Response of R. C. Box Girders Strengthened Using CFRP Sheets

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Abstract Reinforced concrete box girders RCB are important elements in concrete bridge structures, which resist loads acting on the carriage way. The main objective of this study is to investigate the effect of external strengthening technique using carbon fibre reinforced polymer CFRP sheets on the behaviour of RCB girders. The experimental program of this study includes ten RCB girders. Two girders are reference specimens, and the other eight were divided into three groups. Groups G1 and G2 contain three girders each, while group G3 contains two girders. In groups G1, G2, and G3, strengthening sheets were located at the bottom surface, side surface and both bottom, and side surfaces, respectively. The length of such sheet was quarter, half and full span length. The tested girders were loaded by incremental increasing static loads till failure. Crack, ultimate loads, along with under load, and central girder deflections at each load level were recorded. Test results were plotted, analysed, compared with average results from the references, and they were studied, and discussed. Results show an increase in ultimate and crack loads, as well as good improvement in overall flexural behaviour.

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Keywords: Rehabilitation, Reinforced concrete beams, shear zone, confining plates.

1. Introduction

In recent decades, there has been demand for the use of fiber reinforced polymer "FRP" composite materials in rehabilitation, and strengthening of existing structures. Further, increased use of composite materials in structure depends on cost, designer, the structure importance, and fabricators. Bonding Fiber Reinforced Polymer (FRP) strips to a reinforced concrete beam to increase its flexure strength has recently become a very popular method of retrofitting [1-5]. The technique began in the middle 1980s at the Swiss Federal Laboratory for Materials Testing and Research [6]. The main advantages of FRP strips are their high strength-to-weight ratio, which leads to great ease in site handling and application procedures, and the high corrosion resistance compared to that of steel plates. On the other hand, rehabilitation and maintenance of reinforced concrete bridges emerged as a vital feature for structural engineering during the second part of the twentieth century all over the world. A large number of studies have been done on shear or flexural strengthening of RC beams using CFS (carbon fiber sheets). However, because of the specialized nature of the problem and the difficulties in conducting realistic tests and representative analyses, studying the torsional strengthening of reinforced concrete box beams using CFS did not receive much attention. Spandrel beams in structures, eccentrically loaded bridge girders are examples of structural members which may need torsional strengthening [7-9].

FRP provide an attractive alternative to the traditional techniques (steel plates) to correct strength deficiencies. However, due to the linear elastic behavior up to failure and limited strain capacity of FRP's, concrete members strengthened with FRP external plates or laminates show little ductility and exhibit brittle failure mode [10, 11]. The lack of ductility in such members is one of the key issues facing researchers [12]. The ductility of a beam can be defined as its ability to sustain inelastic deformation without loss in load carrying capacity prior to failure and can be defined in terms of deformation or energy.

Several experimental investigations have been reported on the behavior of concrete beams strengthened for flexure using externally bonded FRP plates, sheets, or fabrics [13-15]. In all these investigations, the strengthened beams showed higher ultimate loads compared to the non-strengthened ones. One of the drawbacks experienced by most of these strengthened beams is a considerable loss in beam ductility. To overcome the drawbacks mentioned above, a ductile FRP material with low yield strain value is needed. In order to develop this material, hybridization for different fibers was considered. Hybridization of more than one type of fibrous materials was the interest of many materials science researchers [16-17].

Previous research has attempted to address the various effects of CFRP sheets on the flexural behavior of beams [18, 19]. However the bonding of CFRP plates reduced the ductility of the beam in comparison with control beam [20]. It is found that the use of CFRP sheets in strengthening results in an increase in the working load and the stuffiness of the beam in terms of the reduction in the mid-span deflection [21]. CFRP wrapping was found to improve the shear and flexural capacities of damaged beams by various values according to the position of the CFRP sheets with respect to the beam's cross section or the shape of the strengthening sheets, whether, they are strips on the bottom and/or the sides of the beam or they are U-shaped [22]. The flexural behavior of RC beams strengthened with externally bonded CFRP strips is presented in reference [23]. Different techniques have been developed to retrofit a variety of structural deficiencies. For concrete beams, flexural and shear strengthening have been performed by epoxy bonding steel or CFRP plates to the tension face and the web of the beams. In strengthening reinforced concrete beams with CFRP plates, different failure modes have been reported. Mechanical analysis of reinforced concrete box beam strengthened with carbon fiber sheets under combined actions, torsional strengthening of reinforced concrete box beam using carbon fiber reinforced polymer, CFRP strengthening and monitoring of a box girder bridge had been studied [24-26]. In the present work an experimental program was introduced to investigate the behavior of RCB girders strengthened using CFRP sheets along the cross-section sides, and at the bottom surface of the girder web. The results of the behavior characteristics of the produced CFRP sheets strengthening are investigated and are verified by comparison with the un-strengthen girders.

2. Strengthening Arrangements

The strengthening systems are composed of using three-way technique. First, using CFRP longitudinal sheets put on the bottom surface of the beams and distributed partially along bottom "L/4, L/2, and L". While in the second, CFRP used longitudinal sheets on sides of the cross-section of the beams and partially distributed longitudinally "L/4, L/2, and L". Thirdly, using combination of CFRP sheets put on the bottom surface, sides of the cross-section of the beams, and partially distributed longitudinally "L/4, and L/2". The dimensions of the CFRP sheets have constant width equal 70 mm. Figure: "1-a", and "1-b" show the details of RCB girder.

3. Materials

To evaluate the influence of strengthening on the behavior of R C B girder using CFRP sheets at bottom, sides of the cross-section, and combined, concrete mixes were designed to produce concrete having a 28 days cubic compressive strength of 300 kg / cm2. The constituent materials were:

a) Ordinary Portland cement with properties conforming with limits of Egypt Standards.

b) Local sand of 2.60 t / m3 specific gravity and 1.70 t / m3, volume weight was used in normal concrete..

c) Local gravel of 10 mm maximum nominal size, 2.65 specific gravity and 1.74 t / m3 volume weight was used in normal concrete.

d) Drinking water was used for both mixing and curing.

e) Reinforcing high tensile steel yielded and ultimate strength limits (3600/5200) kg/cm2. conforming with the limits of Egypt Standards.

IV. Test Procedure

This program was carried out in the reinforced concrete laboratory, Zagazig University. Through this program, ten reinforced concrete box girders with rectangular-section of 22 x 32 cm were tested. Two girders were considered reference beams, while the other girders were divided into three groups. Groups one, and two contain three box girders each, while the third group contains two box girders. The tested girders were reinforced with 3 Ø10 and 4 Ø12 as compression and tension reinforcement, respectively. Ø6 @150 mm stirrups were used. Table: "1" shows the experimental program for the tested box girders. Mechanical mixing was employed for all tested girders. All box girders were cast in wood forms, using mechanical vibrator in compaction. Control cubes were cast for each mix. The method of compaction and curing was performed in the same manner as that for all girders. All box girders and control cubes were tested after 28 days. Girders were simply supported and monotonically loaded as shown in fig (1-a). Before cracking, each load increment was 5 kN, but after cracking each increment was 10 kN. The load was kept constant between each two successive increments for about three minutes. During this period, readings of deflection, crack width were recorded and the crack propagation was observed at both the beginning and end of each load increment. The girder deflections were measured using digital dial gauges fixed at mid span, and under points of load application. At each load increment, the width of cracks was measured using an optical micrometer. Measurements were taken on both sides of box girders and at several points along the crack. At the end of each test, crack pattern was sketched.

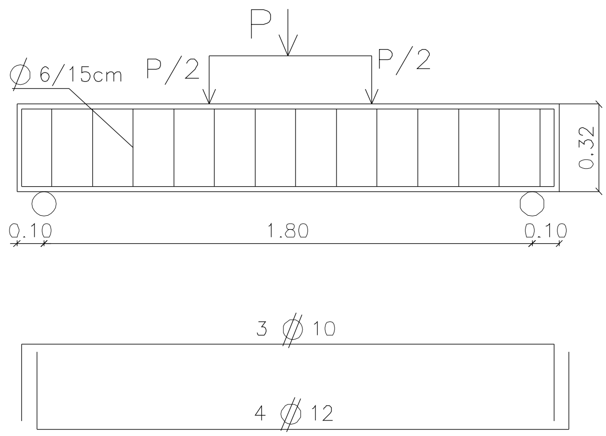
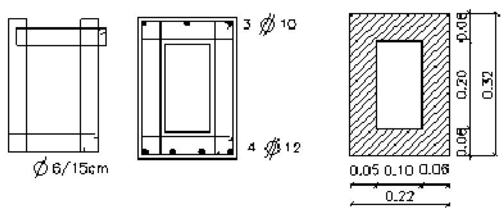


Fig.: (1-a) Details of RCB girder dimension, reinforcement.



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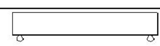
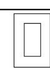
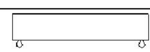
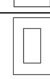
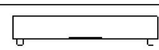
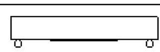
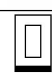
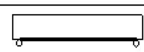
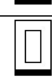
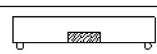
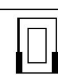
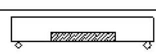
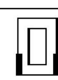
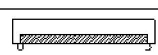
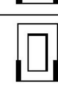
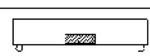
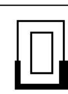
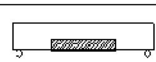
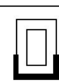
Reference				
				
				
				
				
				
				
				
				
				

5. Results and Discussion

Examination of the test results given in both table: 2 and figures: (2 to 17) show the following:

5, 1. Cracking, Ultimate Loads, and Modes of Failure

Figures (3) through (8) and (14) through (17) in addition to Table (2) show that the strengthening of girders using CFRP sheets is effective in increasing the strength of girders subjected to positive bending moments. The ratio of ultimate strength of the strengthened girders to the reference girders ranged between 108% up to 132%. The figures show that increasing the strengthened length has a slight effect on both the ultimate and cracking loads. In the case of constant strengthening position at the bottom for girders B3, B4, and B5 the gain in ultimate strength is 10%, 20%, and 26% respectively over that of the reference girders. However, the strength gain for the case of constant strengthening position at the sides for girders B6, B7, and B8 is 8%, 15%, and 23%, respectively; when compared with the reference girders. On the other hand strengthening the girders on both bottom and sides for girders B9 and B10 resulted in a more pronounced strength increase of 24% and 32%, respectively.

Test results showed that the strengthening position has an important role in the resulting strength of the strengthened girders. A constant strengthening length of "L/4" in girders B3, B6, and B9 resulted in an ultimate strength increase of 10%, 8%, and 24% respectively. On the other hand, increasing the strengthened length to "L/2" resulted in a strength gain of 20%, 15%, and 24% for girders B4, B7, and B10, respectively. Moreover, for a constant strengthening length of "L" the gain in the girders' ultimate strength were 25% and 23% for girders B5 and B8, respectively over that of the reference girders.

The above results showed that a flexure failure took place at the girders' mid-span, but at higher cracking load. The length of the strengthened part of the girders and the strengthening position also affects both cracking and ultimate loads. The results also showed that increasing the strengthened length enhances the efficiency of the strengthening technique as shown in table (2), and figures (3) through (17). The reference girders failed in flexural failure mode, while failure mode was peeling "de-bonding" failure for girders B4, and B5, and shear failure mode for girders B3, B6 and B10. Photos 1, 2, 3, 4, 5, and 6 show the strengthened girders (B4, B6, B7, B8, B9, and B10) after failure.

5. 2. Ddeflections

The mid-span deflection "Δ1" at L/2, and under loads deflection "Δ2", at L/3 for the tested girders were plotted in Figures "3 to 13". For strengthened girders using CFRP sheets, the deflection decreased at mid-span due to increase in the flexural stiffness of the girder. In general, the change in strengthening sheet length has a slight effect on both mid-span deflection "Δ1" and under loads deflection "Δ2", due to the fact that the increase of strengthening length, usually tends to increase the stiffness of girder. When the wrapping lengths changed from "L/4, L/2, to L", (referring to fig: "3", case of constant strengthening position), the ratio of decrease in mid-span deflections were: 35%, 7%, and 32%, for girders (B3, B4, and B5) in group G1, respectively. As the strengthening position changed from bottom, sides, and combined, (referring to fig: "6"), the ratio of change in mid-span deflections were: -35%, -42%, and +20%, for case of constant strengthening length, for girders (B3, B6, and B9), respectively. Similarly, the same analysis for group G2, (referring to Fig: "4", to Fig: "7"), the ratio of decreases in mid-span deflections were: 42%, 52%, and 19%, with constant strengthening position for girders (B6, B7, and B8), in group G2, respectively. Also as the strengthening position changed from bottom, sides, and combined, the ratio of change in mid-span deflections was: -7%,
-52%, and +12%, for constant strengthening length, for girders (B4, B7, and B10), respectively.

For group G3, and (referring to Fig: "5", to Fig: "8"), the ratio of change in mid-span deflections were: +20%, and +12%, with constant position for girders (B9, and B10) in group G3, respectively. As the position of strengthening changed from bottom, lateral, and combined, while the ratio of change of mid-span deflections were: -32%, and +19%, for constant strengthening length, for girders B5, and B8, respectively.

5. 3. Dductility Rratios

From table: 2, and referring to figures, "2. to 13", it is obvious that, the presence of the strengthening technique for the girders subjected to sagging bending moment increases the beams ductility ratios. The increase in ductility ratios ranged between 2.43 to at 5.82.

6. Conclusions

Based on the results and observations of the experimental investigation presented in this paper regarding the effectiveness of using CFRP sheets externally wrapped on bottom, and sides in strengthened reinforced concrete beams, the following conclusions may be drawn:

1- The test results indicated that the externally wrapped CFRP sheets can be used to enhance the ultimate capacity, and decrease the vertical deflection of the strengthened girders.
2- The strengthening effect is more observed with the increase in sheet length for three positions bottom, sides, and combined used in this study.
3- The results indicated that the use of CFRP sheets in strengthening increase ductility of the strengthened girders.
4- Side wrapping is more effective for reducing the deflections for strengthened girders.

Table: 2. Analyses of test results.

Group No	Girl No	PC(kN)*	PU (kN)*	Δ1mm	Δ2mm	P(PC/Pcr) %	P(PU/Pur)%	P(Δ1 /Δ1r)%	P(Δ2 /Δ2r)%	Δ1y mm	Ducti ratio*	Fail Mode*
Refe	B1	107	171	5.7	4.0	100	100	0.0	0.0	1.2	4.75	F
	B2	102	164	5.6	5.1	100	100	0.0	0.0	1.14	4.9	F
G1	B3	152	188	3.7	3.3	142	110	-35	-33	1.52	2.43	Sh
	B4	157	204	5.3	4.8	147	120	-45	-10	1.26	4.2	Pel
	B5	160	216	3.9	3.1	150	126	-7	-37	1.04	3.75	Pel
G2	B6	142	184	3.5	2.92	133	108	-32	-40	1.27	2.75	Sh
	B7	155	196	2.8	2.71	145	115	-42	-45	0.95	3.03	Sh
	B8	162	210	4.6	4.1	151	123	-19	-16	1.05	4.4	Sh
G3	B9	145	212	6.0	5.9	136	124	+5	+20	1.11	5.36	Sh
	B10	151	226	6.4	5.5	141	132	+12	+12	1.10	5.82	Sh

Notes: all comparison with reference girder B1 * Pc, Pu: are the cracking and failure loads in (kN).
* Δ1, Δ2: are the mid-span and under machine load deflections.
* Δ1y: it the mid-span deflection at yield load .
* p (PC/ Pcr)%, and p (Pu/ Pur)% : are the percentage of increasing in cracking, and ultimate loads compared with the corresponding results from reference girder B1.
* p (Δ1 / Δ1r) %, p (Δ2 / Δ2r)% : are the percentage of change in deflections Δ1, and Δ2, compared to the corresponding from the reference girder B1.
* Fail mode F - flexure failure, Sh - shear failure, Pel – peeling failure "de-bonding".
* Ducti ratio* : is the ductility ratio between deflections at the failure Δ1 , and Δ1y at the yielding load, from recorded results. Δ1y at the yielding load, from recorded results

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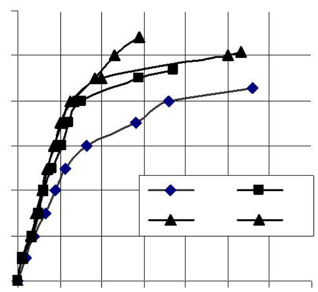
ngth =



Phc

Phc

ater

Strengthening Length = L

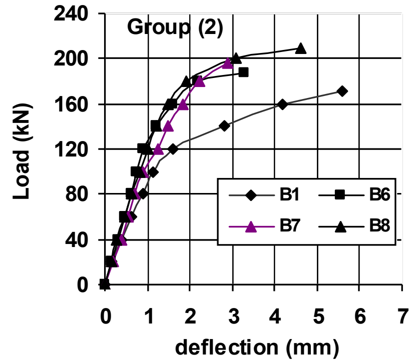


Fig 3. Load versus deflection (Δ1) curves.
Variations in bottom strengthening length.

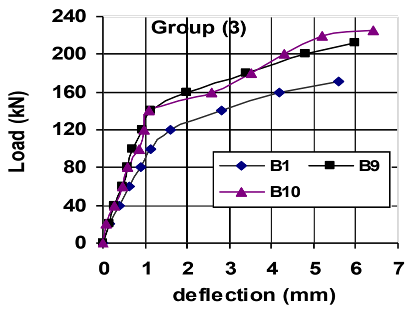


Fig 4. Load versus deflection (Δ1) curves.
Variations in bottom strengthening length

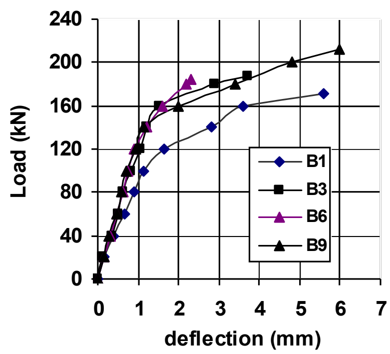


Fig 5. Load versus deflection (Δ1) curves.
Variations in strengthening position

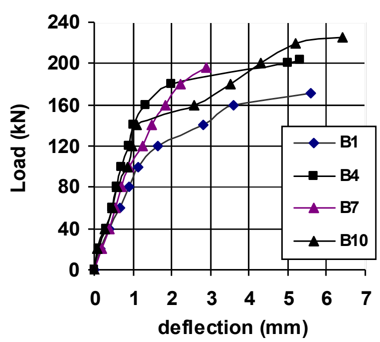


Fig 6. Load versus deflection (Δ1) curves.
Variations in strengthening position.

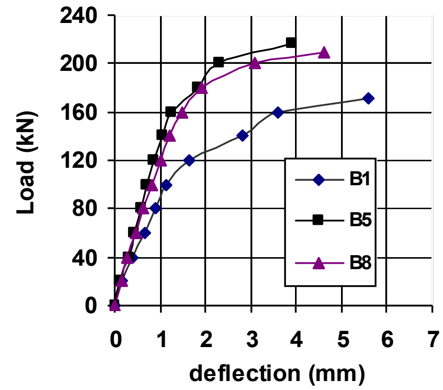


Fig 7. Load versus deflection (Δ1) curves,
Variations in strengthening position

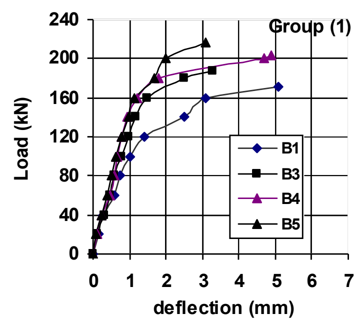


Fig 8. Load versus deflection **(Δ2)** curves.
Variations in bottom strengthening length.

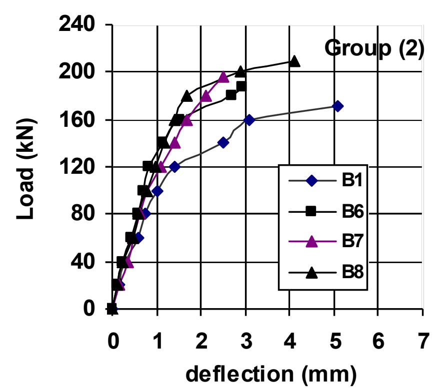


Fig 9. Load versus deflection **(Δ2)** curves.
Variations in bottom strengthening length.

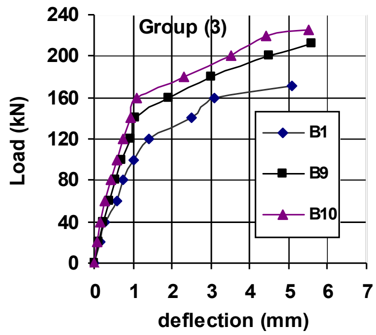


Fig 10. Load versus deflection **(Δ2)** curves
Variations in bottom strengthening length.

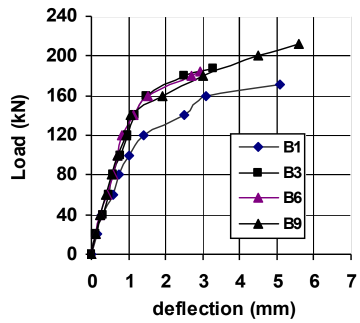


Fig 11. Load versus deflection **(Δ2)** curves.
Variations in strengthening position.

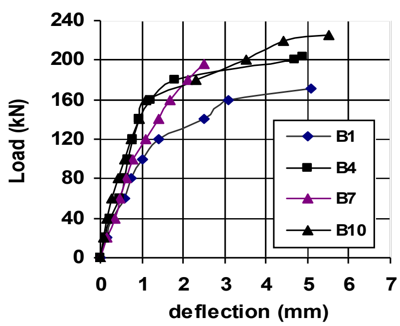


Fig 12. Load versus deflection **(Δ2)** curves.
Variations in strengthening position.

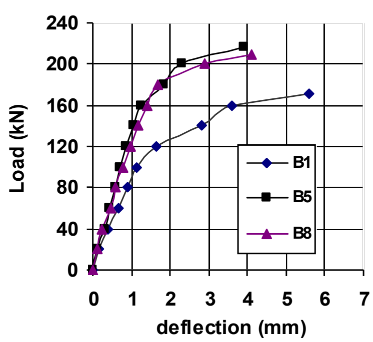


Fig 13. Load versus deflection **(Δ2)** curves.
Variations in strengthening position.

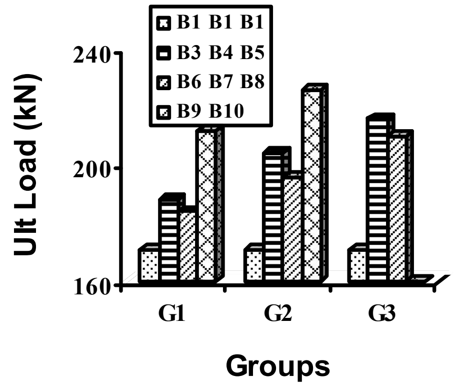


Fig 14. Ultimate load and strengthening length
for all girders in groups (1, 2 and 3)

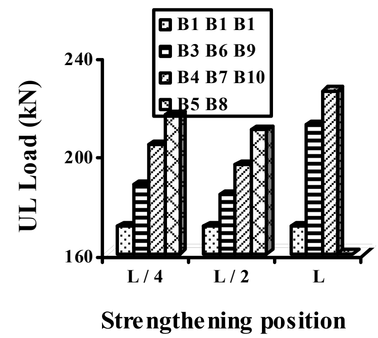


Fig 15. Ultimate load and Strengthening position
for all girders in groups (1, 2 and 3).

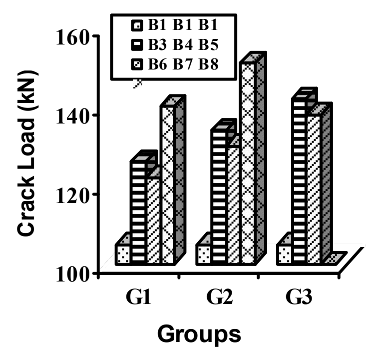


Fig 16. Cracking load and strengthening length
for all girders in groups (1, 2 and 3)

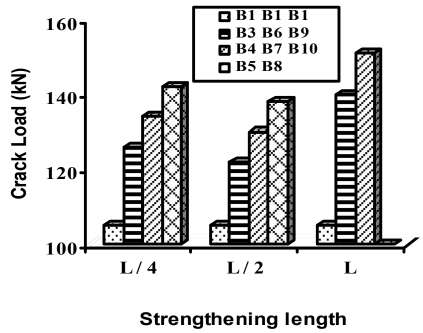


Fig 17. Crack loads and strengthening length for all girders in groups (1, 2 and 3)

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