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The bonding strength of GFRP bars embedded within concrete under direct pull-out test

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Abstract. Most of the reinforced concrete (RC) structures in the marine environment attacked with corrosion of steel reinforcements that required costly repairs or replacements. The utilization of FRP bars as a non-corrosion material is one of the solutions to increase the durability of RC structures in the marine environment. The innovation of using FRP bars should be developed to improve the quality and reduce the construction cost such as by removing the concrete cover and shear rebar. By removing the concrete cover, the depth of the beam can be minimized without reducing the effective depth of the beam. To substitute the conventional shear rebar, the GFRP sheet strip will be attached to the shear span after concrete hardened. However, the problem is that the bonding area between FRP bars and concrete reduced due to the removal of concrete cover. Therefore, before applying this innovation to the beams' structure, the pull-out test should be conducted in order to clarify this behavior. The influence of the location of FRP bars and the effect of the U-Wrap GFRP sheet on the bond-slip curves will be analyzed. It is expected from this study that the bonding strength between FRP bars and concrete does not reduce significantly and hence, the innovation for constructing RC beams without a concrete cover on the tensile zone can be applied.

1. Introduction

The utilization of concrete as a construction material for civil infrastructure is still more dominant than other materials. Concrete is a material formed from aggregate, cement and water through hydrolysis reaction where there is binding of cement to aggregates. The water in the concrete is lost in the hydrolysis reaction and partially forms a pore in the concrete causing the concrete to become non-impermeable material. However, the concrete material has several advantages such as having high strength and stiffness, cheap, easy to form and low maintenance cost. These advantages make the use of very wide concrete materials in the construction industry including for building structures on coastal areas or in the influence of the marine environment such as piers, breakwater structures, bridge piles, the foundation of coastal buildings.

In reinforced concrete elements that carrying a flexural load, the cross-section of the beam suffers compressive bending stress and tensile bending stress. The compressive stress is retained by the concrete element and the tensile stress is held by the steel reinforcement. The nominal flexural moment of the cross-section is affected by the effective depth, the area of the reinforcement, and the



compressive strength of the concrete. The concrete cover in the reinforced concrete element serves to protect the steel reinforcement against corrosion and adds to the concrete-steel bonded. The more aggressive environment the thicker concrete cover is given so that the structure dimension increases.

In marine or coastal environments where contact with seawater can't be avoided, reinforced concrete structures that use steel reinforcement may be vulnerable to corrosion as shown in figure 1. Corrosion of steel bar in concrete element still vulnerable even though using thick concrete cover. Corrosion in steel reinforcement is one of the main factors causing the declining strength of reinforced concrete structures [1]. Corrosion reduces the area of the steel so as to decrease its mechanical properties, cracking or separating on the concrete cover and reducing the bond performance of the concrete.



Figure 1. Damage to concrete structures due to corrosion.

When environmental conditions are very aggressive, the use of FRP materials as reinforcement on structural elements is the right choice. The advantages of FRP materials in addition to corrosion resistance include high strength, magnetic-induced, good fatigue resistance, lightweight and low thermal and electrical conductivity [2]. Given the potential of the FRP Bar reinforcement, the use of concrete cover can be ignored. If the concrete cover is removed, then the cross-sectional height, the volume of concrete and the weight of the structure can be reduced, without reducing the effective height of the cross-section.

Nowadays, the use of FRP materials is more on structural strengthening. The structural strengthening technology using FRP materials in the current concrete structure comprises an external reinforcement of an FRP Sheet attached by resin on a concrete surface and an FRP Bar or FRP Strip mounted on a groove prepared on a concrete surface and attached by a resin (Near Surface Mounted). The researcher examined the effect of incorporating the NSM FRP Bar and U-Wrap FRP Sheet methods to the flexural behavior of reinforced concrete beam in static loading [3]. The results showed that the combined NSM-FRP Bar and U-Wrap FRP Sheet along the beam, the NSM-FRP Bar and the U-Wrap FRP Sheet along the shear area increased the bending capacity above 60% against the beam without strengthening. The use of FRP BAR replacing steel reinforcement has been made and several concrete standardizations such as ACI, NSA, ISIS, JSCE have established reinforced concrete design guidelines that use FRP Bar instead of steel reinforcement [4].

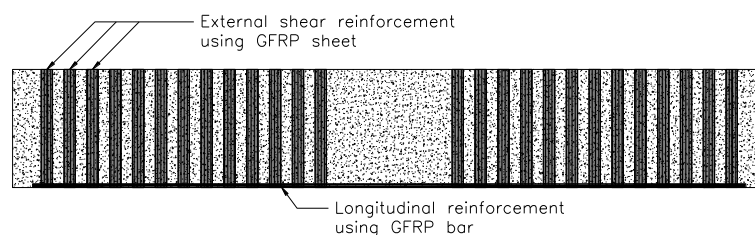


Figure 2. FRP reinforced concrete beams without concrete cover with FRP-Sheet as shear reinforcement.

The innovation of reinforced concrete structures using FRP Bar as longitudinal reinforcement and FRP sheet as shear reinforcement that easy implementation and efficient without reducing the moment capacity and shear capacity need to be developed. The proposed innovation is similar to the NSM (Near Surface Mounted) method where straight FRP bar is placed on the tension side of the beam. Unlike NSM methods that use grooved on hard concrete and then attach resin in it, the bond between FRP bars and concrete is obtained when the concrete is hard. Implementation of reinforced concrete casting work with this method is very easy where the FRP bar is only placed on formwork without a spacer and then cast. Further shear reinforcement in the beam is given after the concrete hardens by the U-Wrap FRP Sheet method according to required shear capacity. Illustration of FRP concrete beam without a concrete cover can be seen in figure 2.

The problem with this innovation is the bond between the FRP bar with the concrete around it where the concrete cover is removed. The research revealed that the bond between the reinforcement and the concrete is an important design parameter that affects the development length, deflection, spacing and crack width [5]. According to the research, the bonding between FRP and concrete reinforcement depends on several factors such as friction by the roughness of the FRP rebar surface, mechanical locking of FRP rebar to concrete, chemical bonds, hydrostatic pressure to FRP rebar due to hardened concrete shrinkage and swelling of FRP rebars due to changes in temperature and water absorption [6]. Pull-out testing has been commonly adopted as a practical approach to assessing the bond performance for both steel and FRP bars embedded in concrete. Therefore, before applying this innovation to the beams' structure, the pull-out test should be conducted in order to clarify this behavior. The influence of the location of FRP bars and the effect of the GFRP sheet on the bond-slip curves will be analyzed.

2. Experimental program

2.1 Specimen preparation

The specimens used were spiral GFRP bar diameter $\frac{1}{2}$ " (12.7 mm) embedded in a concrete cube with dimensions of 20 cm x 20 cm x 20 cm. The embedment depth of GFRP Bar in the concrete is taken 5db (62 mm) as bonded length refers to the ASTM D7205 standard [7]. The specimen model consists of three types: (1). GFRP Bar embedded in the center of the concrete cube (2). GFRP Bar embedded at the edge of the concrete cube (3). GFRP Bar embedded on the edge of the concrete cube then covered with GFRP sheet as wide as 62 mm. Specimens detail can be seen in figure 3.

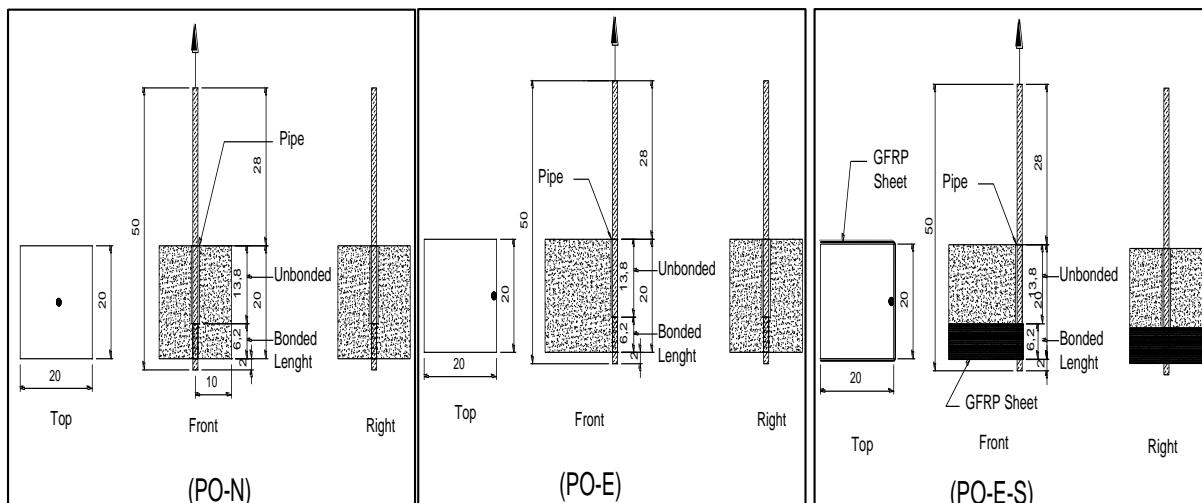


Figure 3. Specimens detail.

2.1.1 Materials

GFRP Bar and GFRP Sheet used is Tyfo Fiber Rebar production FYFE, Material Properties of GFRP bar can be seen in figure 4. The properties of the GFRP Bar can be seen in table 1. Concrete cube specimens with a compressive strength of f'_c 20 MPa is prepared based on the DOE formula.

Table 1. Mechanical properties of the GFRP bar.

Bar diameter	The nominal cross-sectional area (mm ²)	Guaranteed tensile strength f_{tu}^{**} (MPa)	Modulus of elasticity (Gpa)	Ultimate Elongation (%)
12.7 (#4)	129	708	43.9	1.79

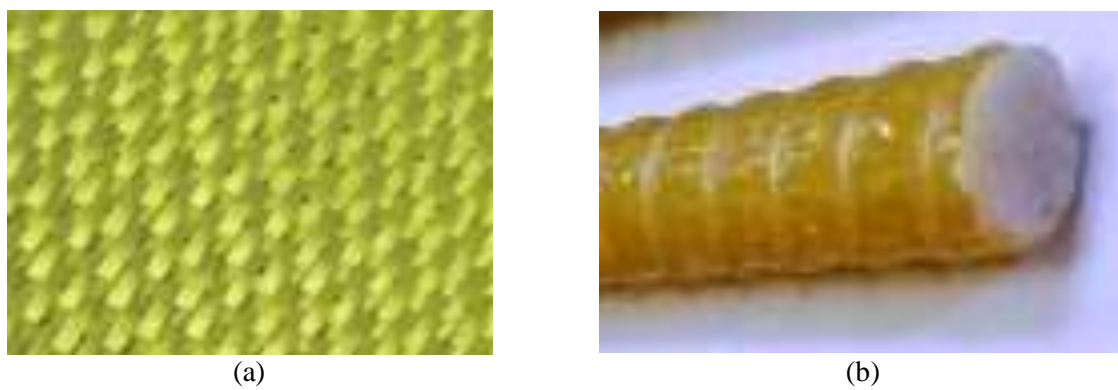


Figure 4. Fiber-reinforced polymer materials (a) GFRP sheet (b) GFRP bar.

2.1.2 Preparation

After casting, the cube specimen was curing using a wetted burlap sack to equalize the curing treatment of the beam sample. After 26 days all specimens were dried and on day 27, Specimen (PO-E-S) filleted its edges by grinding machine then wrapped it with GFRP Sheet. The wrapping method as a recommendation of ACI 440.2R-08 [8]. Furthermore, the instrument (strain gauge) is applied to read the strain on each specimen. Strain gauge position as shown in figure 5. Tests of specimens were performed when the age of concrete reached 28 days and the curing time of the U-wrap GFRP sheet reached three days.

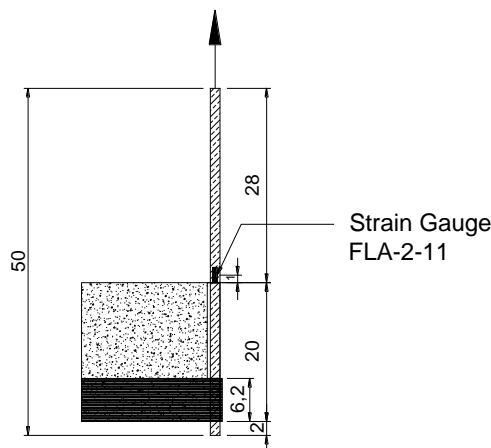


Figure 5. Strain gauge position.

2.2 Testing setup

Pull out Test used UTM (Universal Testing Machine) with Capacity of 1000 kN. The specimens were inserted in a cage then tightened so it won't wobble and ensure the position of the GFRP rod was perpendicular to the pulled cube side to minimize moments or frictions. The displacement control was set at 1.2 mm/min, less than 1.3 mm / min based on ACI 440 3R. The testing setup installation can be seen in figure 5.

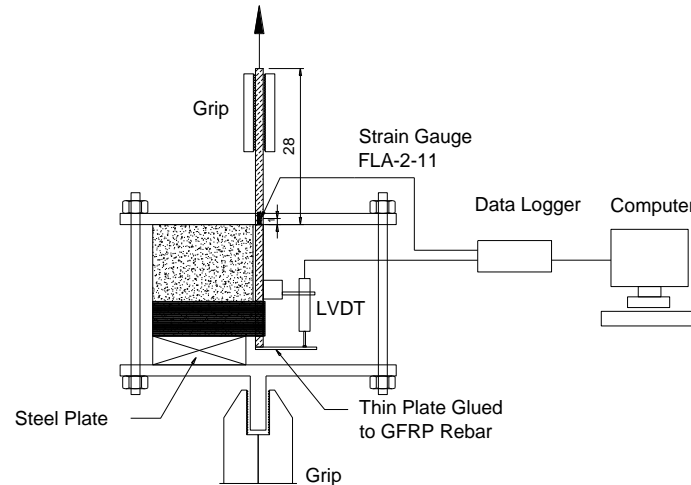


Figure 6. Testing setup.

3. Experimental result and discussion

3.1 Average bond stress

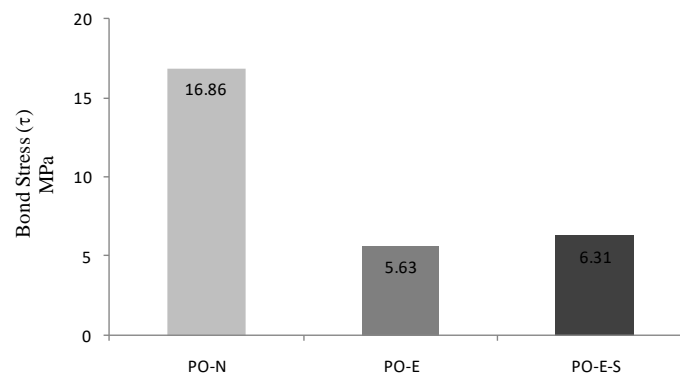


Figure 7. Bond stress of specimens.

The bonding stress of FRP bar to the concrete is calculated based on the formula [9]:

$$\tau = \frac{P}{\pi d_b l_b} \quad (1)$$

where P is the maximum tensile load, d_b is the nominal diameter of FRP bar, l_b is the length of FRP bar bonded to concrete. Bond stress of specimen PO-N, PO-E, PO-E-S are 16.86 MPa, 5.63 MPa, 6.31 MPa respectively as shown in figure 7. If the bond stress value of PO-E and PO-E-S compared with a bond stress value of PO-N, there was a reduction of 66.6% and 62.56% respectively. The average stress shown in figure 6 indicates that the removal of the concrete cover has decreased the bond strength of the reinforcement to the concrete. This result was parallel with tests performed by another researcher which also found a 15% to 30% reduction in stresses at maximum bonding with a

concentric pullout test compared with the eccentric pullout test with a concrete cover width of 20 mm to 10 mm [10]. The addition of external reinforcement as shear reinforcement by the U-Wrap method with the FRP sheet just improved the bond stress by 4%.

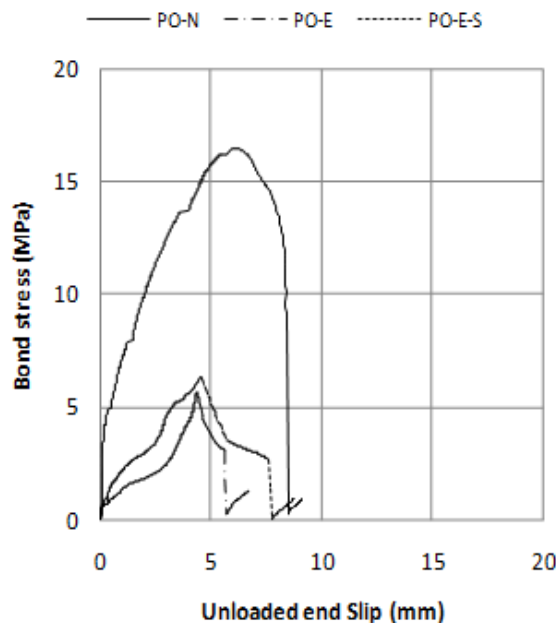


Figure 8. Bond stress – end slip relationship.

3.2 Bond stress- end slip relationship

The bond stress due to the adhesion between the bar reinforcement and the concrete indicated by the vertical line in the bond stress-end slip relationship's graph. The behavior of bonding strength between concrete and steel bars has been investigated by some researchers [11-12].

The vertical line found at the beginning of the loading where the slip between the bar reinforcement and the concrete has not occurred. Bond stress caused by adhesion in PO-N, PO-E, PO-E-S were 2.39 MPa, 0.582 MPa, 0.870 Mpa respectively as shown in figure 7. Bond stress after these values until collapse may be caused by mechanical bonds between rebar and concrete.

In figure 7 it is seen that the angle of the curve is different between the three samples. The PO-N sample has a larger inclination angle compared to the PO-E-S sample and the PO-E-S sample has a greater inclination angle than the PO-E sample before reaching the maximum stress. The magnitude of the slope angle of the curve indicates the strength of the reinforcement-concrete bonded before it is delamination [10]. PO-N curve length Post-delamination until rupture and PO-E-S curve length post-delamination until rupture similar that indicates the use of GFRP Sheet as external reinforcement could retain bonding stress longer after delamination or concrete splitting.

3.3 Failure mode

Shows that the failure mode in the concentric pull test sample is the failure to pull out, while in the cube sample without the concrete blanket with the test of the eccentric pull test is the splitting failure in the concrete. The pullout failure mode of sample PO-N caused by concrete peeled off as shown in figure 9 (a).

Failure mode on reinforced concrete reinforced without concrete cover with U-wrap GFRP Sheet also shows splitting failure in concrete. The observations show that U-Wrap GFRP Sheet has delamination around the reinforcement. There is the possibility of a concrete crack around the reinforcement due to the delamination of the GFRP sheet so that confinement of GFRP sheet to the concrete around the reinforcement becomes weak.

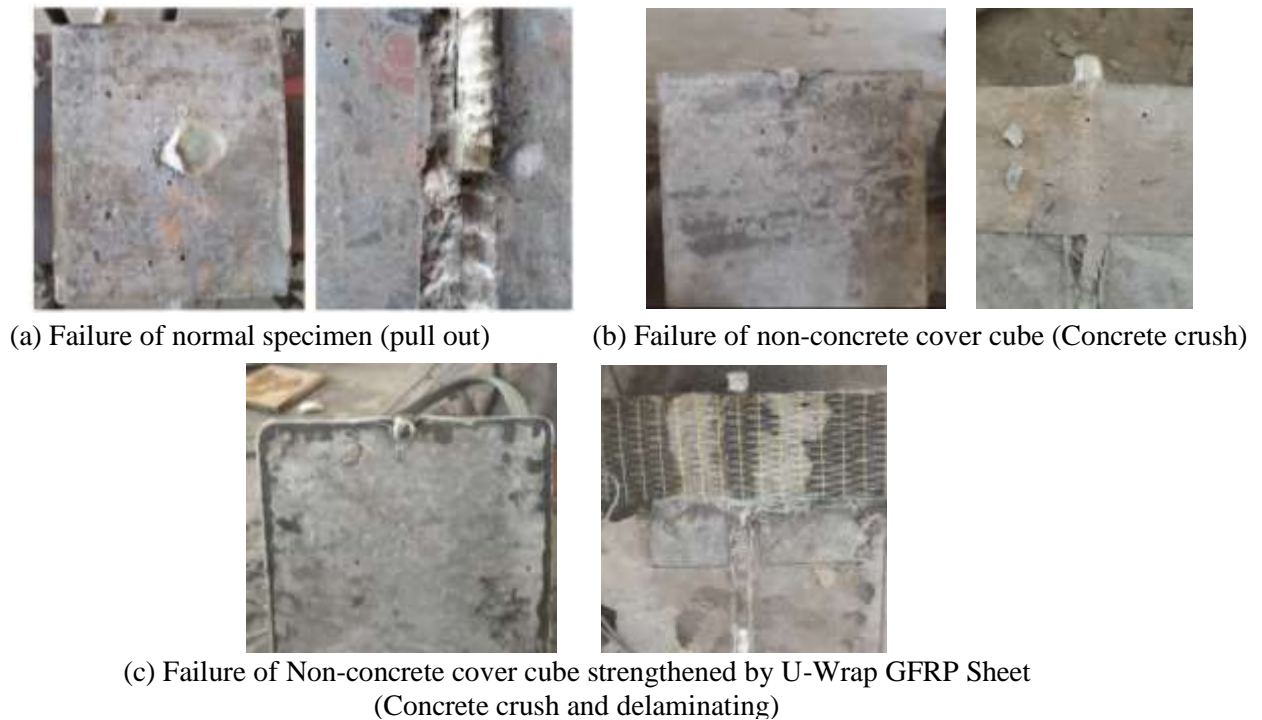


Figure 9. The failure mode of specimens.

4. Conclusions

An experimental study was carried out to examine the bond stress of reinforced concrete without concrete cover by comprised of concentric pull out a test and eccentric pullout test. Test result could be summarised as follows:

- Splitting failure mode occurred on reinforced concrete using the GFRP bar without concrete cover by direct pullout test and the U-Wrap GFRP sheet strengthening method didn't change its failure mode.
- U-Wrap GFRP sheet strengthening method increased average bond stress but its effect not significant.
- U-Wrap GFRP sheet strengthening method could retain bonding stress longer after delamination or concrete splitting.

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