Journal of Babylon University/Engineering Sciences/ No.(1)/ Vol.(24): 2016

Experimental Investigation for Behavior of Spliced Continuous RC Girders Strengthened with CFRP Laminates

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Abstract

In this paper, the behavior of spliced continuous reinforced concrete girders was experimentally investigated. The main objective was to examine the contribution of the carbon fiber reinforced polymer (CFRP) laminates in strengthening the spliced continuous reinforced concrete girders. Eight models of continuous reinforced concrete girder were constructed and tested. The test variables were strengthening the splice joints by different schemes of CFRP laminates, presence of horizontal stirrups through the interfaces of the joints and using binder material at the interfaces of the joints. The results showed that strengthening the continuous spliced girders with 45° inclined CFRP laminates led to an increase in the ultimate load in a range of (47 to 74%). Besides, strengthening the continuous spliced girder with horizontal CFRP laminates bonded at its lateral faces could increase the ultimate load by 70%. Additionally, the ultimate load of the continuous spliced girder was increased by (30%) due to presence of the horizontal steel stirrups through the interfaces of the joints.

Keywords: Spliced Girders, Continuous, Reinforced Concrete, CFRP Laminates

الخلاصة

تقدم هذه الدراسة تقصيا عمليا لسلوك الروافد الخرسانية المسلحة المستمرة الموصولة. ركزت هذه الدراسة على تقييم كفاءة اشرطة الياف الكاربون البوليميرية (CFRP) في تقوية الروافد الخرسانية المسلحة المستمرة الموصولة. تضمنت الدراسة انشاء وفحص ثمانية نماذج للروافد الخرسانية المستمرة. وتضمنت المتغيرات العملية تقوية مناطق الوصلات بأشرطة الـــ (CFRP) وبتشكيلات مختلفة، وجود الاطواق الفولاذية الافقية خلال أوجه مفاصل الالتقاء واستعمال مادة لاصقة على أوجه مفاصل الالتقاء. أظهرت النتائج بان تقوية الروافد الموصولة ذات الاسناد المستمر باستعمال اشرطة مائلة بزاوية 45° من الـــ (CFRP) أدت الى زيادة الحمل الأقصى بنسبة (47 الى 74%). كما ان تقوية الروافد الموصولة المستمرة باستعمال اشرطة افقية من الـــ (CFRP) ملصقة على الأوجه الجانبية أدت الى زيادة الحمل الأقصى بنسبة (70%). إضافة الى انه الحمل الأقصى للروافد المستمرة الموصولة قد ازداد بنسبة (30%) نتيجة لوجود الاطواق الفولاذية الافقية المارة خلال أوجه مفاصل التقاء.

الكلمات المفتاحية: الروافد الموصولة، مستمرة الاسناد، خرسانة مسلحة، اشرطة الياف الكاربون البوليميرية.

1. Introduction and Background

It was found that the span ranges for precast concrete girders could be significantly increased by utilizing the splicing girder technique **(Castrodale and White, 2004)**. A spliced girder is defined as a prefabricated reinforced concrete member that is made of two or more relatively long segments that are assembled together to produce a single girder. Splicing allows designers to overcome limitations of fabrication, shipping, and erection that have prevented the use of very long precast concrete girders in the past. Furthermore, the use of spliced girders leads to increase the girder spacing **(Castrodale and White, 2004)**.

Cast-in-place reinforced concrete joints are usually utilized to connect the adjacent precast segments of the spliced girders. The performance of the cast-in-place joints greatly governs the overall performance of the spliced girders. The cast-in-place joints are usually subjected to shear, tension or flexure. The integrity of the reinforced concrete joints may be achieved by utilizing reinforcement lap splicing and/or post-tensioning **(Junbao, 2004).**

Post-tensioning is usually used to reinforce the connection between girder segments. The use of post-tensioning in these connection systems requires large amount of posttensioning, which requires relatively long time to be installed in the field and considered as very costly **(Badie *et. al.*, 1999).** Furthermore, the use of post-tensioning often requires a special construction control to ensure that the post-tensioning is operating according the specified requests, which lead to rising the cost of construction **(Bell II *et. al.*, 2006)**.Thus, it is significant to investigate the efficiency of the CFRP laminates in strengthening the splice joints.

Several research studies reported in the literature on improving the structural behavior of spliced girders. Two studies are presented in this section.

Al-Mamuree (2008) studied experimentally and numerically the structural behavior of pre-stressed concrete spliced and non-spliced girder models. Sixteen girders of rectangular section were tested. Eight girders were spliced while the other eight were non-spliced. Each spliced girder consisted of three reinforced concrete segments. The variables were amount of post-tensioned tendons area, locations of joints, loading arrangement, span length, girder depth, and whether the segments were pre-tensioned or not. The numerical part of this study included analysis the girders using a modified computer program depending on three dimensional non-linear finite element analysis. The study results showed that the ultimate loads for the non-spliced girders were greater than those of the spliced girders in the range of (12% -17%) and at 50% of the ultimate load, the deflections of the spliced girders were greater than those of the non-spliced girders in range of (10% -15%). The study results showed also that the increase in the pre-stressed tendons area in the range of (50% -100%) led to increasing in the ultimate load in range of (11% -16%) and decreasing in the deflection in range of (8% -14%).

Al-Quraishy (2011) presented an experimental and theoretical study to investigate the effect of using strengthening steel plate at splices and post-tensing the spliced segments on the overall behavior of the spliced reinforced concrete girders. Fifteen girders of rectangular section (100 × 140 mm) were tested. The experimental variables were present or absent of strengthening steel plate at splices, whether the segments were post-tensioned or not, number and locations of joints, and loading arrangement. All tested girders were analyzed using the computer program ANSYS. The results of this study referred to the presence of splicing joints in the girders had led to an increase in the deflection values at 50% of the ultimate load between (17%-50%) with respect to the non-spliced girder. In the same time, the ultimate load of spliced girders decreased by (12%-52%) of that of non-spliced girder. This study referred also to that strengthening the splices joints with steel plates led to reducing the deflection of the spliced strengthened girders at about 50% of the ultimate load by (2%-20%) with respect to the non-spliced girder. The ultimate loads of spliced strengthened girder increased by (1%-7%) of that of the non-spliced girder. Finally, this study showed that post-tensioning the spliced girders decreased the deflection at a load of 50% of the ultimate load by (26% -43%) with respect to those of non-prestressed girders. Besides the post-tensioning increased the ultimate loads by (70% -132%).

There is no available work has been found on the strengthening of spliced reinforced concrete girders using FRP products (neither laminates nor bars).

2. Experimental Program

2.1 Design of Test Specimen

The test program consisted of eight models of continuous girder. Each girder was continuous over two spans, each span length was 900 mm and the total length of the girder was 2,000 mm. One concentrated loading point was applied at the center of each span. Flexural reinforcement consisted of two steel bars of φ 10 mm on each the top and bottom sides. Transverse reinforcement consisted of φ 6 mm closed stirrups spaced at 50 mm on center for the region between the loading points while it spaced at 100 mm on center for the spans between the loading points and the boundary supports.

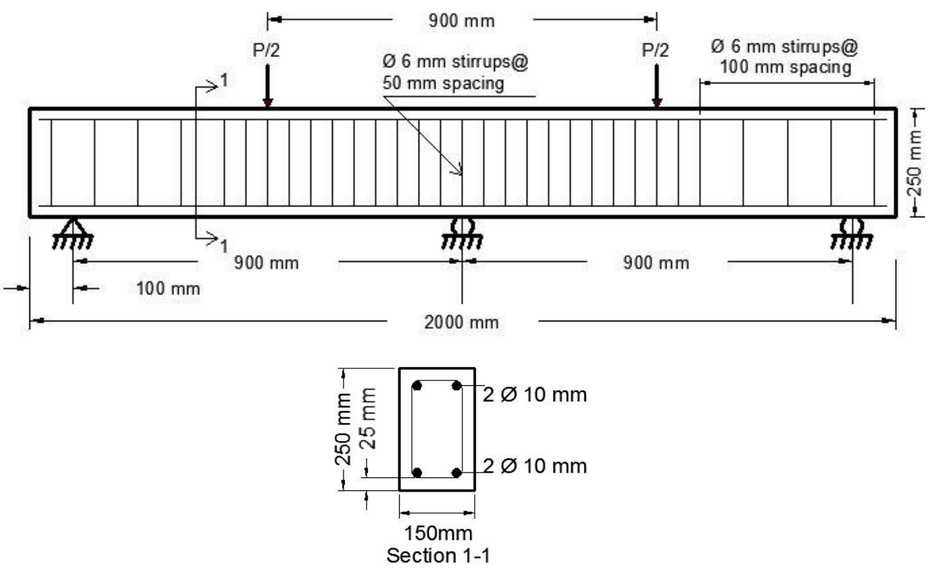
One of these girders was a control girder, denoted by (**CB**) and utilized for comparison purposes, see Fig. 1, whereas the others were spliced at the inflection points using splices of hooked dowels anchored into cast in place joints. Each spliced girder consisted of three precast segments and two joints in between. Two precast segments were at the boundaries, while the third precast segment was at the middle. The steel bars of the main reinforcement were extended out of; the interior end of each outer precast segment and both ends of the middle precast segment as 90^0 hooks, as shown in Figs. 2 and 3. The concrete of the joints was casted after two weeks. These joints represented the splice regions of the extended hooks formed from the assemblage of the precast segments. The length of each joint was equal to the development length of the 90^0 hook plus a distance of 20 mm between the end of one of the precast segments and the hooks of the opposite precast segment. The 90^0 hook was designed according to ACI 318-11(see Appendix A).

For all the seven spliced girders, the development length for the 90^0 hook of each joint was (**0.5l_{dh}**) and the shear reinforcement was provided even in the joints. However, these girders differed in other details of the joints as follows:

- Girder (**CB.5l_d**): without any strengthening at joint. See Fig. 4.
- Girder (**CB.5l_dE**): strengthened by adding a binder (**Epoxy-resin concrete bonding agent**) at the interfaces between the hardened concrete of precast segments and the fresh concrete of the joint. See Fig. 5.
- Girder(**CB.5l_dHS**):strengthened with internal horizontal stirrups(two horizontal stirrups of φ 6 mm) which extended out from each precast segment into the joints. See Fig.6.
- Girder (**CB.5l_d-LCF**): strengthened at the joints with longitudinal CFRP laminates as two strips with total width of 68 mm bonded at each top and bottom faces. The longitudinal CFRP laminates extended 245 mm from the outer side of each joint and continued between the joints. See Fig.7.
- Girder (**CB.5l_d-HCF**): strengthened at joints with horizontal CFRP laminates as two strips bonded at each lateral side of the joints (through the depth) with development length of 120 mm before and after each joint. Each strip had a width of 100 mm. A full wrapped CFRP laminate of 50 mm width was used at each end of the horizontal CFRP laminate as additional anchorage technique. See Fig.8.
- Girder (**CB.5l_d-ICF**): strengthened at joints with 45^0 inclined CFRP laminates as three strips bonded at each lateral side of the joints (through the depth) with

development length in the same inclined direction through the top and bottom faces. Each strip had a width of 50 mm and consisted of two plies. In this case, each interface was strengthened with two strips of two plies at each lateral side, which equal the same area of CFRP laminates used for each interface in girder (**CB.5l_d-HCF**). See Fig.9.

- Girder (**CB.5l_d-2ICF**): strengthened at joints by the same strengthening technique used in girder (**CB.5l_d-ICF**) but each strip consisted of only one ply instead of two plies.



a- End Segment b- Middle Segment

Fig. 2- Precast segments

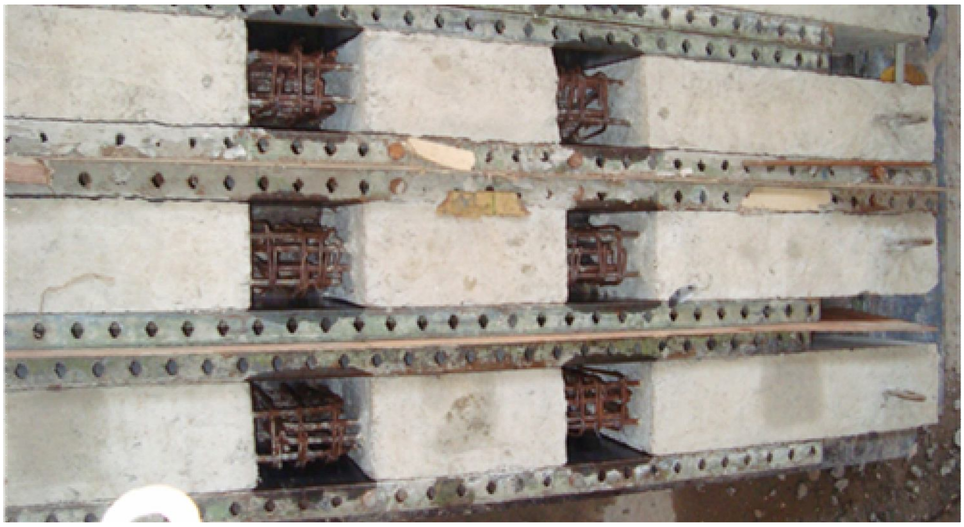


Fig. 4- Details of Girder CB.5l_d

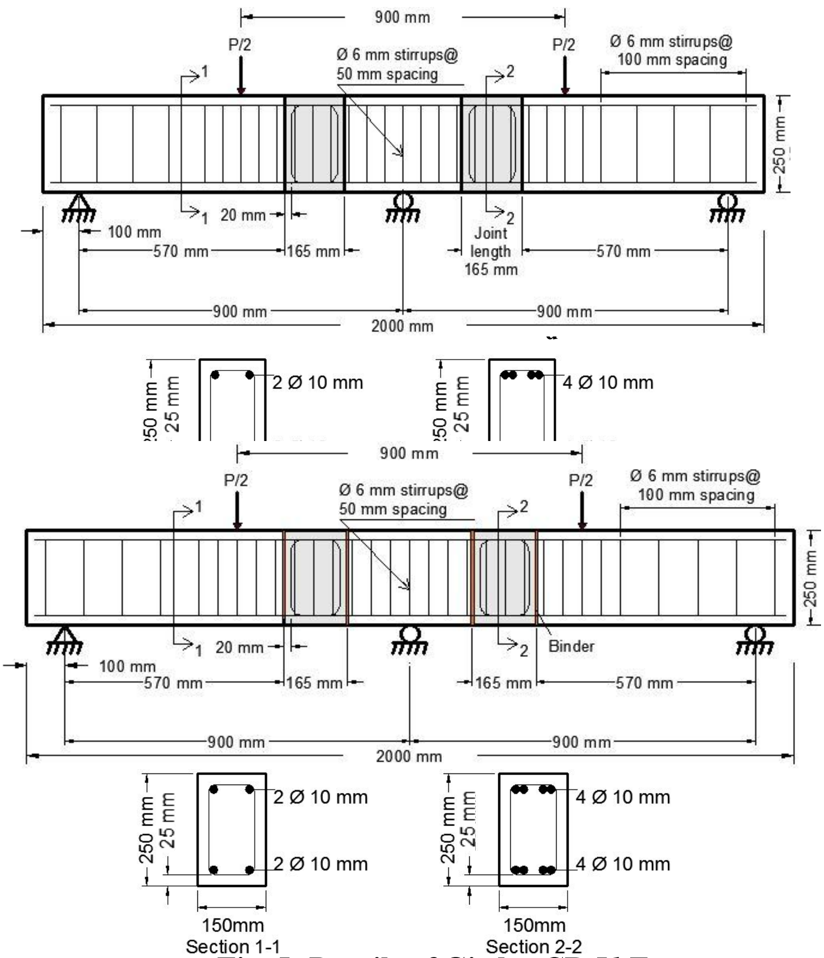


Fig. 5- Details of Girder CB.5l_dE

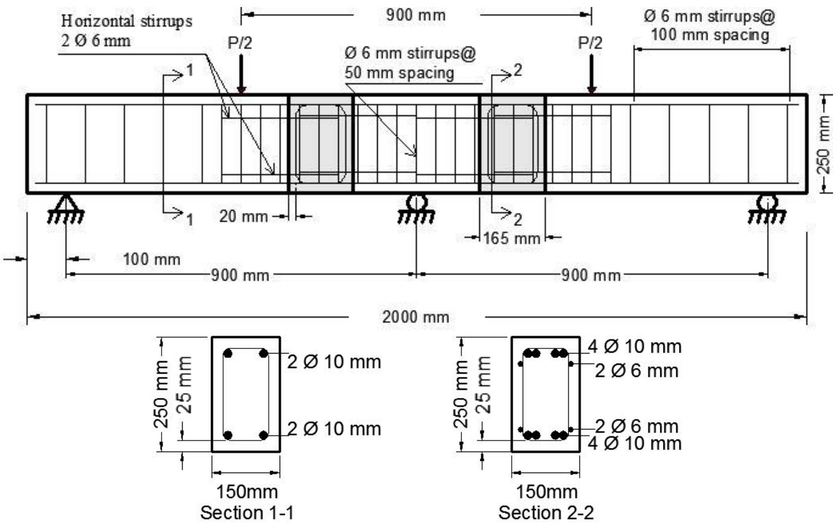


Fig. 6- Details of Girder CB.5l_dHS

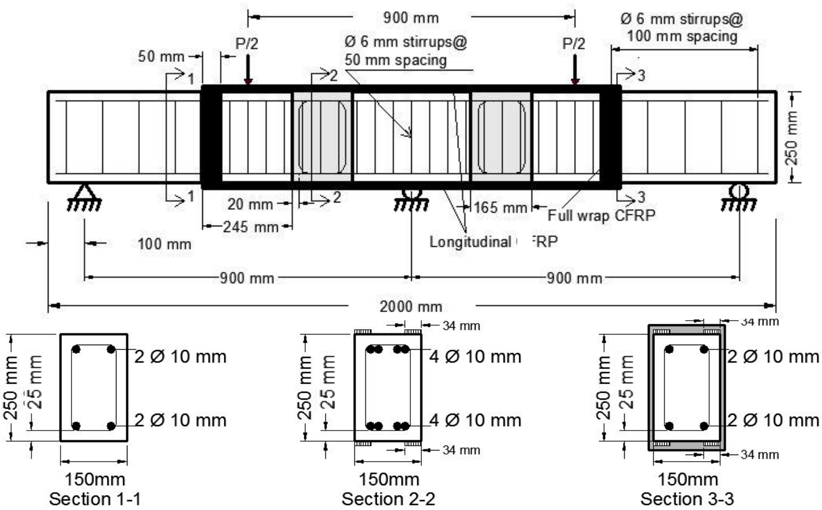


Fig. 7- Details of Girder CB.5l_d-LCF

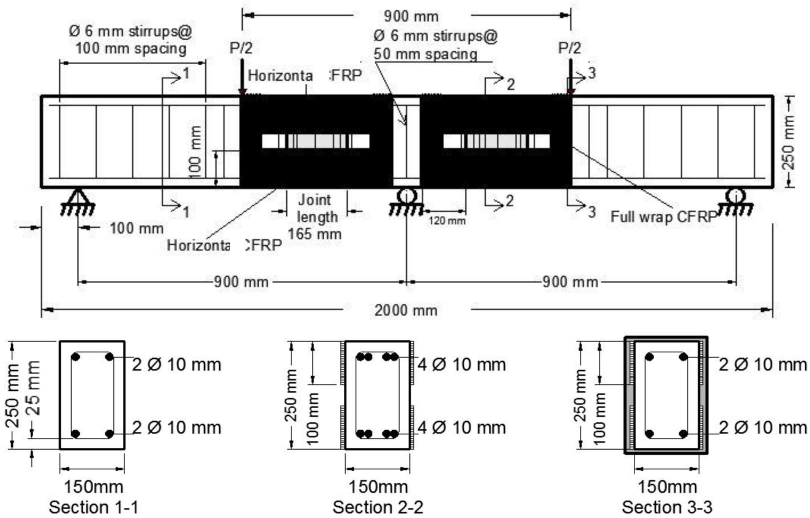


Fig. 8- Details of Girder CB.5l_d-HCF

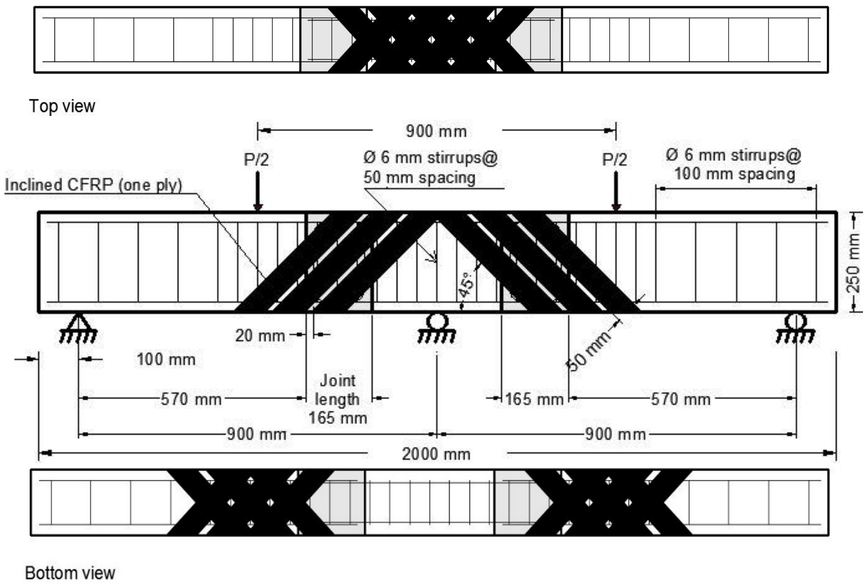


Fig. 9- Details of Girder CB.5l_d-ICF

2.2 Materials

The steel reinforcing bars were in two sizes. The average yield stresses were 707 MPa for the bars size φ 10 mm and 462 MPa for the bars size φ 6 mm. Tensile test of steel bars were performed according to ASTM C615-05 (**ASTM, 2005**). The cubic compressive strengths of concrete were 41.74 MPa for precast segments and 44.13 for joints. The designed mix proportions were (1 cement : 1.8 sand : 2.73 gravel). The cement content was 440 kg/m^3 and the water cement ratio was 0.4. The compressive strength test of concrete cubes was carried out in accordance with BS1881 (**BS, 1990**).

CFRP system composed of unidirectional woven carbon fiber fabric (SikaWarp®-230 C/45) and epoxy adhesive (Sikadur®-330). The properties of the fiber fabric and epoxy adhesive are presented in Tables 1 and 2 respectively as supplied by manufacturer. A wet layup procedure was used to install the dry CFRP sheets with an epoxy resin on-site after preparing the concrete surface.

The properties of Epoxy-resin concrete bonding agent, Fosroc Nitobond EP which was used in one case in this study, are listed in Table 3, as supplied by manufacturer. This bonding agent is utilized for bonding new cementitious materials to existing cementitious surfaces.

Table 1- Properties of Carbon Fiber Fabric (Sika, 2009a)

Fiber orientation	Weight	Thickness	Tensile strength	Tensile E-modulus	Elongation
0°	230 g/m^2	0.131 mm	4300 MPa	234 GPa	1.8 %

Table 2- Technological Properties of the Sikadur-330 Epoxy Resin (Sika, 2009b)

Tensile strength	Tensile E-modulus	Elongation
30 MPa	4500 MPa	0.9%

Table 3- Properties of Fosroc Nitobond Epoxy Resin (Fosroc, 2012)

Compressive strength	Tensile strength	Slant shear bond
50 MPa at 7 days	20 MPa at 7 days	25 MPa at 7 days

2.3 Test Procedure

The girders were tested using a servo-hydraulic actuator of 2000 kN capacity. The girders loaded monotonically in increments of 10 kN. At each load stage, deflection readings at mid span and cracks width were recorded.

3. Test Results and Discussion

All the spliced girders were provided with adequate reinforcement to avoid any failure outside the joints. Therefore, the structural behavior and failure modes of the spliced girders were governed by the characteristics of the joints. A summary for the test results of tested girders is shown in Table.4. The listed data include, first interface cracking load, first flexural cracking load, ultimate load and mode of failure. The cracks that initiated at interfaces between the precast segments and the joints are called as interface cracks. Figs 10 to 17 show the failure modes of the tested girders.

The failure mode of the non-spliced control girder (**CB**) was flexural mode characterized by yielding the tension steel reinforcement followed by crushing the concrete. While the non-strengthened spliced girder (**CB.5l_d**) failed due to relative vertical movements occurred between the end segments and the middle segment which can be attributed to the direct shear stresses that developed at the interfaces. The effect of the strengthening techniques are discussed in the following subsections. In girder **CB.5l_d-ICF** the second ply of CFRP laminates debonded firstly and then the first ply ruptured at failure. While in girder **CB.5l_d-2ICF** the only one ply of CFRP laminates ruptured at failure.

Table 4. Summary of Experimental Results

Girder symbol	Interface cracking load (kN)	Flexural cracking load, (P_{cr}) (kN)	Ultimate load, (P_u) (kN)	* $\frac{P_{u(i)}}{P_{u\,(cont}}$	Failure mode
CB	-	70	360	1	Flexural
CB.5l_d	10	40	230	0.64	Direct shear
CB.5l_d.E	20	50	230	0.64	Direct shear
CB.5l_d.HS	25	50	300	0.83	Direct shear
CB.5l_d-LCF	20	40	245	0.68	Direct shear
CB.5l_d-HCF	50	40	390	1.08	Direct shear
CB.5l_d-ICF	20	70	400	1.11	Flexural followed by direct shear
CB.5l_d-2ICF	20	70	337	0.94	Direct shear

- $\mathbf{P_{u(i)}}$: the ultimate load of considered girder and, $\mathbf{P_{u(cont.)}}$: the ultimate load of control girder.

Fig. 10- Failure Mode of Girder CB

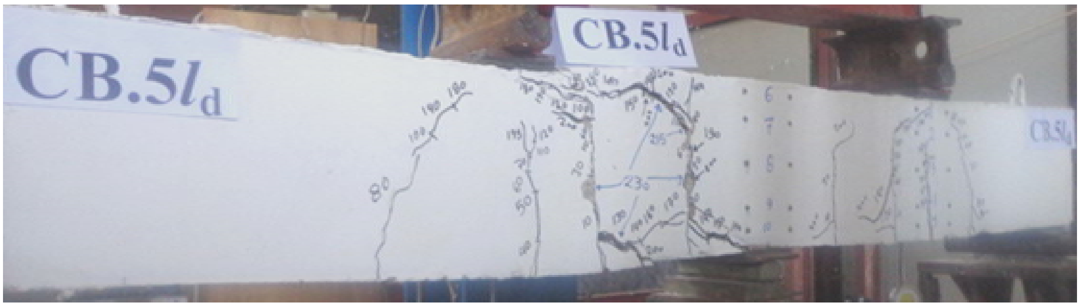


Fig. 11- Failure Mode of Girder CB.5l_d

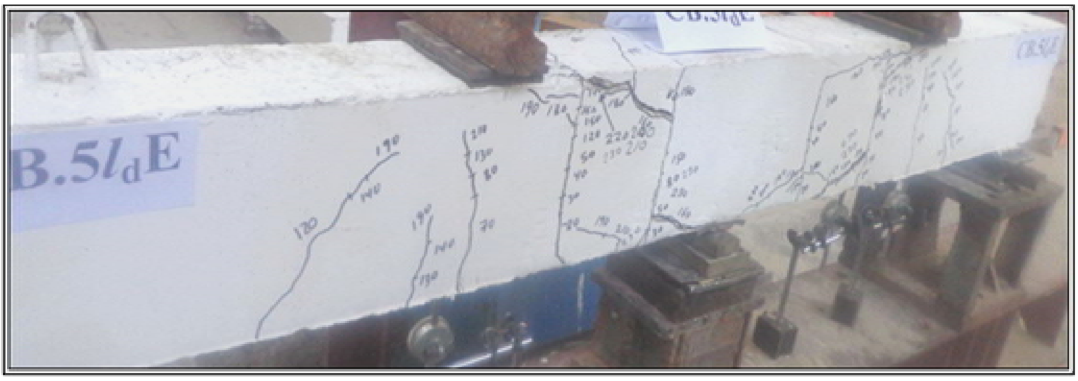


Fig. 12- Failure Mode of Girder CB.5l_dE

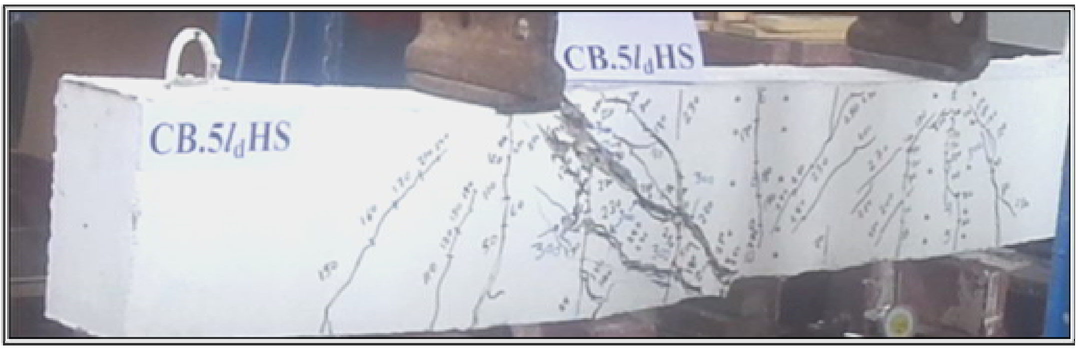


Fig. 13- Failure Mode of Girder CB.5l_dHS

Fig. 14- Failure Mode of Girder CB.5l_d-LCF

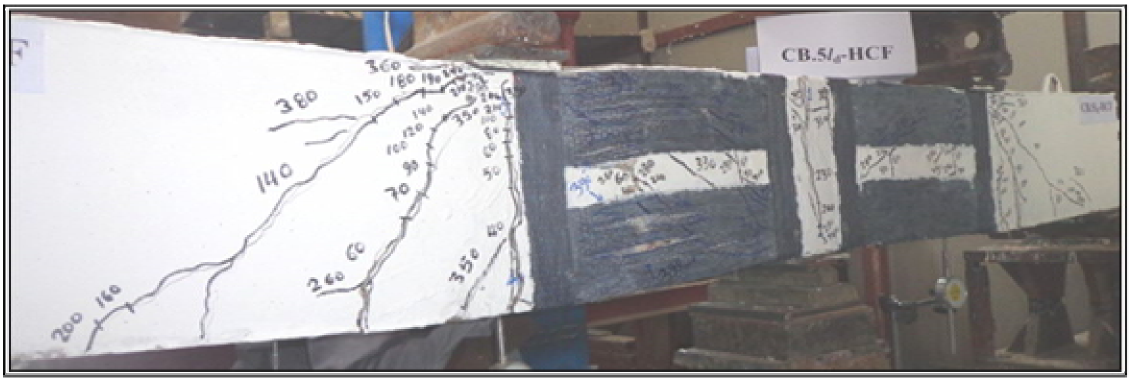


Fig. 15- Failure Mode of Girder CB.5l_d-HCF

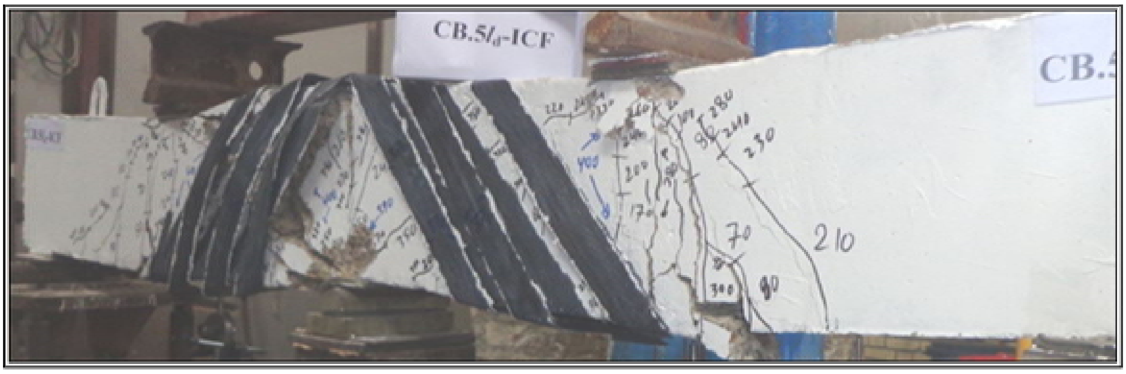


Fig. 16- Failure Mode of Girder CB.5l_d-ICF

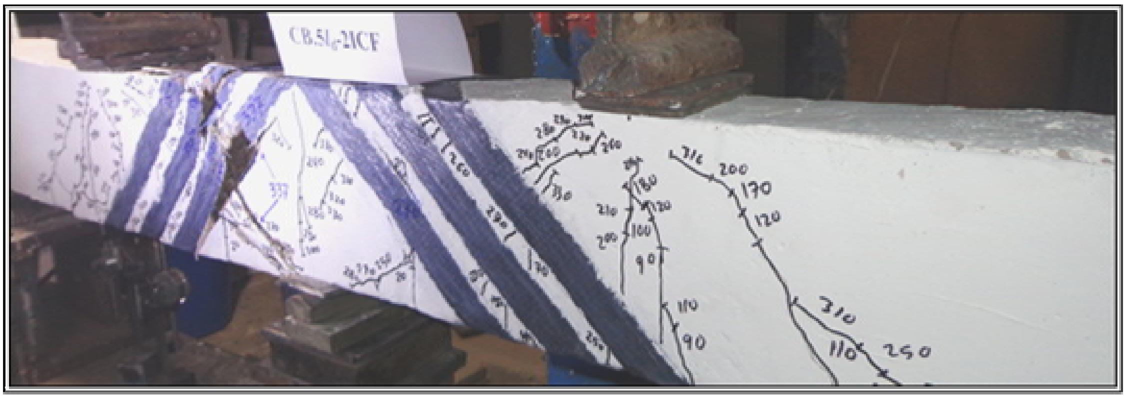


Fig. 17- Failure Mode of Girder CB.5l_d-2ICF

3.1 Effect of Glued Interfaces and Longitudinal CFRP Strengthening

The experimental results showed that both the adding binder material at interfaces or bonding CFRP laminates on the top and bottom of the joints had reduced the width of the interface cracks, as shown in Fig.18.

Although both strengthening techniques had no significant effect on the ultimate load of continuous spliced girders, they reduced the deflection of these girders especially in girder **CB.5l_d-LCF**, as shown in Fig.19.

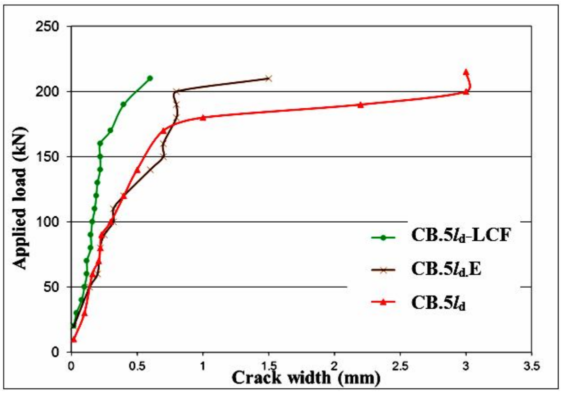


Fig. 18- Load-Crack Width Curves for Max. Interface Cracks of Girders CB.5l_d-LCF, CB.5l_d.E and CB.5l_d

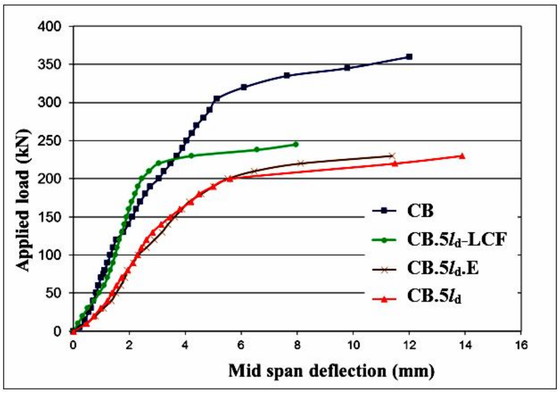


Fig. 19- Load-Deflection Curves of Girders CB.5l_d-LCF, CB.5l_d.E, CB.5l_d and CB

3.2- Effect of Horizontal Strengthening

The horizontal strengthening significantly reduced the width of the interface cracks of the spliced girders, as seen in Fig.20.

In comparison with the corresponding non-strengthened spliced girder **CB.5l_d**, the ultimate load for the horizontally strengthened spliced girders increased by 30% for girder **CB.5l_d.HS** which was strengthened with horizontal stirrups and by 74% for girder **CB.5l_d-HCF** which was strengthened with horizontal CFRP laminates, as seen in Fig.21. The corresponding increase in the mid span deflection at ultimate load was 42% for girder **CB.5l_d-HCF** that indicated the positive effect of using CFRP laminates as horizontal strengthening on the ductility of the load-deflection behavior as seen in Fig.21.

Another indication of the improved integrity when the horizontal strengthening was used is the presence of flexural cracks in the middle precast segments of the horizontally strengthened spliced girders. Whereas these cracks did not appear in the middle precast segment of non-strengthened spliced girder **CB.5l_d** as well as in girders **CB.5l_d-LCF** and **CB.5l_d.E**.

The improvement achieved when the horizontal strengthening was used can be attributed to that both the CRFP laminates and internal steel stirrups act as clamping forces across the interfaces as well as the dowel action of the internal steel stirrups.

It is clear that an increase in the flexural capacity of girder **CB.5l_d-HCF** had occurred which can be ascribed to the confinement provided by the full wrapped CFRP laminates used to anchor the horizontal CFRP laminates.

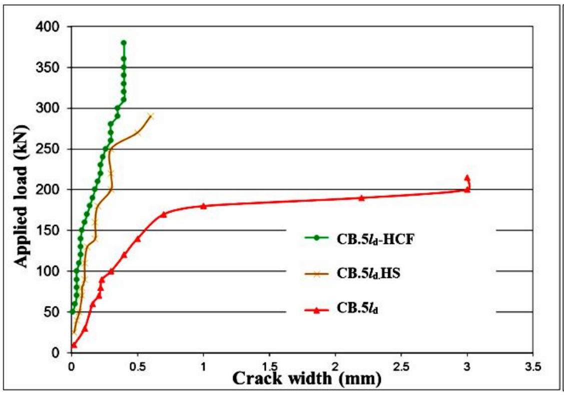


Fig. 20- Load-Crack Width Curves for Max. Interface Cracks of Girders CB.5l_d-HCF, CB.5l_dHS and CB.5l_d

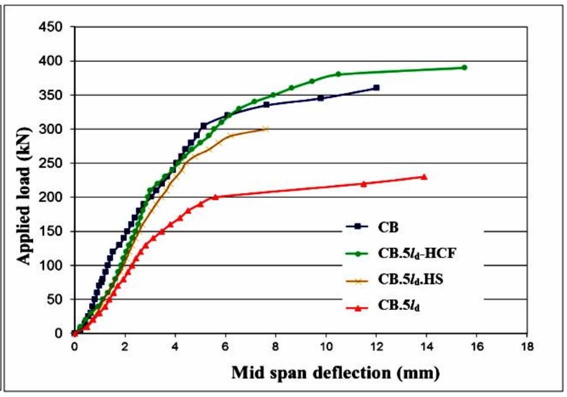


Fig. 21- Load-Deflection Curves of Girders CB.5l_d-HCF, CB.5l_d.HS, CB.5l_d and CB

3.3- Effect of Inclined Strengthening

The inclined strengthening technique was more effective than the previous techniques to restrain the interface cracks of the continuous spliced girders. This strengthening technique succeeded in keeping the width of the interface cracks within 0.1 mm, as seen in Fig.22.

The ultimate load for girders **CB.5l_d-ICF** and **CB.5l_d-2ICF**, which were strengthened with 45° inclined CFRP laminates, increased by 74% and 47%, respectively in comparison with the corresponding non-strengthened spliced girder **CB.5l_d**, as seen in Fig.23. The effect of this strengthening technique was more pronounced and significant when using two plies of the CFRP laminates as in girder **CB.5l_d-ICF**. The mid span deflection at ultimate load for girder **CB.5l_d-ICF** increased by 42% in comparison with the corresponding non-strengthened spliced girder **CB.5l_d**, which indicates the positive effect on the ductility of the load-deflection behavior.

Furthermore, the failure mode of this girder changed from direct shear failure to flexural followed by flexural shear failure. This also indicates that the inclined CFRP laminates increased the flexural capacity of this girder.

The flexural behavior of the middle precast segments of the spliced girder strengthened by this technique can be considered as another indication of the improved integrity (as described in the previous subsection).

The improvement achieved when the inclined strengthening was used can be attributed to that the CRFP laminates act as clamping force across the interfaces and the inclination of the CRFP laminates increased their efficiency.

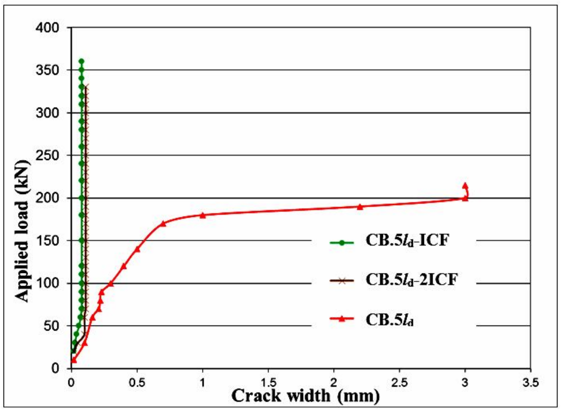


Fig. 22- Load-Crack Width Curves for Max. Interface Cracks of Girders CB.5l_d-ICF, CB.5l_d-2ICF and CB.5l_d

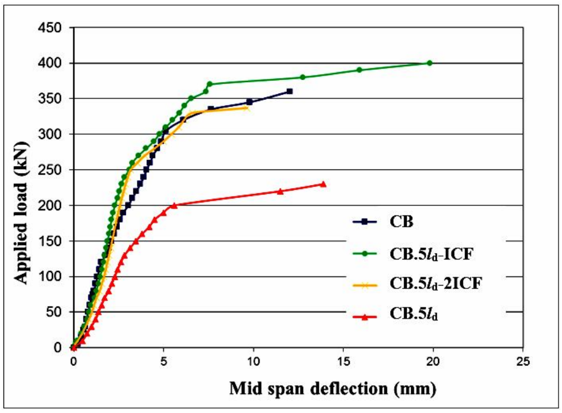


Fig. 23- Load-Deflection Curves of Girders CB.5l_d-ICF, CB.5l_d-2ICF, CB.5l_d and CB

4. Conclusions

Depending on the analysis of the test results of this study, the following points can be concluded:

1. The ultimate load of continuous girder, spliced at inflection points using spliced 90° hooks extending for half of the standard development length, decreased by 36% in comparison with the corresponding non-spliced continuous girder. The failure was due to relative movement between the precast segments and the joints.
2. Strengthening the continuous spliced girders with 45°, inclined CFRP laminates at the joints had a significant effect on the joint integrity and overall behavior of the continuous spliced girders. The ultimate load increased in a range of (47 to 74%) in comparison with the corresponding non-strengthened spliced girder.
3. Strengthening the continuous spliced girder with horizontal CFRP laminates bonded at lateral faces of girder crossing the joints could effectively enhance the overall behavior of the continuous spliced girders. This strengthening technique could increase the ultimate load by 70% in comparison with the corresponding non-strengthened spliced girder.
4. The ultimate load of the continuous spliced girder was increased by (30%) due to presence of the horizontal steel stirrups through the interface between the joints and the precast segments.
5. All the strengthening techniques which including the use of CFRP laminates succeeded in reducing the deflection of the strengthened spliced girders in comparison with the corresponding non-strengthened spliced girder at its failure load (230 kN). The mid span deflection values at load of 230 kN were reduced by (43%), (74%) and (80-81%) due to longitudinal, horizontal and inclined CFRP strengthening techniques respectively. The presence of the horizontal steel stirrups through the interfaces also led to reducing the deflection value at load of 230 kN by (71%).
6. Both the strengthening techniques of bonding horizontal and inclined CFRP laminates at lateral faces of girder crossing the joints could significantly reduce the width of the interface cracks. The width of these cracks not exceeded 0.1 mm in the girders strengthened with inclined CFRP laminates and 0.4 mm in the girder strengthened with horizontal CFRP laminates, while in the corresponding non-strengthened spliced

girder the width of the interface cracks reached 3 mm. The presence of the horizontal steel stirrups through the interfaces also led to keeping the width of the interface cracks not more than 0.6 mm.

7. Both the strengthening techniques of using binder material at interfaces and bonding longitudinal CFRP laminates at the top and bottom of continuous spliced girders had no significant effect on the ultimate load of the continuous spliced girder

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Appendix A

Design of Standard Hook

According to ACI-Code 318-11, development length for deformed bars in tension terminating in a standard hook, (see Fig.A.1), l_{dh}, shall be determined as follows:

$$l_{dh} = \frac{0.24 f_y}{\sqrt{f_c'}} d_b$$

(For normal concrete and uncoated bar)

But, l_{dh} shall not be less than the larger of $8d_b$ and 150 mm.

Where:

f_y : Yield strength of reinforcing bar in (MPa)

f_c' : Compressive strength of concrete in (MPa)

d_b: Diameter of reinforcing bar in (mm) .

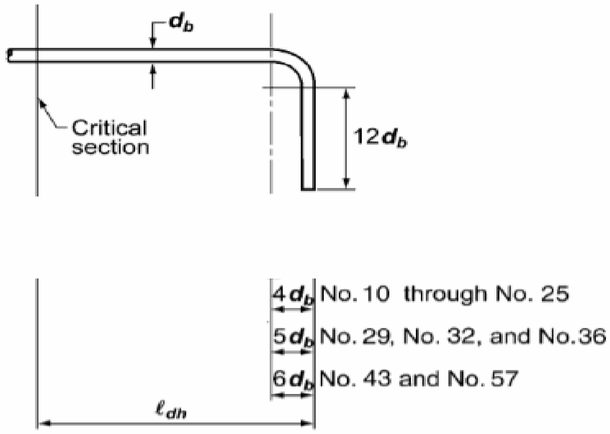

Fig. A.1 Hooked Bar Details for Development of Standard Hooks (ACI 318-11)

- **For the tested girders**

f_y = 707 MPa
f_c' = 35.3 MPa
d_b= 10 mm
Thus,

$$l_{dh} = \frac{0.24 * 707}{\sqrt{35.3}} * 10 = 285.6\ mm \approx 290\ mm$$

$$12d_b + 4d_b = 16d_b = 160\ mm$$