International Journal of Scientific Engineering and Applied Science (IJSEAS) – Volume-3, Issue-9, September 2017
ISSN: 2395-3470
www.ijseas.com

Strengthening of Reinforced Concrete Box Girders in Tension Zone Using New Materials

Askar[1], R. A., Abd-El Magid[2], S. S., and Nawar[3], A. K.

1 Associate prof., structural Engineering Department, Faculty of Engineering, Zagazig University, Egypt
2 Associate prof., structural Engineering Department, Faculty of Engineering, Zagazig University, Egypt
3 M.Sc., structural Engineering Department, Faculty of Engineering, Zagazig University, Egypt

ABASTRACT

Reinforced concrete box girders RCBG 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 techniques on the strengthening of RCBG using modern materials as carbon fibre reinforced polymer CFRP sheets , glass fibre reinforced polymer GFRP sheets and STEEL GRID. The experimental program of this study includes twelve RCBG with span 2m each. Three girders are reference specimens, and the other nine were divided into three groups. Groups G , C ,and S contain three girders each. these groups contain constant technique ; GFRP was used as a strengthening material for group G ,where CFRP was used for group C ,and STEEL GRID was used for group S. All girders' strengthening length ,for all techniques, was quarter ,half ,and full span .The tested girders were loaded by incremental static loads till failure. Crack loads, 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, then they were studied, and discussed. Results show an increase in ultimate and crack loads, as well as good improvement in overall flexural behaviour.

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 girder 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 girders using (FRP) [7-9].

FRP provide an attractive alternative to the traditional techniques (steel plates) to correct strength deficiencies. However, due to the linear elastic behaviour 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].

It is found that the use of FRP 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 [18-19]. The flexural behavior of RC beams strengthened with externally bonded FRP strips is presented in reference [20]. 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 FRP plates to the tension face and the web of the beams. In strengthening reinforced concrete beams with FRP plates, different failure modes have been reported. Strengthening of Reinforced Concrete Box (RCB) girders had been studied [21, 22, and 23]. Increasing the number of GFRP sheet more than two sheets is found to be brittle failure [24].Strengthening of reinforced concrete beams using GFRP was studied ; the results indicated that strengthening up to the neutral axis of the beam ,increase in the ultimate load carrying capacity of the beam is not significant and cost involvement is almost three times compared to the beam strengthen by GFRP sheet at the soffit only [25]. In the present work an experimental program was introduced to investigate and compare the behaviour of RCB girders strengthened using GFRP ,CFRP sheets and STEEL GRID along the cross-section sides, and at the bottom surface of the girder web.

STREGTHENING ARRANGEMENT

The strengthening systems are composed of using three different materials with three-type technique. For all types, the strengthening sheets which are 50cm constant width were located as follows: 22cm at the bottom surface and extend to 14cm of the two sides of the cross section . First, using Bi-directional GFRP longitudinal sheets put on the bottom surface, sides of the cross-section of the girders and partially distributed longitudinally (L/3, 2L/3, and L). While in the second, using Uni-directional CFRP longitudinal sheets put on the bottom surface, sides of the cross-section of the girders and partially distributed longitudinally (L/3, 2L/3, and L). Where ever in group S, using STEEL GRID (2mm thickness) put on the bottom surface, sides of the cross-section of the girders, and partially distributed longitudinally (L/3, 2L/3, and L). The dimensions of the strengthening sheets have constant width equal 50 mm. Figure (1-a), and (1-b) show the details of RCBG.

MATERIALS

To evaluate the influence of strengthening on the behavior of RCBG using CFRP, GFRP sheets ,and STEEL GRID, concrete mixes were designed to produce concrete having a 28 days cubic compressive strength of 300 kg/cm^2. The constituent materials were:

a) Ordinary Portland cement with properties conforming with limits of Egyptian Codes of Reinforced Concrete Structures 2003.
b) Local sand of 2.60 t/m^3 specific gravity and 1.70 t/m^3 volume weight was used in normal concrete.
c) Local gravel of 10 mm maximum nominal size, 2.65 t/m^3 specific gravity and 1.74 t/m^3 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/cm^2. conforming with the limits of Egyptian Codes of Reinforced Concrete Structures 2003 .

TEST PROCEDURE

This program was carried out in the reinforced concrete laboratory, Zagazig University. Through this program, twelve reinforced concrete box girders with rectangular-section of 22 x 32 cm were tested. Three girders were considered reference girders, while the other girders were divided into three groups. Groups one, two and three contain three box girders each. The tested girders were reinforced with 3 Ø10 and 4 Ø10 used as compression and tension reinforcement, respectively. While Ø8 @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 steel 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). Load increment was 5 kN before and after cracking. 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.

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.

RSULTES AND DISCUSSION

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

1- Cracking, Ultimate Loads, and Modes of Failure

Figures (2) to (17) in addition to Table (2) show that the strengthening of girders using GFRP, CFRP sheets and STEEL GRID are 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 105% up to 168%. Test results showed that the strengthening materials has an important role in the resulting strength of the strengthened girders. As the strengthening material changed from GFRP,CFRP ,and STEEL GRID with A constant strengthening length of (L/3) in girders G1, C1, and S1,the result was an increase in the ultimate strength of 11%, 6%, and 5% respectively. On the other hand, increasing the strengthened length to (2L/3) resulted in a strength gain of 45%, 31%, and 23% for girders G2, C2, and S2, respectively. Moreover, for a constant strengthening length of (L) the gain in the girders' ultimate strength were 68%,56% and 51% for girders G3, C3, and S3, respectively over that of the reference girders, (referring to fig 14).

The figures show that increasing the strengthened length has a slight effect on both the ultimate and cracking loads. In the case of using GFRP sheets for girders G1,G2, and G3 the gain in ultimate strength is 11%, 45%, and 68% respectively over that of the reference girders. However, the strength gain for the case of using CFRP sheets for girders C1, C2, and C3 is 6%, 31%, and 56%, respectively; when compared with the reference girders. On the other hand strengthening the girders using Steel GRID(2mm thickness) for girders S1,S2 and S3 resulted in an increase of 5% , 23% and 51% respectively, (referring to fig 15).

The above results showed that a flexure failure took place at the girders' mid-span, but at higher cracking load. The strengthening materials and the length of the strengthened part of the girders 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 (2) through (17). The reference girders failed in flexural failure mode, while failure mode was shear failure for the strengthened girders. Photos (1) to (6) show the strengthened girders (G2, G3, C2, C3, S2, and S3) after failure.

2- Deflections

The mid-span deflection (Δ1) at L/2, and under loads deflection (Δ2), at L/3 for the tested girders were plotted in Figures (2) to (13). For strengthened girders using GFRP, CFRP sheets and STEEL GRID, the deflection decreased at mid-span due to increase in the flexural stiffness of the girder. In general, the change in strengthening 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/3, 2L/3, to L), (referring to fig 3, case of using GFRP sheets), the ratio of change in mid-span deflections were: -17%, -13%, and +15%, for girders (G1, G2, and G3) in group G1, respectively. Similarly, the same analysis for group C, (referring to fig 3), the ratio of change in mid-span deflections were: -18%, -15%, and +1%, with using CFRP sheets for girders (C1, C2, and C3), in group C, respectively. For group S, and (referring to fig 4), the ratio of decrease in mid-span deflections were: -4%, and -31% and -17% ,with using STEEL GRID for girders (S1, S2and S3) in group S, respectively. As the strengthening material changed from GFRP, CFRP, and STEEL GRID, (referring to fig 5), the ratio of change in mid-span deflections were: -17%, -18%, and -4%, for case of constant strengthening length(L/3), for girders (G1, C1, and S1), respectively. Also, (referring to fig 6), the ratio of change in mid-span deflections was: -13%,-15%, and -31%, for constant strengthening length(2L/3), for girders (G2, C2, and S2), respectively.

But, (referring to fig 7), the ratio of change of mid-span deflections were: +15%, +1%,and-17% , for constant strengthening length(L), for girders (G3,C3 and S3), respectively.

3- Ductility ratios

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 1.1 to at 2.96 .

CONCLUSIONS

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

1- The test results indicated that three materials 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 materials.

3- The results indicated that the use of those three materials in strengthening increase ductility of the strengthened girders.

4- Strengthening RCBG using GFRP enhances the ultimate capacity (141%),and the crack capacity (228%). On the other hand using CFRP enhances ultimate capacity (131%),and crack capacity (188%). But using STEEL GRID improved ultimate capacity with (126%) ,and crack capacity with (170%) _all values in average_ respectively .

5- GFRP is more effective and gives more improved results than the two other materials, then CFRP comes next, then finally STEEL GRID.

REFERENCES:

1. Saadatmanesh, H., and Ehsani, M.R. (1991). "R C Beams Strengthened with GFRP Plates I: Experimental Study". Journal of Structural Engineering. ASCE Vol 117, No. 11, pp.3417-3433.

2. Nanni, A. (1995). "Concrete Repair with Externally Bonded FRP Reinforcement: Examples from Japan", Concrete International, Vol. 17, No. 6, pp. 22-25.

3. Nanni, A. (1997), "CFRP strengthening". Concrete International, ACI, Vol 19, Vo. 6, pp. 19-23.

4. Chaallal, 0., Nollet, M.J., and Perraton, D. (1998), "Strengthening of Reinforced Concrete Beams with Externally Bonded Fibre Reinforced Plastic Plates: Design Guidelines for Shear and Flexure", Canadian Journal for Civil Engineering, Vol. 25, No.4, pp. 692-704.

5. Grace, N.F., Sayed, G.A., Soliman, A.K., and Saleh, K.R. (1999), "Strengthening Reinforced Concrete Beams Using Fibre Reinforced Polymer (FRP) Laminates", ACI Structural Journal, Vol. 95, No, 5, pp. 865-874.

6. Meier, U., Deuring, M., Meier, H., and Schwegler, G. (1993). "CFRP Bonded Sheets. Fibre Reinforced Plastic (FRP) Reinforcement for Concrete Structures: Properties and Applications", Nani, A. (editor), Elsevier Science, Amsterdam, The GRIDherlands.pp7

7. Burgoyne, Chris J. "Advanced Composites in Civil Engineering in Europe". Struct Eng Int, SEI 1999;9(4):267-73.

8. Fukuyama H. "Fiber-Reinforced Polymers in Japan". Struct Eng Int J Int Assoc Bridge Struct Eng (IABSE) 1999;4:263- 73.

9. Karbahari VM. "Fiber-Reinforced Polymers Composites for Civil Infrastructure in the USA". Struct Eng Int J Int Assoc Bridge Struct Eng (IABSE) 1999;4:274-7. pp1

10. Ritchie A., Thomas D., Le-Wu and Connelly G., (1991) "External Reinforcement of Concrete Beams Using Fiber Reinforced Plastics", ACI Structural Journal, pp. 490-500.

11. Alfarabi S., Ghazi, J., Istem A, BaluchM.H., and BaderN.G., (1994) "Strengthening of Initially Loaded Reinforced Concrete Beams Using FRP Plates", ACI Structural Journal, pp. 160-168.

12. Razaqpur A., and Ali M., (1996) "Ductility and Strength of Concrete Beams

Externally Reinforced with CFRP Sheets". Advanced Composite Materials in Bridges and Structures, Canadian Society for Civil Engineering, Montreal, Canada, pp. 505-512.
13. Triantafillou, T. C. (1992) "Strengthening of R C Beams with Epoxy-Bonded-Fiber-Composite Materials", Materials and Structures, Vol. 25, pp. 201-211.
14. Norris, T., Saadatmanesh, H., and Ehsani, M. R, (1997) "Shear and Flexure Strengthening of R/C Beams with Carbon Fiber Sheets", Journal of Structural Engineering, ASCE, Vol. 123, No. 7, pp. 903-911.
15. Bunsell, A. R, and Harris B. (1974) "Hybrid Carbon and Glass Fiber Composites", Composites, Vol. 5, pp. 157-164.
16. Manders. P. W., and Bader, M. G. (1981) "The Strength of Hybrid Glass / Carbon Fiber Composites: Part 1, Failure Strain Enhancement and Failure Mode", Journal of Materials Science, Vol. 16, pp. 2233-2245. pp5
17. Ahmed, O., and Van Gemert, D., (1999), "Shear Behavior of R C Beams Strengthened by Longitudinal CFRP Laminates", The Second Middle East Symposium on Structural Composites for Infrastructure Applications, Hurghada, Egypt, pp. 312-323.
18. Shaheen, H., Taerwe, L., and Khalil, H., (1999), "Flexural Strengthening of Loaded RC Beams by External CFRP Sheets", The Second Middle East Symposium on Structural Composites for Infrastructure Applications, Hurghada, Egypt, pp. 312-323.
19. Mahfuz, I., Sarkani, S., and Rizk, T., (1999), "Experimental and Theoretical Investigation of the Behavior of Reinforced Concrete Structures Upgraded Using Fiber Reinforced Polymers". The Second Middle East Symposium on Structural Composites for Infrastructure Applications, Hurghada, Egypt, pp. 295-311.
20. Ritchie. P. A, Thomas. D. A., Lu. Le-Wu., and Connelly. G.M., (1991) "External Reinforcement of Concrete Beams Using Fiber Reinforced Plastics", ACI Structural Journal, Vol. 88,No. 4,pp. 490-500. pp8
21. Meny. J, Jurgen. G. "Mechanical Analysis of Reinforced Concrete Box Beam Strengthened with Carbon Fiber Sheets Under Combined Actions". Journal of Composite Structure. 73. (2006) 488-494.
22. Meny. J., Werasak. R. Z., "Torsional Strengthening of Reinforced Concrete Box Beam Using Carbon Fiber Reinforced Polymer". Journal of Composite Structure. 78 (2007). 264- 270.
23. Taljsten, B., "CFRP Strengthening and Monttoring of a Box Girder Bridge". Sensing Issues in Civil Structural Health Monttoring. 373-352 (2008).
24. Muthuramu, K.L., Chandran, A., Govindarajan, S., Karunanidhi, S., "Strengthening Of Reinforced Concrete Elements Using Glass Fiber" . 35th conference on Our World In Concrete & Structures, singapore . 25-27 (2010) .
25. Kusuma, S.K., "Strengthening Of Reinforced Concrete Beams Using Glass Fiber Reinforced Polymer" . International Journal Of Research & Development Organization . 2455-6653 (2016).

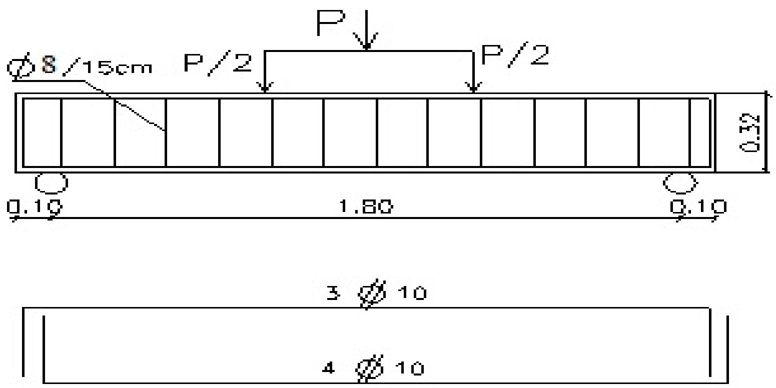
ملخص البحث

تعتبر كمرات الخرسانة المسلحة الصندوقية من أهم العناصر في كباري الخرسانة حيث أنها تقاوم الأحمال المؤثرة علي سطح الكوبري. والهدف الرئيسي لهذه الدراسة هو المقارنة وإكتشاف تأثير التدعيم بإستخدام شرائح من ألياف الكربون والألياف الزجاجية والشبك الممدد بسمك (2مم) علي سلوك هذه الكمرات. واشتمل البرنامج العملي علي دراسة إثني عشرة كمرة.ثلاثة

International Journal of Scientific Engineering and Applied Science (IJSEAS) – Volume-3, Issue-9, September 2017
ISSN: 2395-3470
www.ijseas.com

وثلثه. وتم رسم العلاقات وتحليل النتائج. حيث ثبت أن هذه الأساليب من التدعيم ترفع من كفاءة هذا النوع من الكمرات ويزيد من قوة تحملها للشروخ والانهيار ويقلل من قيمة سهم الإنحناء ويزيد ممطولية الكمرة وبالتالي فهي مفيدة للمهندس المصمم والمنفذ.

كمرات كمرجعيات وثلاثة كمرات للمجموعات الأولي والثانية والثالثة.



واشتملت المتغيرات المدروسة علي

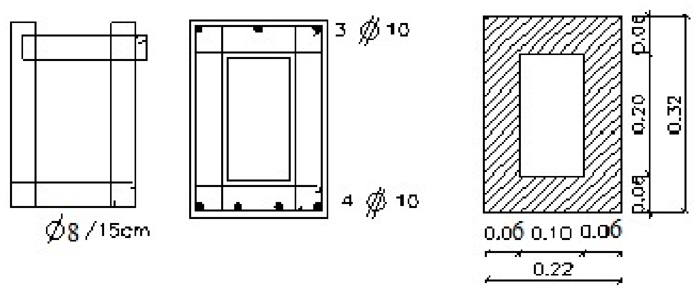


Fig.: (1-a) Details of RCBG dimensions ,and reinforcement.

طول التدعيم الذي تراوح ما بين كامل طول البحر أو نصفه أو ربعه.وتم
تحميل الكمرات بقيم من الأحمال المتساوية حتي حدوث الشروخ والإنهيار وأيضا تم تسجيل جميع البيانات الخاصة بهما وقيمة سهم الإنحناء عند منتصف البحر

Fig: (1-b) Details of cross-section for RCBG

Table1: Experimental program for the test box girder

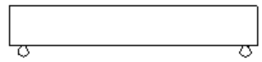
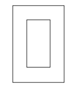
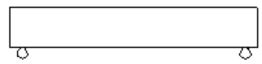
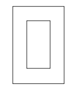
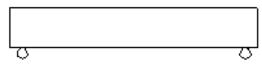
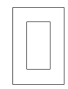
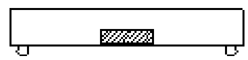
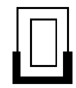
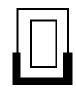
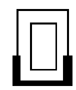
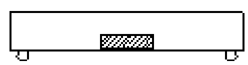
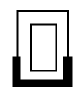
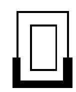
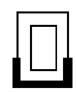
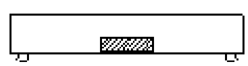
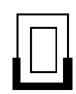
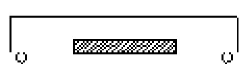
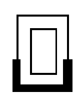
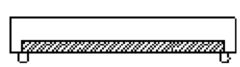
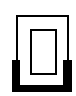
Group No	Girder No	Material & Strengthening Length	longitudinal Shape	Section Shape
Reference	R1	-		
	R2	-		
	R3	-		
G	G1	GFRP - L/3		
	G2	GFRP -2L/3		
	G3	GFRP - L		
C	C1	CFRP - L/3		
	C2	CFRP - 2L/3		
	C3	CFRP - L		
S	S1	Steel GRID - L/3		
	S2	Steel GRID - 2L/3		
	S3	Steel GRID - L		

Table 2: Analyses of test results.

Group No	*Gir No*	*Pc (kN)**	*Pu (kN)**	*Δ1 mm*	*Δ2 mm*	*P(Pc/ Pcr)%*	*P(Pu/ Pur)%*	*P(Δ1 / Δ1r)%*	*P(Δ2 / Δ2r)%*	*Δ1y mm*	*Ducti ratio**	*Fail Mode**
Refe	*R1*	35	80	4.02	3.7	100	100	0.0	0.0	1.2	1.61	*F*
	R2	37	84	4.06	3.8	100	100	0.0	0.0	1.2	1.64	*F*
	R3	33	76	3.98	3.6	100	100	0.0	0.0	1.2	1.59	*F*
G	*G1*	55	88.9	3.32	2.63	157	111	-17	-29	1.52	1.54	*Sh*
	G2	75	116.5	3.5	3.64	214	145	-13	-1	1.26	1.28	*sh*
	G3	110	135	4.62	3.34	314	168	+15	-10	1.04	2.96	*sh*
C	*C1*	45	85.2	3.28	2.95	128	106	-18	-20	1.27	1.44	*Sh*
	C2	60	105	3.42	3.1	171	131	-15	-16	0.95	1.1	*Sh*
	C3	93	125.5	4.06	3.5	265	156	+1	-5	1.05	2.59	*Sh*
S	*S1*	40	83.9	3.86	3.05	114	105	-4	-17	1.27	1.23	*Sh*
	S2	55	98.5	2.77	3.05	157	123	-31	-17	0.95	1.18	*Sh*
	S3	84	121.5	3.32	3.32	240	151	-17	-10	1.05	2.35	*Sh*

Notes: all comparison with reference girder R .
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 R.
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.

Photo1. Girder G2 - Strengthening Length = 2L/3

Photo2. Girder G3 - Strengthening Length = L

Photo3. Girder C2 - Strengthening Length = 2L/3.

Photo4. Girder C3 - Strengthening Length = L

Photo5. Girder S2 - Lateral, Bottom Strengthening Length = 2L/ 3

Photo6. Girder S3 - Lateral, Bottom Strengthening Length = L

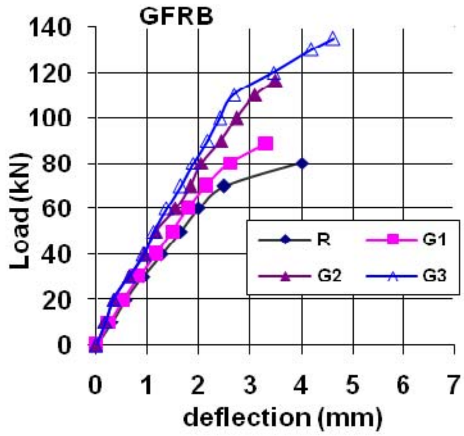


Fig.2. Load versus deflection (Δ1) curves. Variations in strengthening length.

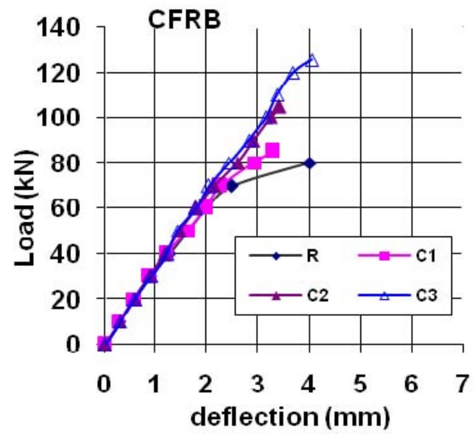


Fig. 3. Load versus deflection (Δ1) curves. Variations in strengthening length.

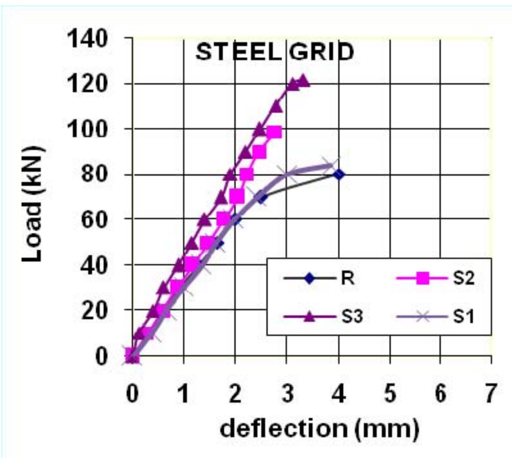


Fig. 4. Load versus deflection (Δ1) curves. Variations in strengthening length.

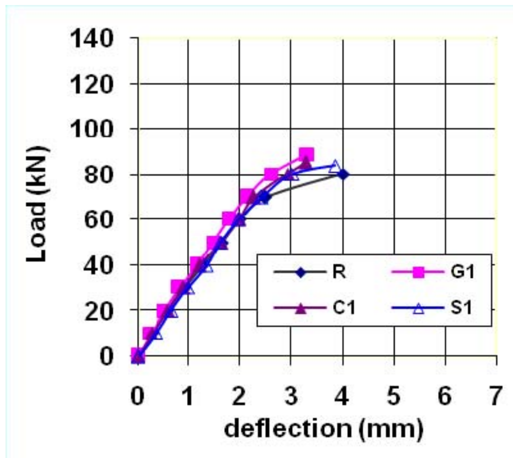


Fig. 5. Load versus deflection (Δ1) curves. Variations in strengthening material.

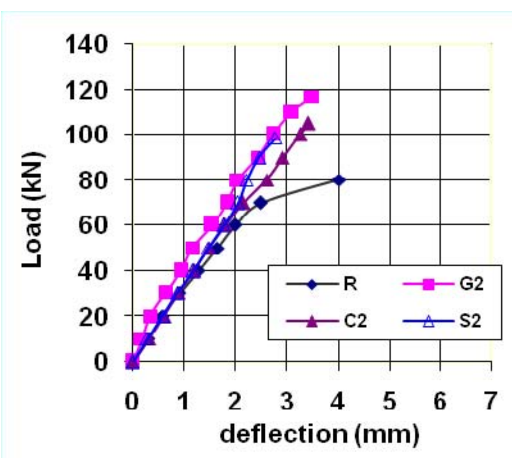


Fig. 6.Load versus deflection (Δ1) curves. Variations in strengthening material.

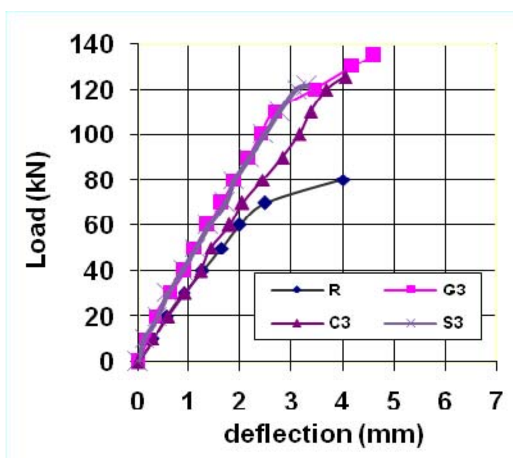


Fig. 7. Load versus deflection (Δ1) curves. Variations in strengthening material.

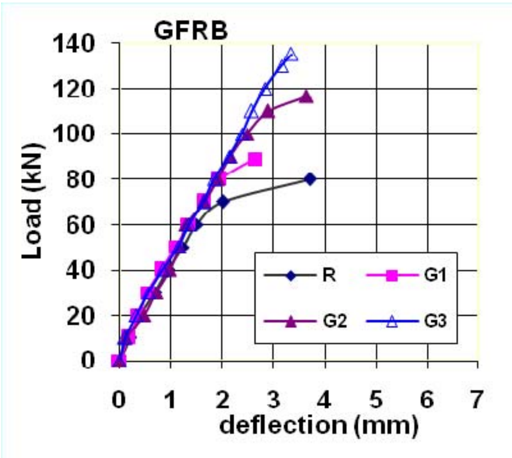


Fig. 8. Load versus deflection (Δ2) curves. Variations in strengthening length.

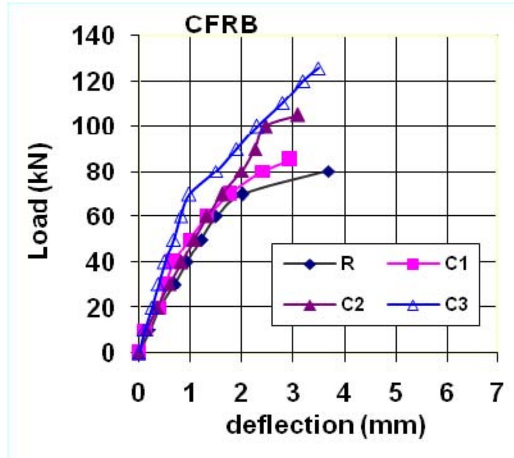


Fig. 9. Load versus deflection (Δ2) curves. Variations in strengthening length.

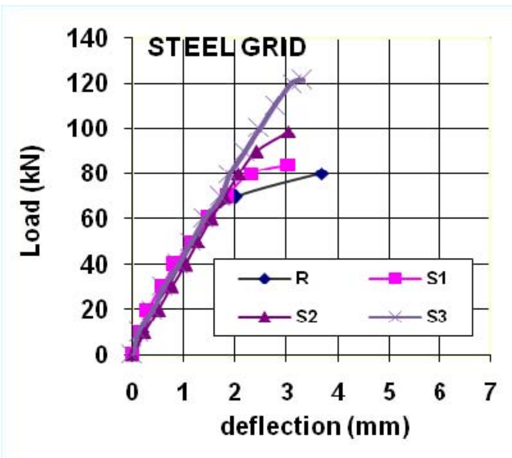


Fig. 10 . Load versus deflection (Δ2) curves. Variations in strengthening length.

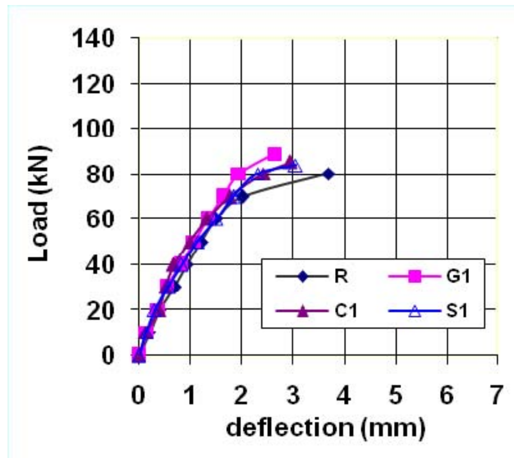


Fig. 11 . Load versus deflection (Δ2) curves. Variations in strengthening material.

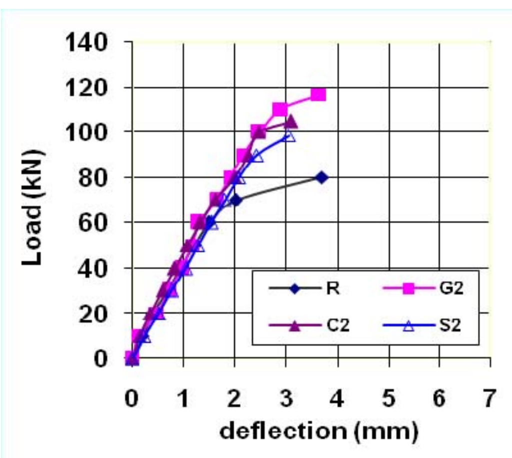


Fig. 12 . Load versus deflection (Δ2) curves. Variations in strengthening material.

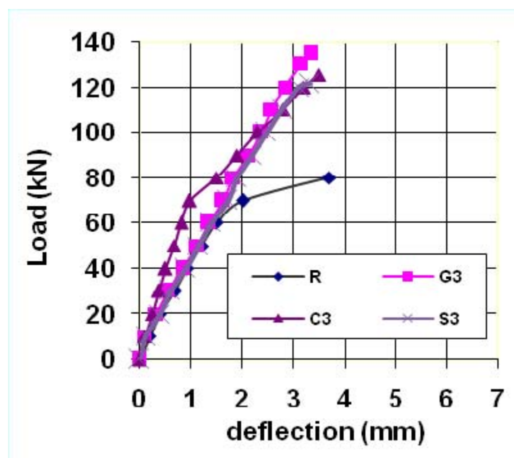


Fig. 13 . Load versus deflection (Δ2) curves. Variations in strengthening material.

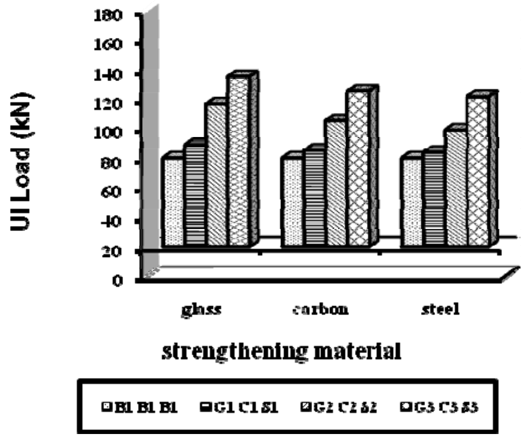


Fig .14. Ultimate load and strengthening material for all girders.

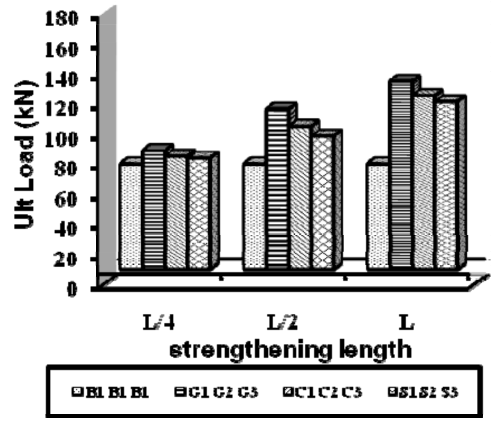


Fig .15. Ultimate load and Strengthening length for all girders.

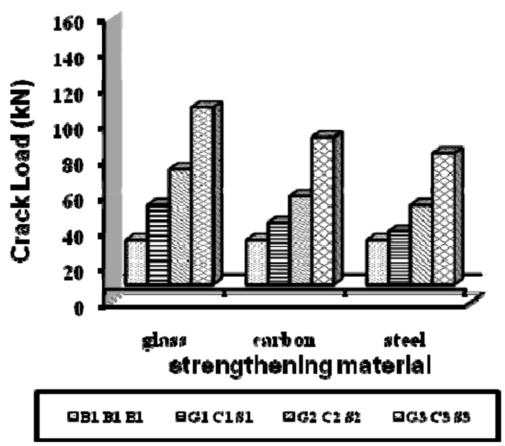


Fig 16. Cracking load and strengthening material for all girders

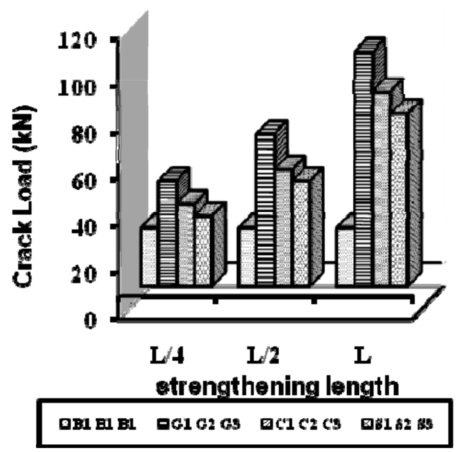


Fig 17. Crack loads and Strengthening length for all girders.