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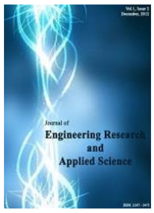

Effect of lap splice of GFRP reinforcements on development length

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Abstract
In the existing international FRP reinforced concrete codes ACI 440.1R-15 and CSA S6-10, equations for both development length and lap splice length are proposed. However, as a result of the experimental studies in the literature, it is stated that these equations give extremely safe results. Usually the lap splice length is determined by multiplying the development length by a constant coefficient. However, due to the differences between the coefficients recommended in the literature and regulations, it is unclear to what extent the development length is affected by the lap splice length. In this study, the effect of splice on development length is examined by accounting for the surface properties of GFRP and steel reinforcement. A total of 4 hinged beam specimens with no lap splice and 4 hinged beam specimens with lap splice, prepared with sand coated, wound and ribbed GFRP and steel reinforcement types, were tested under 4 point bending. The study yielded to the conclusion that the splice in steel reinforcement increases the development length, while surprisingly decreasing the development length in the FRP reinforcement.

Keywords: Development length; splice length; GFRP reinforcement; hinged beam; bond strength.

1. Introduction

As an alternative to steel reinforcement in reinforced concrete structures, the use of FRP reinforcement is increasing nowadays. FRP reinforcement is preferred over conventional steel reinforcement due to its properties including non-corrosive and non-magnetic nature, high tensile strength and lightness.

The bending behavior of FRP reinforced concrete elements significantly affects the bond between the FRP reinforcement and the concrete, which in turn affects the load bearing capacities, ductility and energy absorption capacities of the bending members. There are many variables affecting the bond between FRP reinforcement and concrete. These variables are reinforcing fiber type (carbon, glass, basalt), reinforcement surface feature (sand coated, ribbed, wound), embedment (bond) length, reinforcement diameter, concrete cover, concrete compressive strength and reinforcement position. In order to provide sufficient bond strength between the FRP reinforcement and the concrete, the embedment (development) length should be adequate in any case. However, the influence of the presence of lap splices in beams, obtained by overlapping separate reinforcing bars to reach continuous reinforcement, on the development length is not clear up to now.

To the best of knowledge of the authors, this topic has been studied very limitedly in the literature. Yun, Choi and Choi [1] analyzed 63 beams by finite element method for the determination of lap splice length. Their work indicated that if the FRP reinforcement ratio is above the balanced reinforcement ratio, the lap splice length should be 1.6 times the development length. Otherwise, the respective value should be 1.7 times the development length. Aly et al. [2] showed that the lap splice length values are $70d_b$ (d_b is the bar diameter) for 9.5 mm sand-coated CFRP reinforcement, 90 d_b for sand-coated CFRP reinforcement, 40 d_b for 15.9 mm sand coated GFRP reinforcement, 40 d_b for 15.1 mm sand coated GFRP.

Most of the international FRP codes specified the lap splice length by taking advantage of the development length. ACI 440.1R-15 [3] and CSA S6-10'da [4] recommended a development length value about 1.3 times the lap splice length.

However, as a result of the experimental studies conducted in the literature, development length equations are shown to be over-conservative, and therefore, the lap splice lengths from these equations

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are also too conservative. [5–9]. In addition, the development length equation recommended in the ACI 440.1R-15 [3] does not include some variables, such as the reinforcement surface properties, which significantly affects bond strength and bond behavior. In addition, the coefficients recommended in the literature and codes have an indefinite coefficient (lap splice length to development length ratio) between 1.3 and 1.7. Additionally, since the same coefficient for the lap splice length was used for all reinforcing bars with different surface texture properties in the codes, it is obvious that extensive studies on the relationship between the lap splice length and the development length for various types of reinforcement are needed.

In this study, the effect of splice on development length is examined for different reinforcement surface properties. Therefore, a total of 4 hinged beam specimens without splice and 4 spliced hinged beam specimens, prepared with sand-coated, wound and ribbed GFRP and steel reinforcement types, were tested under 4 point bending.

2. Experimental test program

2.1. Description of the specimens

The hinged beam test specimens consist of two parts, the splice hinged beam (Fig. 1) and un-splice hinged beam (Fig. 2). All specimens have a cross section of 160x240 mm^2 and a total length of 800 mm. Specimens were similar to the hinged beam specimen in the code EN 10080-2005 [10] and were modified in order to determine how development length was affected by the lap splice length.

There are 2 tensile reinforcements with 80mm ($10d_b$) embedment length in un-splice hinged specimen. There are 4 tensile reinforcements with 40mm ($5d_b$) embedment length in splice hinged specimen. In order to investigate the effect of GFRP reinforcement with various surface properties, fine sand-coated, ribbed and wound GFRP reinforcements with a nominal diameter of 8mm were used for tensile reinforcement.

In addition, specimen of steel reinforced beams with a nominal diameter of 8 mm were prepared to compare the test specimens prepared with GFRP reinforcements. Furthermore, all specimens are designed to be pullout failure.

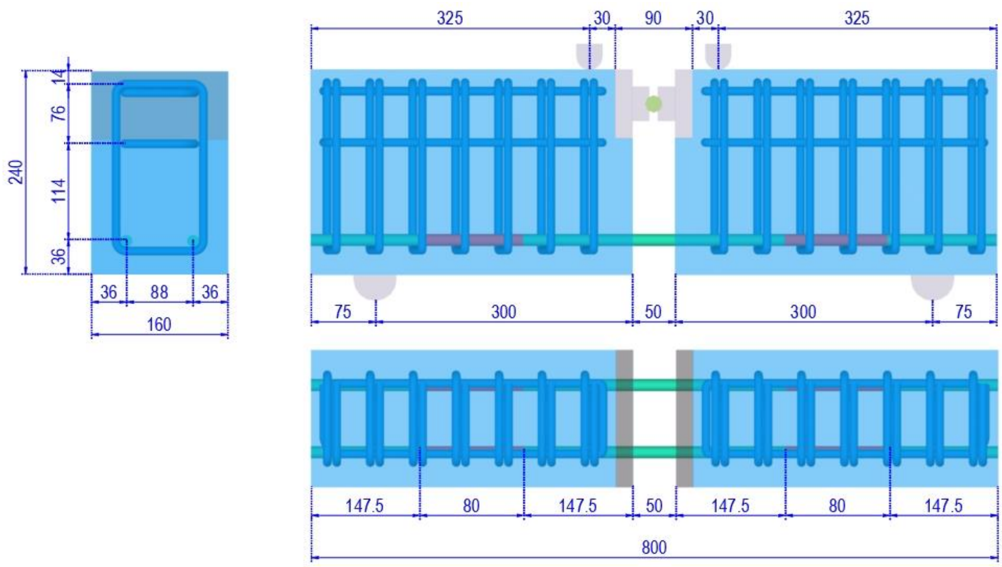


Figure 1. Reinforcement details of un-splice hinged beam and dimensions.

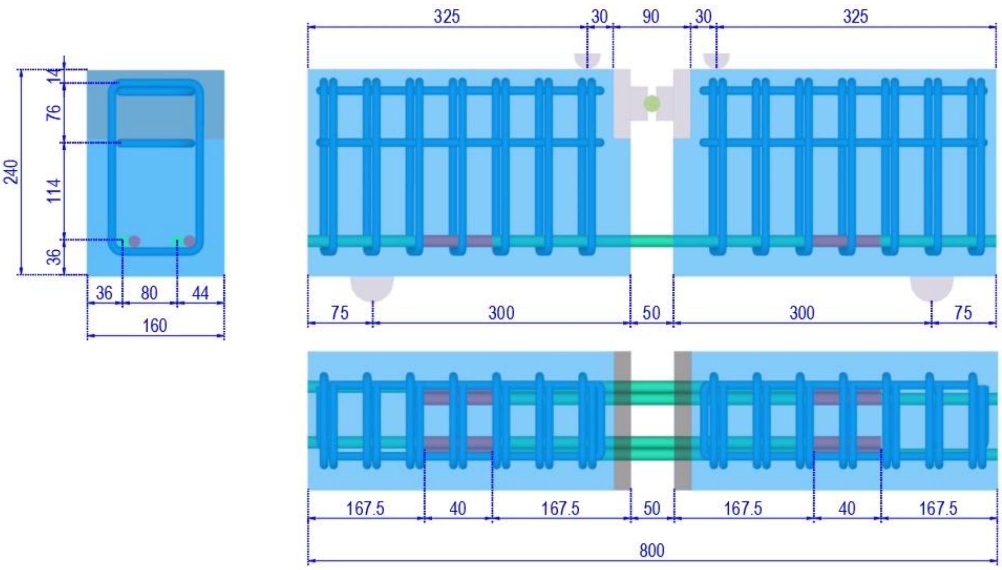


Figure 2. Reinforcement details of splice hinged beam and dimensions.

In all beams, using 8 mm diameter transverse steel reinforcement with 50 mm spacing, diagonal cracks in the shear span are prevented from affecting the beam behavior. In addition, in order to prevent possible horizontal shear cracking in the horizontal direction, 2Φ8 steel web reinforcement and 2Φ8 steel compression reinforcements have been used.

In the hinged beam specimen notations, first letter is reinforcement type (G = GFRP; S = Steel), the second and third letters indicate the reinforcement surface texture (Sf = fine-grained sandblasted; R = Ribbed; WO = Corrugated) and the "S" letter at the end indicates that the specimen has lap splice. For example, in GWO-S specimen; G is the GFRP reinforcement; WO indicates that the reinforcement surface feature is wound type, and S indicates that the specimen is made with splice.

2.2. Material properties

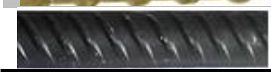
2.2.1. Concrete

In the test beams, ready mixed concrete with the largest aggregate diameter of 16mm was used to minimize the differences due to concrete. Concrete specimens with 150x150x150mm^3 size taken from concrete were tested after being kept for 28 days in the same conditions as beams. The average concrete compressive strength of these samples was determined as 35.90 MPa.

2.2.2. Bars

Tensile tests were performed to determine the yield and tensile strength of the steel reinforcements used in the study. However, the mechanical properties of FRP reinforcements were obtained from the manufacturers. The mechanical properties of the reinforcement used in the study are given in Table 1.

Table 1. Mechanical properties of reinforcement.

	Reinforcement Type	Surface Properties	Nominal Diameter (mm)	Outer Diameter (mm)	Yield Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
	Glass	Fine sand coated	8	8.2	-	>1000	>38
	Glass	Wound	8	8.9	-	>1000	>63.5
	Glass	Ribbed	8	8	-	>800	>50
	Steel	Ribbed	8	8	592	696	200

2.3. Test setup and measurement

A total of 4 un-splice hinged beam specimens and 4 splice hinged beam specimens prepared with sand coated, wound and ribbed GFRP and steel reinforcement types, were tested under 4 point bending. The test specimens were placed on 2 rollers to allow the system to act as a simple beam.

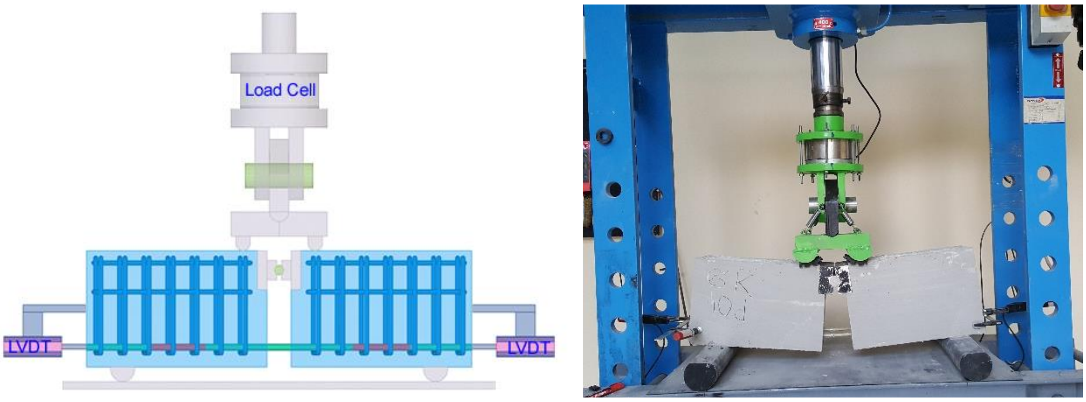


Figure 3. The experimental setup.

In the experiments, the forces applied to the beams were measured with a load cell having a capacity of 200 kN. Two linear potentiometers (LVDTs) which were placed diagonally at the ends of the reinforcement were used to measure reinforcement slip in the hinged beam specimen (Fig. 3).

3. Test results and discussions

The test results of the hinged beams prepared with various types of reinforcement under four-point bending are presented in Table 2.

The hinged beam specimens exhibit simple truss behavior under the applied force due to the loading and support conditions in the test. Therefore, the average bond stresses between the reinforcement and the concrete were calculated by Equation 1 where the beam dimensions were included.

$$u = \frac{0.762F_a}{\pi d_b l_e n} \quad (1)$$

Where, u=bond strength (N/mm^2); F_a=applied load (kN); d_b=nominal diameter of reinforcement (mm); l_e=embedment length or splice length(mm); n=number of tensile reinforcement.

Table 2. Test results.

Specimen description	Rebar Type	Rebar Surface Type	Splice	Max. Load (kN)	Max. Bond Strength (MPa)	Failure Type
SR	Steel	Ribbed	-	90.63	17.18	Bar Yielding
SR-S	Steel	Ribbed	Avaliable	76.88	14.57	Pullout
GR	Glass	Ribbed	-	79.55	15.08	Pullout
GR-S	Glass	Ribbed	Avaliable	93.08	17.64	Pullout
GSf	Glass	Fine sand coated	-	41.90	7.75	Pullout
GSf-S	Glass	Fine sand coated	Avaliable	46.71	8.64	Pullout
GWO	Glass	Wound	-	66.86	11.39	Pullout
GWO-S	Glass	Wound	Avaliable	71.33	12.15	Pullout

3.1. Effect of reinforcement surface property on bond strength

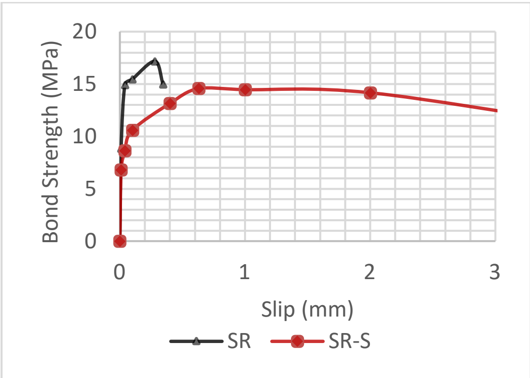
As can be seen from Table 2, among the un-splice hinged specimens, SR reinforced specimen has the highest bond strength value. The ratios of the maximum bond strength of GR, GSf and GWO reinforced specimens to the bond strength of SR reinforced specimen were 0.88, 0.45 and 0.66, respectively.

However, among the spliced hinged specimens, GR-S reinforced specimen has highest bond strength. The ratios of maximum bond strength of the GR-S, GSf-S and GWO-S reinforced specimens to the bond strength of the SR-S reinforced specimen were 1.21, 0.59 and 0.83, respectively.

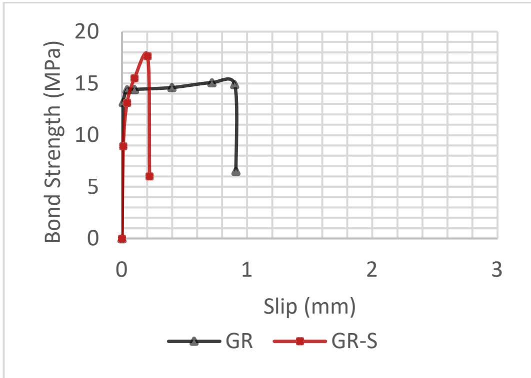
I is evident from the test results of both splice and un-splice specimen that the reinforcement surface properties significantly affects the development length. In addition, the reinforcement with the mechanical interlocking (ribbed) was found to have the highest bond strength values. On the other hand, the bond strength of GSf reinforcements, which provides the bond by friction, has the lowest bond strength values. The bond strength of the GWO reinforced specimen is between the respective values of specimens transferring the stresses by mechanical locking (GR) or friction (Gsf), as expected.

3.2. Effect of lap splice on development length

When the bond strength-slip graphs of the un-splice and splice hinged beams formed with steel reinforcements (Fig. 4.a) were examined, the bond strength of the reinforcements at the 0.01mm slip were measured as 8.84 and 6.80MPa respectively. As can be seen from Fig. 4.a, the stiffness of the beam decreased by 23% at slip of 0.01mm. Un-splice steel reinforcing beams, yield has occurred in the reinforcement since full bond occurs. When the maximum bond strength is examined, the ratio of bond strength in the un-splice specimen to bond strength in splice specimen is 1.18.



(a)



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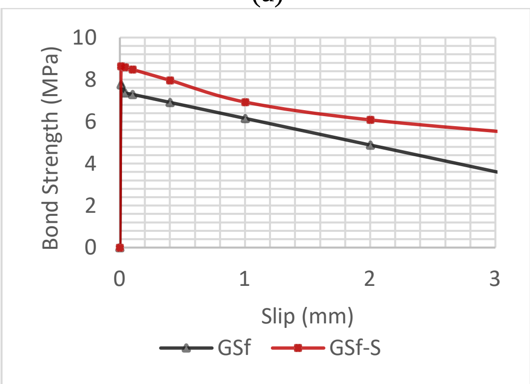

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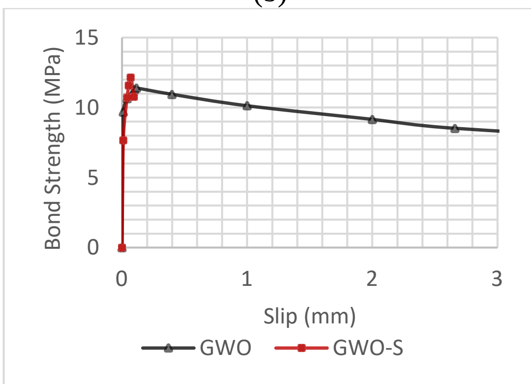

(d)

Şekil 4. Bond Strength-slip diagrams (a)Steel-reinforced specimens (b)Ribbed GFRP-reinforced specimens (c)Fine san coated GFRP-reinforced specimens (d)Wound GFRP reinforced specimens.

When the bond strength-slip graphs of the un-splice and splice hinged beams formed with GFRP reinforcements (Fig. 4.b.c.d) were examined, the bond strength of the reinforcements at the 0.01mm slip were measured as 13.14 and 8.92MPa for GR reinforced specimens, 7.75 and 8.64 MPa for GSf reinforced specimens, 9.69 and 7.67MPa for GWO reinforced specimens, respectively. As can be seen from Figure 4.b.c.d, at 0.01mm slip, beam stiffness decreased by 32% and 21% similar to steel reinforcement in GR reinforced specimen and GWO reinforced specimen. However, the initial beam stiffness of GSf reinforced specimen increased by 11%.

When the maximum adherence values of GFRP-reinforced samples are examined, the ratio of the maximum bond strength between un-splice specimen and splice specimen is 0.85 in GR reinforced specimens, 0.90 in GSf reinforced specimens and 0.94 in GWO reinforced specimens.

From these values, it can be concluded that the lap splice length can be obtained by reducing the respective development length by 6 % to 15 %. Although these results seem unexpected, the lack of experimental studies on the lap splice length and the development length with the same test conditions and with the same type of experiment is far from substantiating the present results. This may be explained by the fact that, when the FRP reinforcements come into contact with each other, the peeling in the reinforcement surface are partially prevented by the softening effect and the bond strength increases due to the increased friction.

4.Conclusions

In this study, the effect of splice on development length was studied for different reinforcement surface properties (fine sand coated, ribbed and wound). In this context, a total of 8 hinged beams with splice and un-splice were tested. The study yielded to the following conclusions:

- GFRP reinforcement-concrete bond strength is significantly affected by reinforcement surface properties. The ratio of maximum bond strength of GR, GSf and GWO reinforced specimens to the bond strength of SR reinforced specimen was 0.88, 0.45 and 0.66, respectively.
- It was observed that the length of lap splice in steel reinforcement was 1.18 times the development length of the same bar on average. However, the FRP reinforcement-concrete bond strength was surprisingly higher in the splice hinged specimens than the un-splice hinged specimens. Lap spliced lengths in GR, GSf and GWO reinforced specimens were 0.85, 0.90 and 0.94 times of development length, respectively.

Acknowledgement

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