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Behaviour of RC beams strengthened with mechanically fastened FRP system

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ABSTRACT: This research examines a, relatively, newly developed technique for the flexural strengthening of reinforced concrete beams. This technique is referred to as mechanically fastened (MF) fiber-reinforced polymer (FRP) system. The results of this research work confirmed that the MF-FRP strengthened specimens showed higher load capacity compared to those of the corresponding reference specimens. Full-length strengthened specimens showed higher load carrying capacity than the partial-length counterparts. The strengthening effect was more noticeable for specimens of low reinforcement ratio as compared to those with high reinforcement ratio. It is recommended when using MF-FRP strengthening systems for flexural strengthening of beams is to extend the strips over the entire span and use epoxy injection in the predrilled holes prior to installing the fasteners. Using such epoxy injection improves the attachment of the FRP and concrete and indeed protects the fasteners against theft and corrosion.

1 INTRODUCTION

Research investigators have examined the feasibility of the MF technique for the external strengthening of reinforced concrete beams (Borowicz et al., 2004, Rizzo, et al., 2005). Beams strengthened with this technique were tested, and the results compared with those when using the conventional bonding method was reported. When using the MF method, it was possible to achieve a failure mode similar to that of a standard reinforced concrete beam. In addition, several case studies were also performed to address the analysis, design, installation, and testing for old deficient bridges. The MF-FRP system has proved to be an advantageous solution for the strengthening of major damaged areas of bridges (Rizzo, et al., 2005).

In the work of Elsayed, et al. (2009a, 2009b), screw fasteners were utilized for the direct shear application (Elsayed, et al., 2009a) and strengthening of RC two-way slabs with and without cut-outs (Elsayed, et al., 2009b). The fasteners used by Elsayed, et al. were driven directly inside the concrete as the threads of fasteners can carve the concrete while being driven in.

In fact, the utilization of screw bolts embedded in the concrete to mechanically attach or fasten the strengthening material has been introduced in several research works. Steel bolts were placed all the way through concrete slabs and the externally bonded (EB) steel or FRP plates for strengthening slab-column connections (Ebead and Marzouk 2002a, 2002b, 2004). Therefore, in the work of Ebead and Marzouk, MF/EB hybrid strengthening system was utilized for strengthening slab-column connections. It is obvious that the fastener type matters for proper evaluation of the MF-FRP system. Driving the fasteners using a shot gun, Lamanna, et al. (2001, 2004) may cause local damage in the concrete unlike driving a screw type of fasteners using appropriate screw driver (Elsayed, et al., 2009a, 2009b). In this research work, the MF-FRP system is introduced for flexural strengthening of reinforced concrete beams. This system utilizes a different screw type of small-diameter fasteners from those presented in other studies. These fasteners have been provided with nylon anchors for a better grasp of the concrete. This is regarded important as many available screw types of fasteners cannot carve or cut the concrete while being driven in. On the other hand it is very common that these ordinary screw fasteners are provided with such nylon anchors to function properly.

A total of 21 specimens have been tested; 18 of which utilize different beam/strengthening system configurations. The remaining three specimens are kept control. One-third of the strengthened specimens utilized two-part epoxy grout injection in the predrilled holes prior to driving the fasteners inside the concrete. The utilization of this grout was to substitute for the weakness due to and to fill the fissure cracks that may occur when the nylon anchors are expanded while driving the fasteners inside the concrete. The grout was also used to encase fastener heads as a practical implementation of anti-theft safety precaution against any malicious act of maliciously un-tightening the fasteners after being installed in a real-life application.

2 EXPERIMENTAL INVESTIGATION

2.1 Materials

The concrete mix is designed for an average target cylinder compressive strength of 35 MPa after 28 days. For each 1 m^3, the mixture proportions are 1160 kg of gravel, 690 kg of sand, 350 kg of cement, and 175 liter of water. The water-cement ratio is 0.5. For each beam specimen, six standard concrete cylinders of dimensions 150 mm in diameter and 300 mm in height were used to evaluate the compressive strength of the specimens. In addition, three other concrete cylinders of the same aforementioned dimensions were cast to evaluate the splitting tensile strength of each concrete patch in addition to concrete prisms measuring 100 × 100 × 400 mm for flexural tests. The samples were tested at the same time as that of testing the corresponding beam specimens. The average actual compressive and tensile strengths are given in Table 1. Grade 725 deformed bars, of diameters 10, 12, and 16 mm are used for all of the reinforcing steel in the beam constructions. The actual mean yield and ultimate stresses and moduli of elasticity of the steel reinforcement, ranged from 520 to 550 MPa, 600 MPa to 630 MPa, and 208 GPa to 214 GPa, respectively. Normal Grade 400 bars of diameter 6 mm are used for all the stirrups in the entire beams.

A special hybrid carbon/glass FRP composite was used in this investigation. This type of FRP product is characterized by its high bearing strength as well as high tensile strength. These combined properties allow this composite to be mechanically attached to a structural member. The strips were tested in a laboratory according to the ASTM D3039 (2000) standards. The stress-strain relationship was essentially linear up to failure. The average modulus of elasticity, E_{FRP}, and tensile strength, f_{FRP}, were found to be 72.02 GPa and 1003.4 MPa, respectively. These special FRP strips are 102 mm in width and 3.2 mm in thickness. This type of FRP contains a combination of unidirectional carbon and E-glass fibers and E-glass continuous strand mats, as reinforcing fibers, and vinylester resin matrix.

A screw-type of fastener was used in this study. The utilized fasteners have been provided with nylon anchors for a better grasping the concrete. In Fig. 1 a typical fastener used in this study is shown. One-third of the strengthened specimens utilized the same fastener type but also using two-part epoxy grout injection in the predrilled holes prior to driving the fasteners inside the concrete. The utilization of this grout was to substitute for the weakness due to and to fill the fissure cracks that may appear when the nylon anchors are expanded while driving the fasteners in.

Table 1 – Characteristics of specimens and experimental results

Designation	f'_c, MPa	f'_t, MPa	P_u, kN	Gain in P_u, %	Failure mode
R-D10	37	2.45	44	----	Ductile Flexure
R-D12	39	2.67	63	----	Ductile Flexure
R-D16	38	3.01	95	----	Flexure
M-F-D10-1	41	2.98	70	59	Flexure+ diagonal crack
BM-F-D10-2	36	3.10	99	125	Flexure+ diagonal crack
M-F-D10-2	38	2.89	77	75	Flexure+ diagonal crack
M-F-D12-1	38	3.21	99	57	Flexure+ diagonal crack
BM-F-D12-2	36	2.87	115	83	Flexure+ diagonal crack
M-F-D12-2	39	2.93	105	67	Flexure+ diagonal crack
M-F-D16-1	40	2.98	130	37	Flexure+ diagonal crack
BM-F-D16-2	37	2.86	140	47	Flexure+ diagonal crack
M-F-D16-2	39	3.00	132	39	Flexure+ diagonal crack
M-P-D10-1	37	2.56	55	25	Flexure+ strip end detachment
BM-P-D10-2	40	2.44	65	48	Flexure+ strip end detachment
M-P-D10-2	38	2.78	60	37	Flexure+ strip end detachment
M-P-D12-1	36	2.45	79	26	Flexure+ strip end detachment
BM-P-D12-2	42	3.18	85	35	Flexure+ strip end detachment
M-P-D12-2	39	2.78	81	29	Flexure+ strip end detachment
M-P-D16-1	36	2.60	105	11	Flexure+ strip end detachment
BM-P-D16-2	38	3.05	120	26	Flexure+ strip end detachment
M-P-D16-2	41	2.90	110	16	Flexure+ strip end detachment

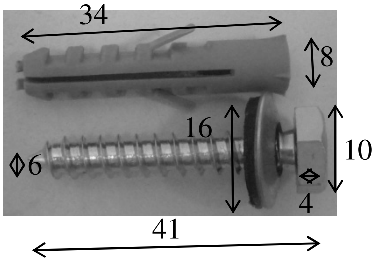


Figure 1. Specifics of a typical fastener (dimensions are in mm)

2.2 Test Specimens

Twenty-one (21) reinforced concrete beams, were tested to assess the MF-FRP strengthening technique. The entire specimens were loaded concentrically as shown in Fig. 2.

Three specimens served as control, un-strengthened, specimens while 18 specimens were strengthened using two different fastener distribution patterns, Patterns P1 and P2. The strengthened specimens were categorized to either full- or partial-length strengthened specimens. The full-length strengthened specimens utilized FRP strips for, almost, the entire support-to-support span. The partial-length strengthened counterparts utilized FRP strips in the middle 1.35 m as shown in Fig. 1 and Table 1. Specimens with epoxy injection were also tested.

The designations of the MF with epoxy injection and MF specimens include the letters “BM” and “M”, respectively. Letter “F” and “P” appears in the designations of specimens utilizing full-and partial-length strengthening, respectively. The partial-length strengthened specimens utilized strips that covered only 60% of the span as clearly shown in Fig. 2.

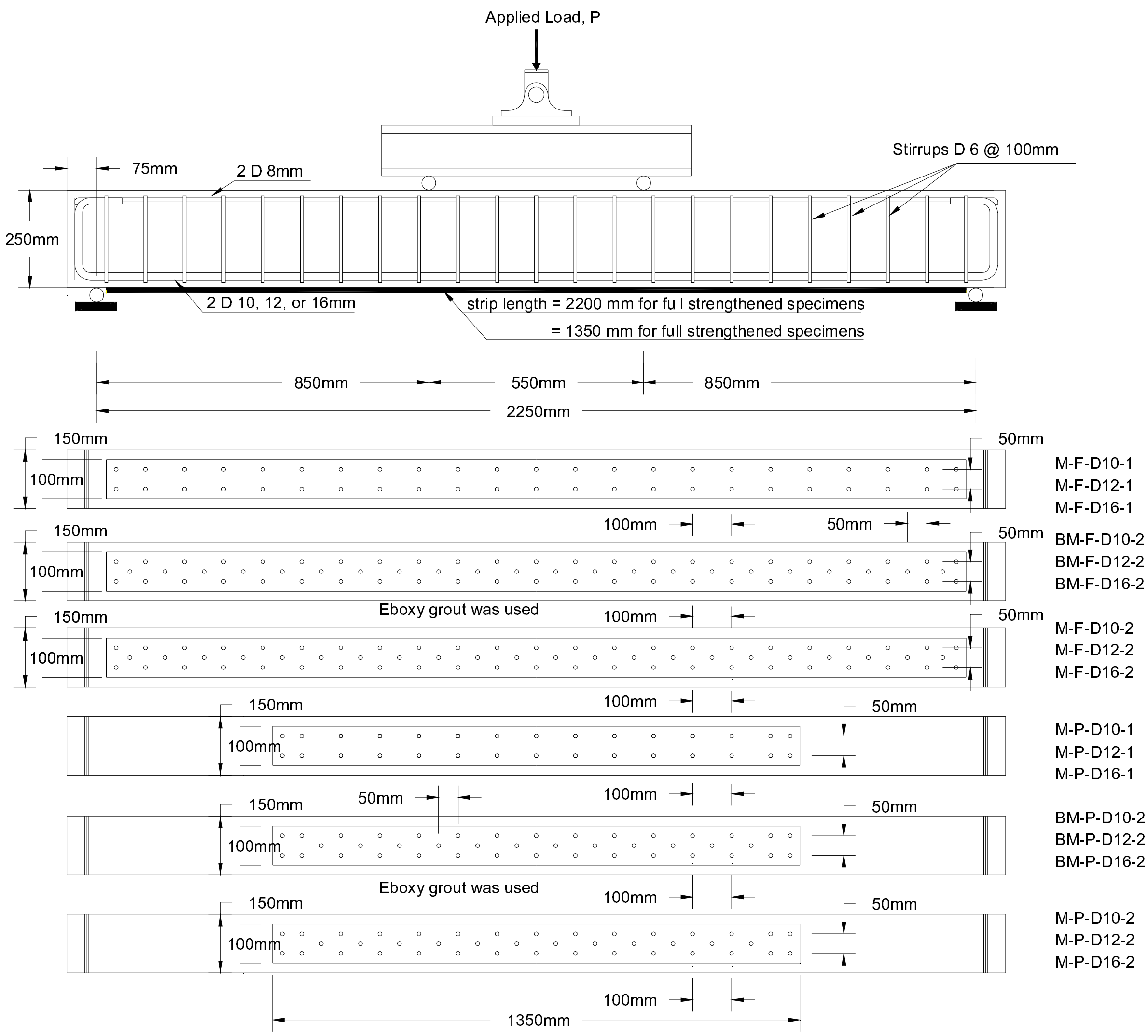


Figure 2. Configuration of tested beams and loading scheme

Two different fastener patterns have been used. Two aligned rows were used for half of the strengthened specimens, Pattern P1 in Fig 1, and for the other half three staggered rows of fasteners have been used, Pattern P2. One third of the strengthened specimens utilized epoxy injection as described below in the “Strengthening Procedure: section. Moreover, partial-length and full-length types of strengthening were investigated.

2.3 Test Setup and Instrumentation

As mentioned in the previous section, all specimens were four-point loaded using a reaction steel loading frame until failure as shown in Fig. 2. The static load was applied using a servo-hydraulic actuator. A load cell was used to measure the load using calibrated electrical resistance strain gages fixed to the inner cylinder of the load cell. The actuator has a maximum load capacity of 300 kN and a maximum stroke of 150 mm. Rubber pieces were placed between the back surface of the tested beams and the supports. The load was applied directly at the mid-span of a 550 mm span steel beam, which in turn transfers the load to the RC beam specimens through the steel beam's supports at two loading points, 550 mm apart. The loading frame is supported to a rigid floor. The load was recorded using the built-in load cell while the deflections at the mid-span of the RC beams were recorded using linear variable displacement transformers (LVDT). Strain gages were glued to locations on the FRP strips and steel reinforcement. Electrical resistance strain gages, 8 mm in length, having a resistance of 120.4 ± 0.5 Ω and a gage factor that is equal to 2.11 ± 1% were used to measure the strains in the steel reinforcement and FRP. The LVDT and the electrical strain gages were connected through a master panel to a data acquisition system. The analog electrical signals of deflections, and steel/FRP strains were converted through the data acquisition system to digital signals and were displayed and recorded for each load increment. Concrete compressive strains 10 mm down the top fiber of the cross sections were monitored and manually recorded using a demic gage installed in the middle section of the tested RC beams. The specimens were loaded centrally until failure at increments of 5 kN. Cracks were tracked after each load increment.

2.4 Strengthening Procedure

Prior to driving the fasteners inside the concrete beams, holes were predrilled to a depth of 34 mm inside the concrete with a diameter of 8 mm. The resulting dust inside the holes was blown out to assure that the holes are clean prior to installing the fasteners. Afterwards, the nylon anchors were hammered in the clean holes. Epoxy was injected inside the holes for one third of the strengthened specimens. For these specimens, FRP strips were then installed and then the fasteners were driven inside the concrete to attach the strips to the concrete beam. As a result of filling the holes with epoxy and then driving the fasteners inside the holes, the portion of the epoxy that was replaced by the fasteners surrounded the fastener locations between the FRP and concrete improving the FRP/concrete attachment at these locations. Moreover, part of this epoxy was getting out of the holes and was manually encasing the fastener heads. The injected epoxy; therefore, improved the attachment, acted as fastener-corrosion inhibitor, and anti-theft precaution. Neoprene backed 16 mm diameter washers were used with each fastener to protect the FRP and to increase the bearing strength of the FRP strip at the fastener locations. In the other two-thirds of the strengthened specimens, fasteners were driven in the predrilled holes directly without the use of epoxy injection. Half of the strengthened specimens were partial-length strengthened in the sense that the FRP strips covered 0.6 of the loaded span of strengthened beams. In the other half of the specimens 2200 mm of the 2250 mm loading span was covered with the MF FRP strips.

3 EXPERIMENTAL RESULTS

3.1 Ultimate Load-Carrying Capacity and Load-Deflection Relationships

Columns 3 and 4 in Table 1 list the ultimate load carrying capacity, P_u , for each specimen and the gain in P_u, respectively. The specimens that utilized the hybrid EB/MF-FRP strengthening system consistently gained higher increases in P_u as compared to those utilized only the MF-FRP system. The ultimate load carrying capacity for Specimen BM-F-D10-2, for example, was 125% over that of the un-strengthened specimen, R-D10. The corresponding increase was 75% for the MF-strengthened counterpart, Specimen M-F-D10-2. Specimens that utilized Pattern 2 showed higher increases in the ultimate load carrying capacity than those utilized Pattern 1. For example, the gain in P_u for Specimen MF-D10-2 is 75%. This ratio is only 59% for Specimen MF-D10-1. The average gain in P_u for full-length strengthened specimens is 2.2 times that for partial-length strengthened counterparts.

The graphs in Figure 3 depict the entire load-deflection plateaus for specimens with 2D10 mm reinforcement, as examples of the results. Figure 3.a is for full-length strengthened specimens, while Figure 3.b is for the corresponding specimens with partial length strengthening. It can be seen that most of the strengthened specimens showed ductile behavior up to failure. EB/MF strengthened specimens showed a relatively brittle behavior as compared to that of the MF FRP strengthened counterparts. For the partial-length strengthened, there was not much distinction, as far as load-deflection relationship is concerned, between the specimen with and without epoxy bonding/injection.

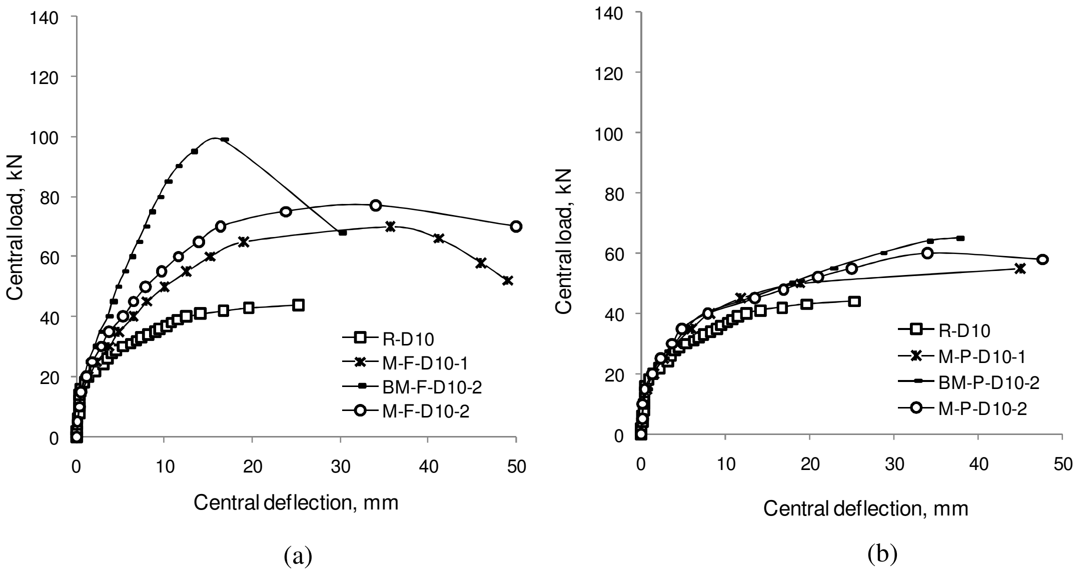


Figure 3. Central load-deflection relationships for strengthened specimens

3.2 Steel Reinforcement Strains

Figures 4a and 4b show the steel strains in specimens that have reinforcement of 2D10 mm and 2D12, respectively. In Figure 4a, for example, it is clear that Specimen BM-F-D10-2, which utilized full-length FRP strips with epoxy bonding/injection, showed the highest post-cracking stiffness among all specimens utilizing the same reinforcement ratio as indicated by the lower values of the steel strains at the same load level. Specimens with partial-length FRP strips showed a decrease in the steel strain values as compared to those of the reference specimen R-D10, yet higher values of steel strains than those of full-length strengthened counterparts at the same load levels.

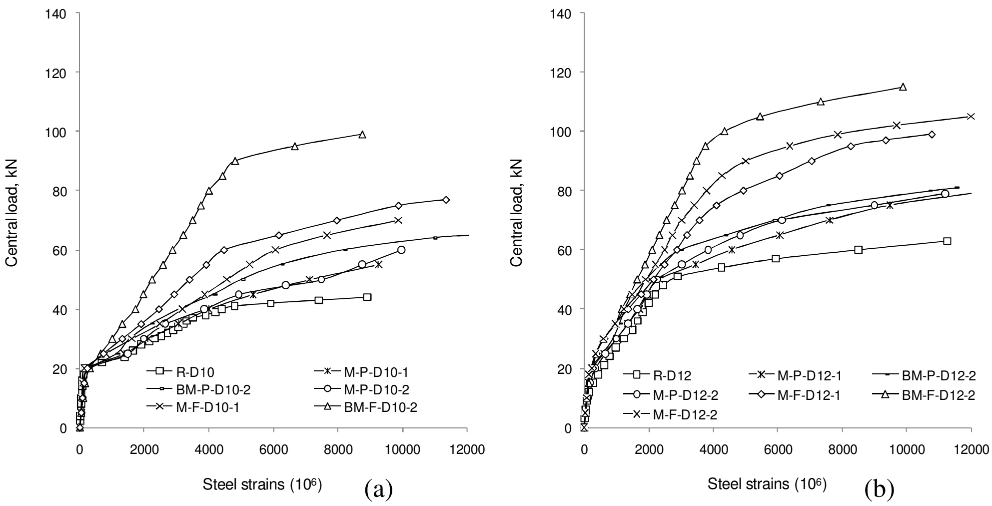
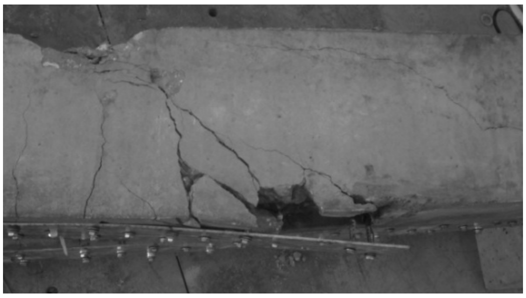


Figure 4. Load-steel strains relationships for tested beams

3.3 Failure Characteristics

Partial-length strengthened specimens have experienced detachment of the FRP off the concrete. The detachment was due to the insufficient development length of the strips which resulted in pulling the fasteners out of the concrete. There is a distinction though between the modes of failure for the hybrid EB/MF specimens and that of the MF counterparts. Most of the specimens that utilized epoxy bonding experienced the failure in the concrete cover with the fasteners pulled out and bent. For the MF specimens, the strip end detachment was due mainly to bending and pulling out of the fasteners as shown in a typical close-up of the strip end in Fig. 5a. Contrary to such behavior, FRP strips remained intact with the concrete surface at the strip end for full-length strengthened specimens. Critical diagonal cracks at the strip end occurred due to opening of the existing predrilled holes caused by the fasteners against concrete/FRP. The occurrence of such critical diagonal crack failure was observed consistently with the specimens strengthened using the full-length FRP strips with and without epoxy bonding/injection, as shown in Fig. 5b for Specimens M-F-D12-1. It is important to emphasize that the critical diagonal crack failure followed a progressive ductile flexural behavior. This is a direct result of using this type of strips that has high bearing strength that allows such a ductile response without a sudden break of the strips



(a)

(b)

Figure 5. Strengthened beams at failure

4 CONCLUSIONS

This research examines a new strengthening technique for flexural strengthening of reinforced concrete beams. This technique utilizes a combination of the external bonding and mechanical fastening of a special type of FRP strips applied for reinforced concrete beams. The system also features the use of nylon anchors for better grasp of the fasteners with the concrete. The results of this research work can be added to those few existing in the literature on the use of mechanically fastened fiber-reinforced polymer strengthening system. Partial-length and full-length strips were used for strengthening specimens of different reinforcement ratios while alternating the fastener patterns.

The utilization of the hybrid mechanically fastened / externally bonded system has shown superior enhancement in the ultimate load carrying capacity and stiffness of beam compared to those utilizing only the mechanically fastened FRP strips without epoxy strip/fastener bonding. The ductility however, of the hybrid system was lower than that of the mechanically fastened system. Full length strengthening allowed better utilization of the strengthening system, as compared to partial length strengthening, by virtue the elastopseudo-plastic nature of the bearing failure at the plate ends.

It was also concluded that, for full-length strengthened specimens, the dominating mode of failure is flexural type of failure initiated at high values of deformations and associated with critical diagonal cracks at the strip end locations. Partial length strengthened specimens suffered from premature detachment due to the insufficient development length. Therefore, it is recommended to use the strips with sufficient development length.

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