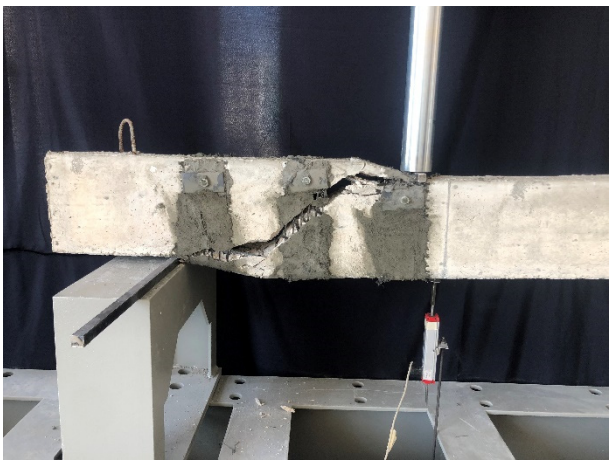


CFRP-L2-S1



CFRP-L1-S0

Figure 10. Failure modes and damage distribution of the specimens strengthening with CFRP.



TRM170-L1-S2

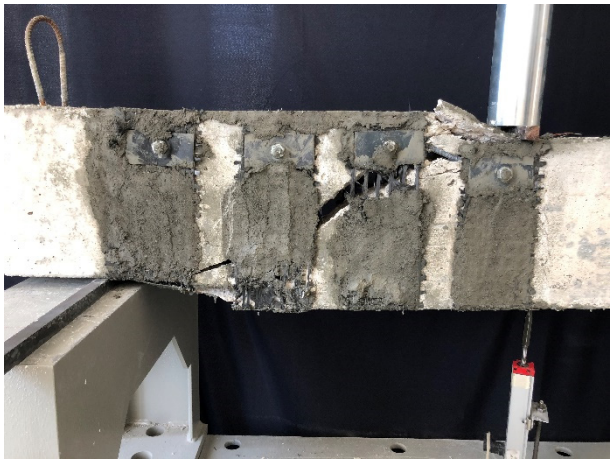


TRM170-L1-S1

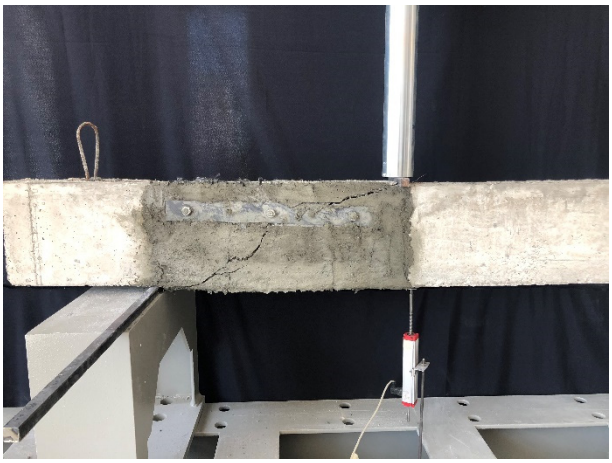
Figure 11. *Cont*.



TRM170-L2-S2



TRM170-L2-S1



TRM170-S0

Figure 11. Failure modes and damage distribution of the specimens strengthening with carbon mesh-170.



TRM350-L1-S2



TRM350-L1-S1

Figure 12. *Cont.*

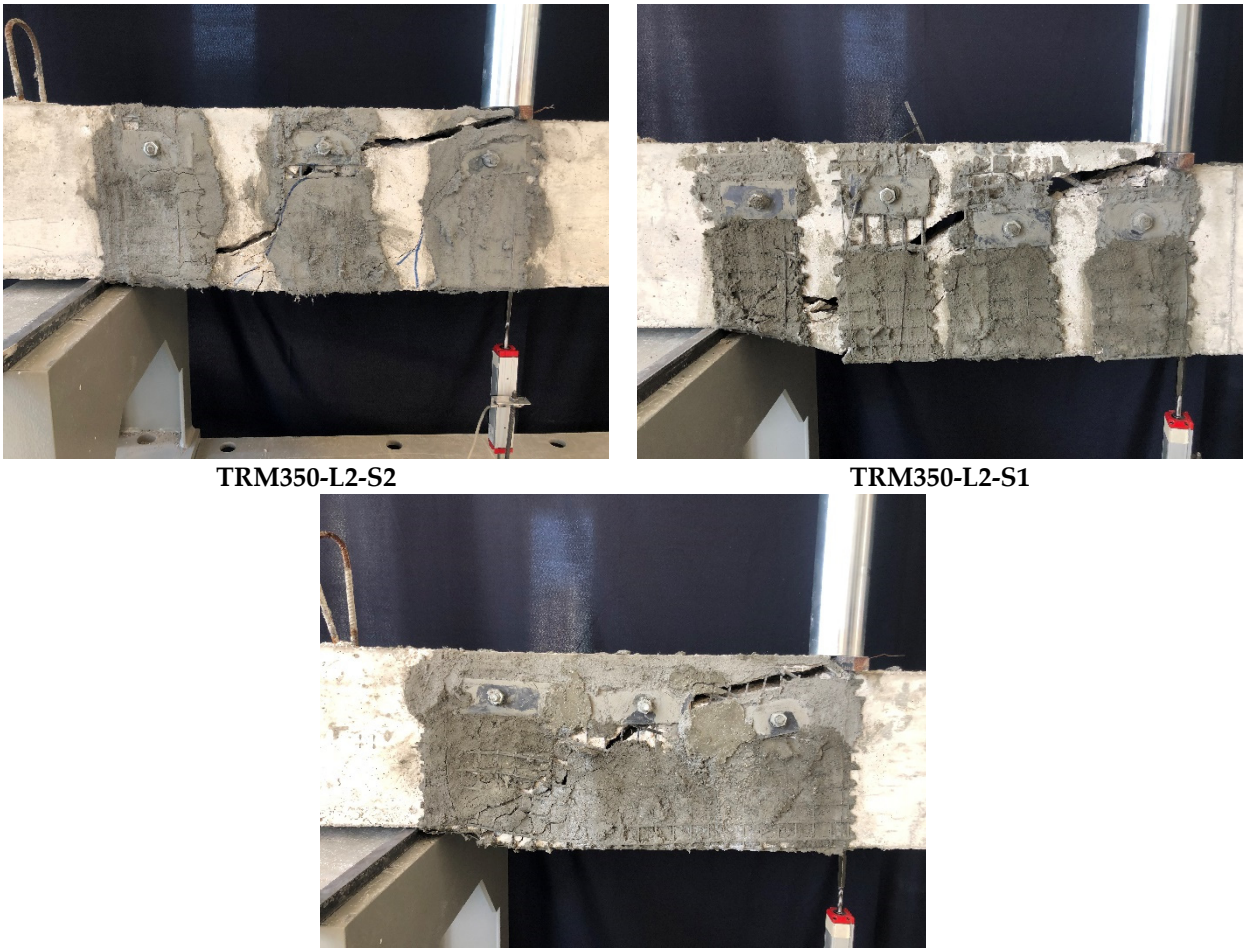


Figure 12. Failure modes and damage distribution of the specimens strengthening with carbon mesh-350.

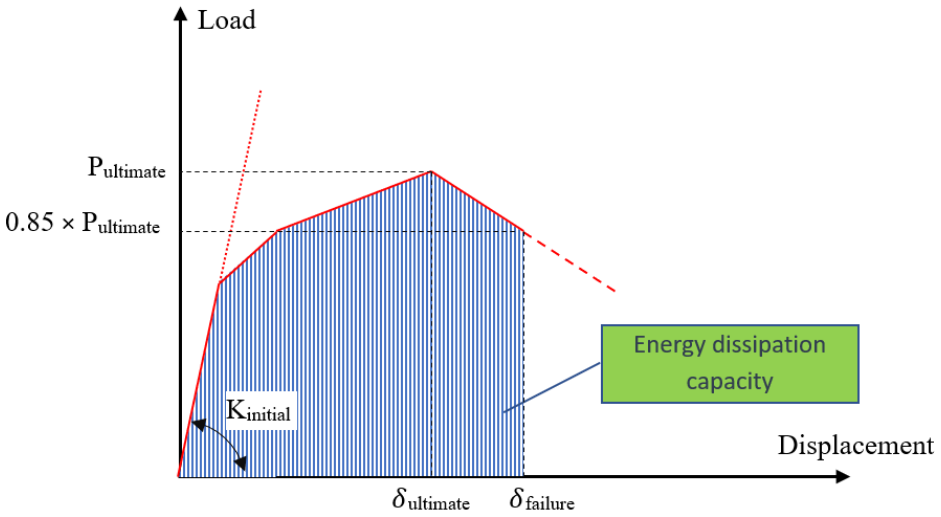


Figure 13. The approach used for calculation of energy dissipation capacities.

A ductility index value μ proposed by Naaman and Jeong [23] was calculated for the beams to assess the beams in terms of ductility. This value determined by Equation (1) is given below. In this equation, E_{tot} represents the total energy, and its value is equal to total area under the curve in Figure 14. E_{el} represents the elastic energy, and its value is

equal to the area of the triangle in Figure 14. Computed ductility index values of the beam specimens are given in Table 6.

$$\mu = \left(\frac{E_{tot}}{E_{el}} + 1\right) \quad (1)$$

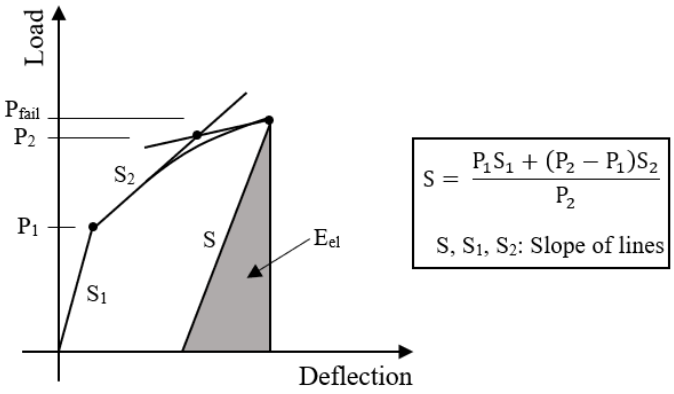
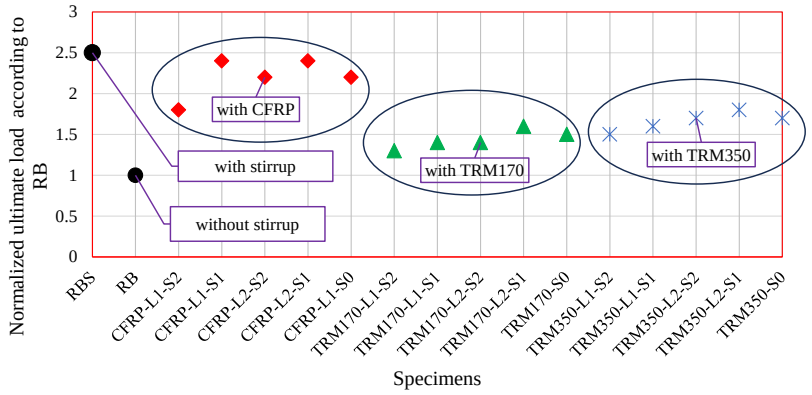
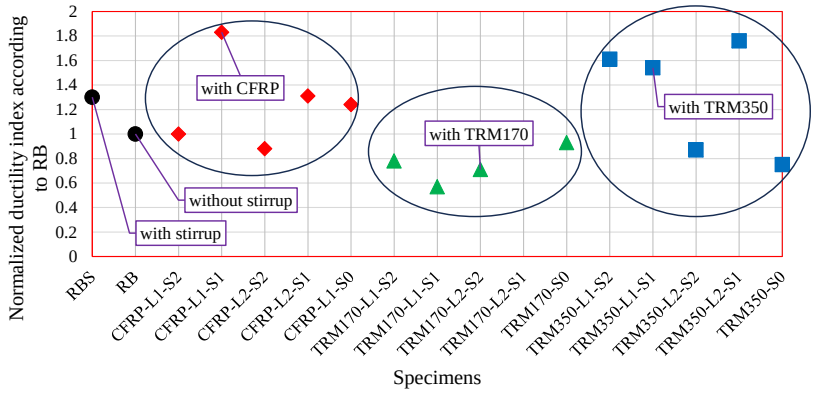


Figure 14. The approach used for calculation of ductility index calculation [23].

Relative comparisons of the strengthened beam specimens with respect to the reference beams RB and RBS in terms of ultimate load, ductility and energy dissipation capacity are shown in Tables 7 and 8, respectively. Also, these relative comparisons are made by graphs shown in Figure 15.

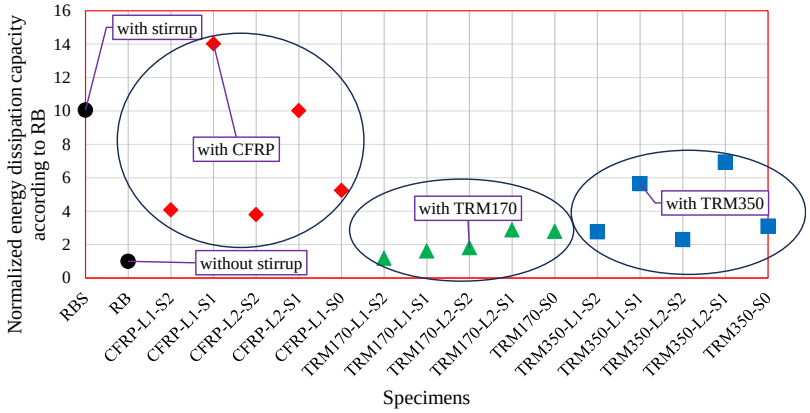


(**a**)



(**b**)

Figure 15. *Cont.*



(**c**)

Figure 15. Normalized (**a**) ultimate load, (**b**) ductility index and (**c**) energy dissipation capacity according to reference beam RB.

Table 7. Comparison with RB.

Specimen	Reference Beam	Ratio of the Ultimate Load	Ratio of the Ductility Index	Ratio of the Energy Dissipation Capacity
RBS	RB	2.5	1.30	10.06
CFRP-L1-S2		1.8	1.00	4.07
CFRP-L1-S1		2.4	1.83	14.02
CFRP-L2-S2		2.2	0.88	3.80
CFRP-L2-S1		2.4	1.31	10.02
CFRP-L1-S0		2.2	1.24	5.24
TRM170-L1-S2		1.3	0.78	1.18
TRM170-L1-S1		1.4	0.57	1.61
TRM170-L2-S2		1.4	0.71	1.81
TRM170-L2-S1		1.6	0.98	2.88
TRM170-S0		1.5	0.93	2.79
TRM350-L1-S2		1.5	1.61	2.76
TRM350-L1-S1		1.6	1.54	5.65
TRM350-L2-S2		1.7	0.87	2.30
TRM350-L2-S1		1.8	1.76	6.94
TRM350-S0		1.7	0.75	3.10

Table 8. Comparison with RBS.

Specimen	Reference Beam	Ratio of the Ultimate Load	Ratio of the Ductility Index	Ratio of the Energy Dissipation Capacity
CFRP-L1-S2	RBS	0.7	0.77	0.40
CFRP-L1-S1		0.9	1.41	1.39
CFRP-L2-S2		0.9	0.68	0.38
CFRP-L2-S1		1.0	1.01	1.00
CFRP-L1-S0		0.9	0.95	0.52
TRM170-L1-S2		0.5	0.60	0.12
TRM170-L1-S1		0.6	0.44	0.16
TRM170-L2-S2		0.6	0.55	0.18
TRM170-L2-S1		0.6	0.76	0.29
TRM170-S0		0.6	0.72	0.28
TRM350-L1-S2		0.6	1.24	0.27
TRM350-L1-S1		0.6	1.19	0.56
TRM350-L2-S2		0.7	0.67	0.23
TRM350-L2-S1		0.7	1.36	0.69
TRM350-S0		0.7	0.58	0.31

3.1. Beams Strengthened with CFRP

The ultimate load capacities of the beam specimens strengthened with CFRP were obtained as 1.8 to 2.4 times that of the reference beam RB. CFRP-L1-S2 having three strips and one layer had the lowest of the ultimate load values with 74.79 kN, and CFRP-L2-S1 having four strips and double layers had the highest value of the ultimate load with 99.35 kN. For CFRP-L1-S1, CFRP-L2-S2, CFRP-L2-S1 and CFRP-L1-S0, the obtained ultimate load capacities were close to that of the other reference beam RBS having steel stirrups along the beam. While CFRP-L1-S2 and CFRP-L2-S2 collapse in shear failure mode, CFRP-L1-S1, CFRP-L2-S1 and CFRP-L1-S0 could reach the bending bearing capacity and collapsed in flexural failure mode. It was observed that decreasing the strip spacing value raises the ultimate load value. For the beams strengthened with one layer and two layers of CFRP strips, decreasing the strip spacing raised the ultimate load capacity 30% and 12%, respectively. Strengthened beams having strips by spacing 167 mm (CFRP-L1-S1 and CFRP-L2-S1) could reach to averagely about 10% more ultimate load value than that of the strengthened beam with one full layer (CFRP-L1-S0). It was seen that increasing the number of layers increased the ultimate load value. CFRP-L2-S2 having two layers of CFRP strips by spacing 250 mm had 18.2% more ultimate load value than that of CFRP-L1-S2 having one layer of CFRP strips by spacing 250 mm. CFRP-L2-S1 and CFRP-L1-S1 having CFRP strips by spacing 167 mm had almost the same ultimate load value. The reason for that is thought to be the reaching of both specimens to the bending bearing capacity.

In terms of ductility index, values greater than the reference beam RB were obtained in most of the beam specimens strengthened with CFRP, with an increase of 24% to 83%. The highest value of 4.07 was obtained from CFRP-L1-S1. The specimen CFRP-L1-S2 had almost the same value as the reference beam RB. Only the beam CFRP-L2-S2 with a value of 1.96 had a smaller ductility index than that of the reference beam RB. When beam RBS was considered as reference beam, it was seen that the ductility index of CFRP-L1-S1 was 41% more than that of the reference beam RBS. The ductility index of CFRP-L2-S1 had almost the same value of the reference beam RBS. The ductility indices of the other beams strengthened with CFRP were 5% to 32% less than that of the reference beam RBS.

The energy dissipation capacities of the beam specimens strengthened with CFRP were obtained as 3.80 to 14.02 times that of the reference beam RB. CFRP-L2-S2 had the smallest value with 498.69 kN-mm, and CFRP-L1-S1 had the highest value of the energy dissipation capacity with 1841.52 kN-mm. Only CFRP-L1-S1 and CFRP-L2-S2 could reach the energy dissipation capacity of the reference beam RBS. While the energy dissipation capacity of CFRP-L2-S1 was almost same as that of the reference beam RBS, the energy dissipation capacity of CFRP-L1-S1 was 39% higher than that of the reference beam RBS. Energy dissipation capacity increased with the decrease in the strip spacings. In one-layered beams, the energy dissipation capacity of CFRP-L1-S1 having strips by spacing 167 mm was 244.5% higher than that of CFRP-L1-S2 having strips by spacing 250 mm. In two-layered beams, the energy dissipation capacity of CFRP-L2-S1 having strips by spacing 167 mm was 163.7% higher than that of CFRP-L2-S2 having strips by spacing 250 mm.

3.2. Beams Strengthened with TRM-170

For the beam specimens strengthened with TRM-170, the ultimate load capacities were obtained as 1.4 to 1.6 times that of the reference beam RB. While the lowest of the ultimate load values was 51.43 kN belonging to TRM170-L1-S2, the highest of the ultimate load values was 65.30 kN belonging to TRM170-L2-S1. None of the beam specimens strengthened with TRM-170 could reach the ultimate load capacity of the reference beam RBS and all of them collapsed in shear failure mode. It was seen that decreasing the strip spacing value raised the ultimate load value. For the beams strengthened with one layer and two layers of TRM-170 strips, decreasing the strip spacing raised the ultimate load capacity 12.9% and 12.6%, respectively. TRM170-L2-S1 having two layers of strips by spacing 167 mm could reach up to 7.6% more ultimate load value than that of the strengthened beam with one full layer (TRM170-S0). Increasing the number of layers also

raises the ultimate load value. TRM170-L2-S2 having two layers of TRM-170 strips by spacing 250 mm had 12.8% more ultimate load value than that of TRM170-L1-S2 having one layer of TRM-170 strips by spacing 250 mm. For the beams strengthened with TRM-170 strips by spacing 167 mm, TRM170-L2-S1 having two layers had 12.5% more ultimate load value than that of TRM170-L1-S1 having one layer.

For the beam specimens strengthened with TRM-170, ductility index values were obtained as 2% to 43% less than that of the reference beam RB. TRM170-L1-S1 had the smallest value with 1.26, and TRM170-L2-S1 had the highest value with 2.17. It can be said that the beam TRM170-L2-S1 had almost the same value as that of the reference beam RB. When the reference beam RBS was considered, ductility index value of the beams strengthened with TRM-170 were 24% to 56% less than that of the reference beam RBS.

For the beam specimens strengthened with TRM-170, the energy dissipation capacities were obtained as 1.18 to 2.88 times that of the reference beam RB. While the lowest of the energy dissipation capacity was 155.53 kN-mm belonging to TRM170-L1-S2, the highest of the energy dissipation capacity values was 377.73 kN-mm belonging to TRM170-L2-S1. Although energy dissipation capacities of the beams increased by strengthening with TRM-170, the capacities could not reach to that of the reference beam RBS for any of them. TRM170-L2-S1, with the highest energy dissipation capacity value, had a value of about 30% of that of the reference specimen RBS. Energy dissipation capacity increased with the decrease in the strip spacings. In one-layered beams, the energy dissipation capacity of TRM170-L1-S1 having strips by spacing 167 mm was 36.2% higher than that of TRM170-L1-S2 having strips by spacing 250 mm. In two-layered beams, the energy dissipation capacity of TRM170-L2-S1 having strips by spacing 167 mm was 59.3% higher than that of TRM170-L2-S2 having strips by spacing 250 mm.

3.3. Beams Strengthened with TRM-350

The ultimate load capacities of the beam specimens strengthened with TRM-350 were obtained as 1.5 to 1.8 times that of the reference beam RB. The smallest and the highest of the ultimate values were 62.58 kN and 74.60 kN, and they were obtained from TRM350-L1-S2 and TRM350-L2-S1, respectively. Although the ultimate load capacities of these strengthened beams were much more than that of the reference beam RB, they could not reach the ultimate load value of the reference beam RBS, and they collapsed in shear failure mode. It was observed that decreasing the strip spacing value raised the ultimate load value. For the beams strengthened with one layer of TRM-350 strips (TRM350-L1-S2 and TRM350-L1-S1), decreasing the strip spacing raised the ultimate load capacity 3.8%. On the other hand, decreasing the strip spacing raised the ultimate load capacity 4.8% for the beams strengthened with two layers of TRM-350 strips (TRM350-L2-S2 and TRM350-L2-S1). TRM350-L2-S1 having two layers of strips by spacing 167 mm could reach to 4.7% more ultimate load value than that of the strengthened beam with one full layer (TRM350-L2-S2). As the number of layers increased, the ultimate load value increased. TRM350-L2-S2 having two layers of TRM-350 strips by spacing 250 mm had 13.7% more ultimate load value than that of TRM350-L1-S2 having one layer of TRM-350 strips by spacing 250 mm. For the beams strengthened with TRM-350 strips by spacing 167 mm, TRM350-L2-S1 having two layers had 14.9% more ultimate load value than that of TRM350-L1-S1 having one layer.

In most of the beam specimens strengthened with TRM-350, ductility index values were greater than the reference beam RB. The change in increase was between 54% and 76%. Beam specimen TRM350-L2-S1 had the highest value with 3.91. The specimen TRM350-S0 with a value of 1.67 had 25% less ductility index than that of the reference beam RB. When beam RBS was considered as the reference beam, it was seen that the ductility index of the specimens TRM350-L1-S2, TRM350-L1-S1 and TRM350-L2-S1 were 24, 19 and 36% more than that of the reference beam RBS, respectively. Beam specimens TRM350-L2-S2 and TRM350-S0 had values of 33% to 42% less than that of the reference beam RBS. Beam specimens TRM350-L2-S2 and TRM350-S0 had ductility index values of 33% and 42% less than that of the reference beam RBS, respectively.

The energy dissipation capacities of the beam specimens strengthened with TRM-350 were obtained as 2.30 to 6.94 times that of the reference beam RB. The smallest and the highest of the energy dissipation capacities were 302.49 kN-mm and 912.03 kN-mm and they were obtained from TRM350-L2-S2 and TRM350-L2-S1, respectively. In terms of energy dissipation capacity, as with the results of the beam specimens strengthened with TRM-170, although the capacity values of the beams strengthened with TRM-350 increased, none of the capacities reached that of the reference beam RBS. TRM170-L2-S1 with the highest energy dissipation capacity value has a value of about 70% of that of the reference specimen RBS. Energy dissipation capacity increased with the decrease in the strip spacings. In one-layered beams, the energy dissipation capacity of TRM350-L1-S1 having strips by spacing 167 mm was 104.8% higher than that of TRM350-L1-S2 having strips by spacing 250 mm. In two-layered beams, the energy dissipation capacity of TRM350-L2-S1 having strips by spacing 167 mm was 201.5% higher than that of TRM350-L2-S2 having strips by spacing 250 mm.

In general, it can be said that the beam specimens strengthened with two layers of strips by spacing 167 mm had the best performance in all types of strengthened beams. When the results of all the beams are examined in general, it is seen that the best results are obtained in the beam specimens strengthened with CFRP, then in the beam specimens strengthened with TRM-350 and then in the beam specimens strengthened with TRM-170.

4. Conclusions

In this research, the effectiveness of the strengthening of reinforced concrete beams with TRM or CFRP against shear was investigated experimentally. Textile type, spacing of strips, number of layers and the scheme of wrapping were adopted as test parameters. In the study, a total of 17 RC beams were tested under the effect of bending by applying three-point loading. One of the beams was fabricated with steel stirrups along its length, while the other sixteen beams were fabricated as they did not contain any stirrups in their short shear span. The beam having steel stirrups along its entire length and one of the beams not having steel stirrups in their short span were considered as reference beams. The other 15 RC beams were strengthened with CFRP or TRM against to shear. The primary conclusions obtained from this study are summarized as follows:

- Reference beam RBS and strengthened beams CFRP-L1-S1, CFRP-L2-S1 and CFRP-L1-S0 could achieve to reach the bending bearing load capacity and collapsed in bending failure mode. The rest of the beam specimens collapsed in shear failure mode.
- For all types of strengthening materials, strengthened beam specimens having strips by spacing 167 mm and double layers had the highest value of the ultimate load capacities.
- In the beams strengthened with CFRP, the beam specimen CFRP-L2-S1 had the highest value of the ultimate load. Its ultimate load capacity was obtained as 2.4 times that of the reference beam RB without stirrups in short shear span. Specimen CFRP-L2-S1 also had the highest value of the ultimate loads in strengthened beams with all types of materials.
- In the beams strengthened with TRM-170, the highest of the ultimate load values belonged to beam specimen TRM170-L2-S1. Its ultimate load capacity was 1.6 times that of the reference beam RB.
- In the beams strengthened with TRM-350, the beam specimen TRM350-L2-S1 had the highest value of the ultimate load. Its ultimate load capacity was obtained as 1.8 times that of the reference beam RB.
- In terms of ductility index, most of the strengthened beam specimens had values almost equal to or higher than that of the reference beam RB.
- When all types of strengthening materials were considered, specimen CFRP-L1-S1 had the highest value. Its value was 41% and 83% more than that of the reference beams RBS and RB, respectively.
- In the beam specimens strengthened with TRM-170, specimen TRM170-L2-S1 reached the highest ductility index value. While specimen TRM170-L2-S1 had almost the

same value with that of the reference beam RB, it had 24% less value than that of the reference beams RBS.

- Specimen TRM350-L2-S1 was the specimen having the highest ductility index value in the beams strengthened with TRM-350. Ductility index value of TRM350-L2-S1 was 36% and 76% larger than that of the reference beams RBS and RB.
- For all types of strengthening, it was observed that energy dissipation capacities of the RC beams increased due to strengthening.
- None of the beams strengthened with TRM-170 or TRM-350 could reach the energy dissipation capacity of the reference beam RBS. The main reason of that was thought that they all collapsed in shear failure mode.
- When all types of strengthening materials were considered, specimen CFRP-L1-S1 had the highest energy dissipation capacity value. Its value was 39% more than that of the reference beams RBS and about 14 times that of the reference beam RB.
- Considering only the beam specimens strengthened with TRM-170, specimen TRM170-L2-S1 reached the highest energy dissipation capacity value. Its energy dissipation capacity value was about 30% of that of the reference specimen RBS and about 2.9 times that of the reference beam RB.
- It was seen that the specimen TRM350-L2-S1 had the highest energy dissipation capacity value, when only the beam specimens strengthened with TRM-350 were considered. It had a value of about 70% of that of the reference specimen RBS and about seven times that of the reference beam RB.
- In general, the beam specimens strengthened with two layers of strips by spacing 167 mm had the best performance when all strengthened beams were considered.
- In general, it is concluded that the best results were obtained in the beam specimens strengthened with CFRP, then in the beam specimens strengthened with TRM-350 and then in the beam specimens strengthened with TRM-170.
- Beams with sufficient shear strength collapse in bending failure mode, which is the desired failure mode. Therefore, the amount of increase in ultimate load capacity achieved by strengthening is the most important evaluation factor to be considered. Only some of the beams strengthened with CFRP were able to provide the required shear resistance, and the beams collapsed in bending failure mode. The required shear bearing capacity was not achieved in any of the beams strengthened with TRM, and the beams collapsed in shear failure mode. However, even in TRM-strengthened beams that failed by shear, the bearing capacity increased significantly (30–80%) with strengthening. According to these results, it is thought that the required shear strength can be achieved in the strengthening method with the TRM textile materials used in this study with changes in practice such as increasing the number of layers or further reducing the strip spacing. It should be kept in mind that, unlike the beams strengthened in this study, the presence of steel stirrups, albeit few, in the beam elements in existing reinforced concrete buildings will provide an additional advantage in the use of these materials in strengthening.

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