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Debonding Failure of Externally Bonded GFRP Sheet on Flexural Strengthening of Reinforced Concrete Beams

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Abstract:* *GFRP sheets are widely used for multipurpose retrofitting of reinforced concrete members by bonding to the external surfaces. The main problems for the application of this material is the debonding of the bonded sheet from the concrete surface. In order to investigate the debonding behavior, this study represents the experimental work of the strengthening reinforced concrete beams using externally Glass Fiber Reinforced Polymer (GFRP). Six RC beams with 3.3 m length and with dimensions of 150.0 mm x200.0 mm were tested. The specimens consisted of three normal beams and three strengthened beams. One layer of the GFRP sheet was bonded on the bottom face of the strengthened beam. The results indicated that the flexural capacity of the strengthened beam enhanced up to 4.3% compared to the normal beam. Moreover, all the strengthened beams failed by the debonding of the bonded sheet, which was initiated by local debonding on the critical bonding stress location.

Keywords: **flexural strengthening, externally bonded, debonding, GFRP.**

I. BACKGROUND

The deterioration of reinforced concrete (RC) structures has become a concern in many countries. This deterioration causes an excessive reduction of flexural capacity as well as stiffness. The damaged structures are required to be immediately retrofitted. There are some conventional strengthening methods to deal with this problem such as steel plate jacket, external post-tensioning tendons, etc. However, the implementation of those methods requires large equipment and consumes a lot of time and labor.

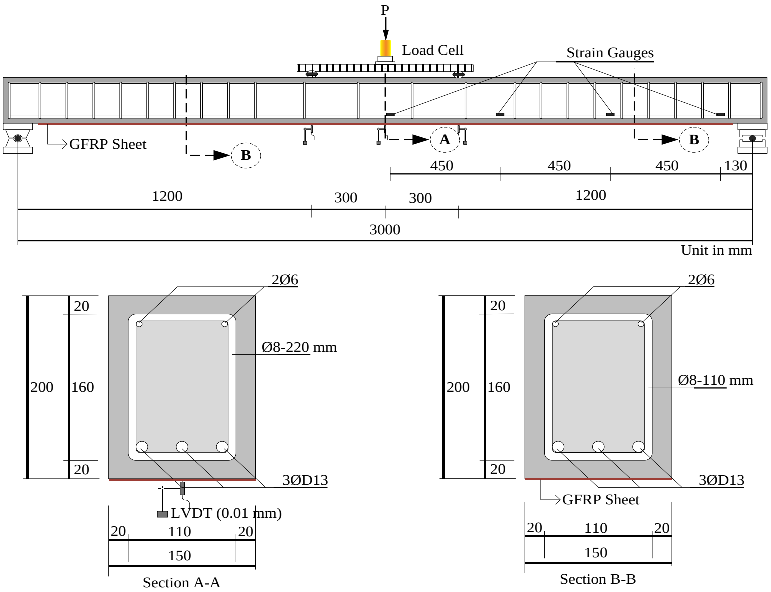
One of the strengthening materials is fiber reinforced polymer. The application of various types of fiber reinforced polymer in RC members has been increased in the last 20 years1), 2). Glass Fiber Reinforced Polymer (GFRP) sheet is a type of FRP, which gains strength by impregnating glass fibers sheets with a polymer matric composite material. The major advantage of GFRP sheets include high tensile strength and corrosion resistance, ease of construction and less impact to the original geometry. Thus, GFRP sheets are widely used for multipurpose retrofitting of RC members by bonding to the external surfaces. In case of flexural strengthening, the sheets are bonded externally to the tension face of the members so that the high tensile strength of GFRP sheets can be utilized.

Available experimental data indicate that almost all beams strengthened by complete wrapping fail due to FRP rupture. It consists, if it occurs, in a brittle failure at the interface between structural members and strengthening materials. Debonding occurs due to many factors such as high stress concentration at the cracks. Debonding at the interface between FRP and concrete can reduce the capacity of the structure significantly, which caused a premature failure at the reinforced concrete strengthened with FRP[3), 4)]. The objective of this study was to investigate the debonding failure of externally bonded GFRP sheet on the flexural strengthening of reinforced concrete beams.

II. SPECIMENS AND TEST SET-UP

A. Specimens

A total six RC beams with 3.3 m length and with dimensions of 150.0 mm x200.0 mm were tested as shown in **Fig. 1**. The specimens consisted of three normal beams and three strengthened beams. The normal beams (BN1, BN2 and BN3) were the control specimen. Meanwhile, the strengthened beams (BGA1, BGA2 and BGA3) were strengthened by using one layer of GFRP sheet on the bottom face of the beam.



Section A-A

Section B-B

Fig. 1: Details of specimen

B. Materials

The concrete was designed with the average 28-day cylinder compressive strength of 25 MPa. The unidirectional GFRP sheets were used and bonded to the concrete surface using an epoxy resin. The properties of GFRP sheet which are obtained from the supplier are given in **Table 1**.

Table 1: Properties of GFRP sheet

Condition	Thickness (mm)	Tensile strength (MPa)	Tensile modulus (GPa)	Ultimate elongation (%)
Typical dry fiber	1.3	3240	72.4	4.5
Composite gross laminate	0.36	575	26.1	2.2

Source: Fyfe Company

C. Fabrication Procedures

The longitudinal GFRP sheets were bonded to the bottom face of the beams oriented to the beam axis by a wet-layup procedure. The U-shaped anchorage sheet was bonded in the transverse direction of the beam with the same method. The U-shaped anchorage sheet aims to prevent the sheet end failure in the non-tested span. The fabrication procedures as follow: First, the concrete surfaces were slightly polished to make them smooth and remove the degradation layer. Then, a surface primer was applied (**Fig. 2(a)**). After that, a GFRP sheet was bonded to the concrete surface by impregnating and hardening with the epoxy resin (**Figs. 2(b)** and **(c)**). The air bubbles between the concrete surface and GFRP sheet were removed by roller brushes. Finally, a coat layer of impregnating resin was pasted. The specimens were cured in room temperature for at least three days before the loading test.

a. Applying epoxy to GFRP **b. Impregnation of epoxy** **c. Bonding GFRP to concrete**

Fig. 2: GFRP Application

D. Instrumentations and loading methods

The beams were subjected to a static four-point bending test as shown in **Fig. 3**. The load was applied by a hydraulic jack setup on a steel contrast frame firmly anchored to the lab floor. The jack was controlled by a hydraulic control unit that imposed the prescribed displacement with the rate of 0.2 mm/sec. A load cell with the capacity of 200 kN was placed between the jack and a distributor beam to measure the applied force precisely. During the loading, all of the measurements were recorded through a data logger. The crack propagations were drawn and marked at each load level during the loading tests. The strain gauges were attached to the tensile reinforcement as shown in **Fig. 1**. Several strain gauges were also attached at the surface of concrete and GFRP sheet as shown in **Figs. 4,** and **5**, respectively. The linear variable differential transducers were used to monitor the vertical displacement of specimens. One transducer was set at the mid-span and the other two were located under the loading point.

III. RESULTS

A. Ultimate Capacity

Table 2 summarizes the experimental results. It was seen that the ultimate loads of the normal beams BN1, BN2 and BN3 were 30.04 kN, 30.57 kN and 30.70 kN, respectively with the average of ultimate load of 30.44 kN. Meanwhile, the ultimate load of strengthened beams BGA1, BGA2 and BGA3 were 31.91 kN, 30.84 kN and 32.51 kN with the average of ultimate load of 31.75 kN. The results indicated that by using one layer of the

GFRP sheet, flexural capacity of the strengthened beams increased by 4.3% compared to the normal beams (BN).The ultimate load on the strengthened beam increased due to the contribution of the GFRP sheet on the bottom face of the beam to resist the applied load. After the longitudinal rebars yielding, the beam could resist the applied load as long as the GFRP sheet still bonded on the concrete surface5).

A. Load-Displacement Relationship

Table 2 summarizes the maximum load and displacement for all beams. The displacement reported herewas the displacement at the midspan of the beam. From **Table 2**, it was seen that the average maximum load and displacement in the normal beam (BN) was 30.04 kN and 73.74 mm, respectively. Meanwhile the average maximum load and displacement in the strengthened beam (BGA) was 30.04 kN and 73.74 mm, respectively. The results indicated that the GFRP sheet decreased the mid-span deflection of the beam.

Table 2: Summary of experimental results

Beam		Ultimate load (kN)	Mid-span displacement (mm)	Failure mode
Normal Beam	BN1	30.0	73.74	Flexural failure
	BN1	30.6	90.80	
	BN1	30.7	71.83	
	Average	**30.44**	**78.79**	
Strengthened beam (one layer GFRP sheet)	BGA1	31.9	33.69	IC debonding
	BGA2	30.8	28.62	IC debonding
	BGA3	32.5	37.03	FRP rupture
	Average	**30.75**	**33.13**	

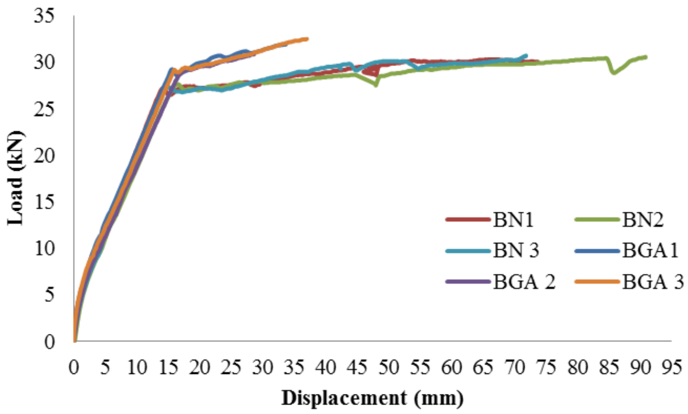


Fig. 6: Load-displacement curves

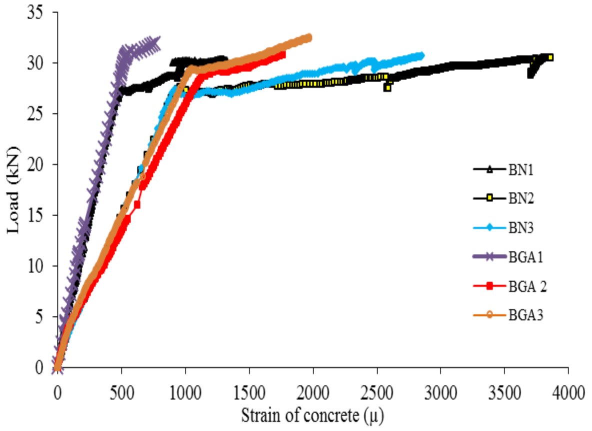


Fig. 7:Load-strain of concrete

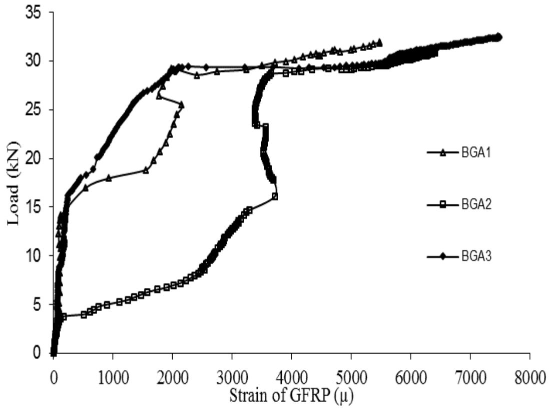


Fig. 8:Load-strain of GFRP

Figure 6 shows the load-displacement curves. As can be seen, the normal beams (BN1, BN2 and BN3) showed a similar behavior with the strengthened beams (BGA1, BGA2 and BGA3) until the yielding load. Beyond the yielding load, the stiffness of strengthened beam was stiffer than the normal one. Thus, by using the GFRP sheet on the bottom of the beams, the post-yielding flexural stiffness of the strengthened beams was significantly enhanced from that of the normal beam.

B. Load-Strain Relationship

Figure 7 illustrates the development of the compressive strains in the top fiber of concrete at the midspan. **Figure 8** shows the relationship between the applied load and the tensile strain in the bonded sheet. It was observed in **Fig. 7** that the ultimate compressive strains of concrete at the BN1, BN2 and BN3 were 900□ □, 3856□ □ and 2852□ □, respectively. Meanwhile, the ultimate compressive strains of concrete at the BGA1, BGA2 and BGA3 were758□ □, 1760□ □and 1969□ □, respectively. The results implied that the normal beams failed when the concrete reached the ultimate strain of concrete (assumed to be equal to 3000□ □ □). By observation, the concrete crushed at the compressions zone of concrete as shown in **Fig. 9(a)**. On the other hand, the strengthened beam failed before reached the ultimate strain of concrete.

Figure 9 shows the relationship between the load and tensile strain in the bonded sheet. It was seen that the measured the tensile strain in the bonded sheet at the peak load for BGA1, BGA2 and BGA3 was 5471□ □, 6397□ □, and 7454□ □, respectively. These values were smaller than the ultimate strain (□$_{fu}$) of GFRP sheet (equal to 20000□ □ □). This indicated that the premature failure occurred at the strengthened beams due to the debonding of the GFRP sheet (**Fig. 9(b)**).

a. Normal beam **b. Strengthened beam**

Fig. 9: Failure pattern

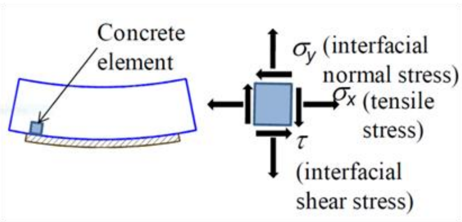


Fig. 10: Stress acting in a concrete element

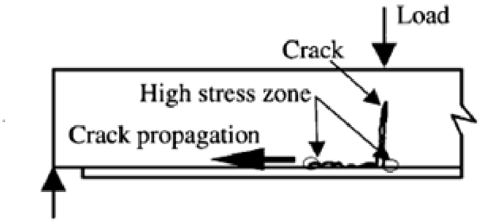


Fig. 11: Failure mode due to IC debonding

C. Failure mode and mechanism

The normal beam failed in flexure, while the strengthened beam failed by debonding as shown in **Figs. 9(a)** and **(b)**, respectively. The failure behaviors of the strengthened beams were explained by an interfacial stress model6), 7) introduced in **Fig. 10**. The stress acting in a concrete element near the interface between concrete and bonded sheets consist of interfacial shear stress (□), interfacial normal stress ($\square_y$), and tensile stress ($\square_x$). The tensile stress at the bottom of the concrete section is due to a bending moment at a considered section. Meanwhile the interfacial stresses show the high concentration at the end of the bonded sheets due to the discontinuity in flexural stiffness. The debonding of the bonded sheets is initiated when the principal stress, which is the combination of three stress components, exceeds the strength of the weakest element. Final debonding was initiated by local debonding on the critical bonding stress location.

The mechanism of debonding may be summarized as follows (**Fig. 11**), when a major flexural crack is formed in the concrete, the tensile stresses released by the cracked concrete are transferred to the FRP sheet. As a result, high local interfacial stresses between the FRP sheet and the concrete are induced near the crack. As the applied loading increases further, the tensile stresses in the sheet and hence the interfacial stresses between the FRP sheet and the concrete near the crack also increase. When these stresses reachcritical values, debonding initiates at the crack and then propagates towards one of the sheet ends8).

IV. CONCLUSIONS

The investigation of debonding behavior of externally bonded GFRP sheet on flexural strengthening of reinforced concrete beams has been presented. The results are summarized as follows:

a. Externally bonded GFRP sheet method effective to enhance the flexural capacity as well as the stiffness of the reinforced concrete beam. The flexural capacity was enhanced up to 4.3%than the normal beam.

b. The strengthened beams failed by the debonding of the bonded sheet, which was induced by the flexural cracks at the constant moment region.

c. Final debonding was initiated by local debonding on the critical bonding stress location.

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REFERENCES

[1] Bakis, C. E., Bank, L. C., Brown, V. L., Consenza, E., Davalos, J. F., Lesko, J. J., Machida, A., Rizkalla, S. H. and Triantafillou, T. C. (2002). Fiber-reinforced polymer composites for construction-state-of-the-art review, Journal of Composites for Construction, ASCE, Vol. 6, No. 2, pp. 73-87.

[2] Wu, Z., Wang, Z. and Iwashita, K. (2007). State-of-the-art of advanced FRP applications in civil infrastructure in Japan, Composites and Polycon, Vol. 37, pp. 1-17.

[3] Djamaluddin, R., Akkas, A.M, Irmawaty, R. (2013)., Debonding behavior of GFRP sheet reinforced concrete, Singapore.

[4] Djamaluddin, R. and Sultan, M. A. Bond Characteristics of GFRP Sheet on Strengthened Concrete Beams due to Flexural Loading, Jeju Island, Korea, IACSIT, The 4th International Conference on Civil Engineering and Materials (ICCEM 2014).

[5] Nguyen, T., T., D., Matsumoto, K., Sato, Y., Iwasaki, A., Tsutsumi, T., and Niwa J. (2014). Effects of externally bonded CFRP sheets on flexural strengthening of pretensioned prestressed concrete beams having ruptured strands, Journal of JSCE, Vol. 2, pp. 25-38.

[6] Teng, J. G. and Chen, J. F. (2009). Mechanics of debodning in FRP-plated RC beams, Proceeding of the Institution of Civil Engineers, Structures and Building, Vol. 162, pp. 335-345.

[7] Smith, S. T. and Teng, J. G. (2001). Interfacial stress in plated beams, Engineering Structures, Vol. 23, pp. 857-871.

[8] Bengar, H. A. and Maghsoudi, A. A. (2010). Experimental investigations and verification of debonding strain of RHSC continuous beams strengthened in flexure with externally bonded FRPs, Materials and Structures, Vol. 43, pp. 815-837.