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Single shear pull-off test of FRP-to-concrete and mortar bond

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Abstract

Externally bonding of fiber reinforced polymer (FRP) composites has been widely used for strengthening existing reinforced concrete structures. In this technique, the bond properties between FRP and concrete play a critical role in the strengthening joint. This has led to numerous numerical and experimental investigations. This paper presents the results of an experimental program investigating the effect of coarse aggregate in concrete on the bond behaviour between FRP and concrete. Two different types of substrate material were used: concrete and mortar in order to highlight the effect of the coarse aggregates. The failure mode of the FRP-to-concrete joints was either the concrete prism failure or debonding at the adhesive-concrete interface rather than a traditional FRP debonding at a very small depth in the concrete. The corresponding strength was also much higher than model prediction. The plausible reasons for such failures are discussed in this paper.

Keywords: bond, experimental investigation, CFRP plate, concrete, mortar

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Introduction

External bonding of carbon fibre reinforced polymers (CFRP) has become a popular technique for retrofitting existing concrete structures. In this technique, the FRP strengthened reinforced concrete (RC) structures usually fail at the FRP-to-concrete interfaces, manifesting as brittle debonding of FRP from concrete, with a thin layer of concrete attached [1]. This has led to focused research on this bond behaviour through experimental, numerical and analytical means in the last two decades. In terms of numerical simulation, considerable research has been conducted, mainly using two dimensional (2D) finite element (FE) models, to investigate the mechanical behaviour of FRP-to-concrete bonded joints. This homogeneous 2D modelling method presents a number of limitations, such as ignoring the 3D nature of the structure due to the spatial shape and distribution of coarse aggregates and other factors.

Single shear pull-off tests were conducted in this study aimed at investigating the difference of the bond behaviour between FRP and concrete/mortar. Compared to concrete, mortar is a much more uniform material so most of the 3D effects introduced by the coarse aggregates may be eliminated and at the same time, mortar shares a similar mechanical behaviour with concrete. This paper presents and compares the failure process and loads of two different bonded joints – FRP-to-concrete bonded joint and FRP-to-mortar bonded joint.

Test Procedure

A steel support and two loading grips for single shear tests were designed and fabricated to carry out all the tests reported in this paper. Detail of the steel support is shown in Figure 1. The setup was mounted to a Zwick machine with a load capacity of 100kN. A total of 18 concrete/mortar blocks of a length of 400mm, width of 100mm, and height of 150mm were used. The mortar shares the same mix design with the concrete except that no coarse aggregate was present. To enhance the FRP-to-concrete bonding, the top surface of the concrete blocks were sand blasted to remove the layer of mortar over the aggregates, achieving a very rough concrete surface. The mortar blocks were treated the same way. Compressed air was used to remove the dust after sand blasting.

The pultruded CFRP plates Sika CarboDur S 1012 were used in this test. The 100m wide and 1.2mm thick plates had a Young's modulus of 170GPa, tensile strength of 3100N/mm^2, and rupture elongation of 1.8%. The CFRP plates were cut to the designed size using mechanical guillotine. As recommended by the manufacturer, Sikadur-30 epoxy resin was used to bond the CFRP plate onto the concrete/mortar substrates. The CFRP plate was attached in the centre on one side of the substrate block, with an unbonded zone of 60mm to the edge. Two different widths of the CFRP plate were adopted: 50mm and 100mm. The bonded length of the CFRP plate was 250mm. Details of the specimen geometry are shown in Figure 2.

Test Results and Discussion

Failure modes and loads

The experimental maximum loads (average of 3 repeated tests) are reported in Table 1 along with the cubic compressive strength (average of 5 specimens) of the substrate material, the CFRP width and the failure type.

All of the concrete specimens bonded with 100mm wide CFRP plate failed in the prism by the formation of a crack in the concrete prism near the free end of the CFRP plate (Figure 3a). Once the crack appeared, it propagated almost immediately towards the upper support block and the specimen failed.

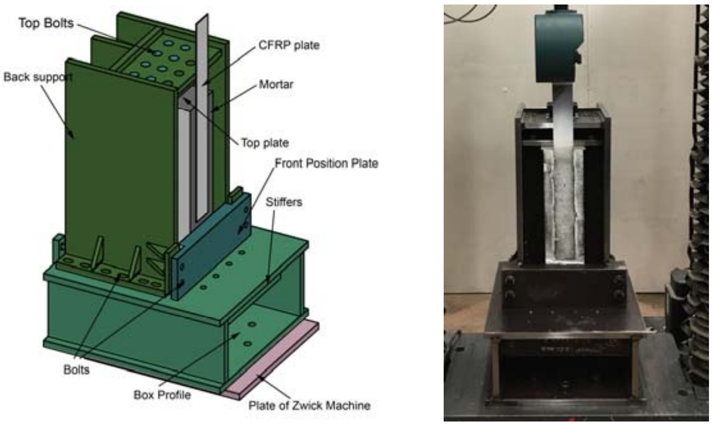
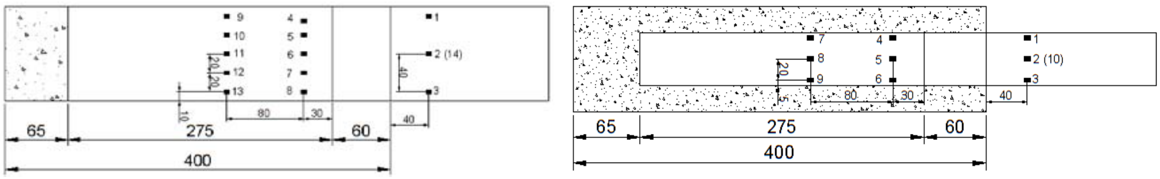


Figure 1: Steel rig and test set-up



(a) (b)

Figure 2: Specimen geometry of (a) specimens with 100mm width CFRP plate and (b) specimens with 50mm width CFRP plate

The mortar specimens with a 100mm CFRP plate failed in a mixed mode (Figure 3b), characterized by the CFRP debonding from the loaded end with the wedge failure of the mortar block, accompanied by the formation of a bulb at the free end.

For concrete prisms with a narrower 50mm CFRP plate, the debonding occurred at the CFRP-adhesive interface (Figure 3c). The mortar prism with the same CFRP plate geometry failed due to debonding in the mortar adjacent to the adhesive-mortar interface, in which a thin layer of mortar was attached to the CFRP plate after failure (Figure 3d).

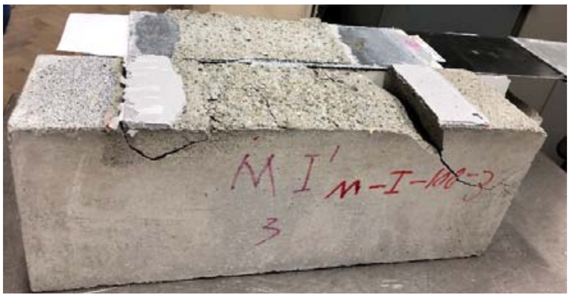
It is worth noting that the failure loads of all the concrete specimens are significantly greater than their mortar counterparts, although the compressive strength of mortar is higher than the concrete (Table 1). This is consistent with the different failure mode of concrete and mortar, indicating that the bonded strength of FRP-to-concrete interface is much higher than that of FRP-to-mortar interface. The reason will be further discussed in the following section.

Table 1: Failure modes and loads

Substrate Material	Cubic Compressive Strength [MPa]	FRP width [mm]	Failure mode*	Max. load [kN]
Concrete	60.5	100	CPF	80.7
	47.0	100	CPF	67.5
	47.0	50	DB-I	38.1
Mortar	75.5	100	DB-M/ MPF	63.8
	55.5	100	DB-M/ MPF	60.3
	55.5	50	DB-M	33.6

* CPF = concrete prism failure, DB-I = debonding at interface, DB-M = debonding in mortar, MPF = mortar prism failure.

(a)



(b)

(c)

(d)

Figure 3: Failure modes: (a) concrete prism failure (CPF); (b) debonding in mortar + mortar prism failure (DB-M/ MPF); (c) debonding at interface (DB-I); (d) debonding in mortar (DB-M).

Discussion of the failure modes

All of the concrete specimens failed due to either the splitting of the concrete prism or the debonding at the adhesive-concrete interface. A plausible reason for these two non-classical failure modes is that the strength of classical failure mode where failure occurs a small distance from the FRP-concrete interface in the concrete is not the lowest among all the possible failure modes. The CPF is related to the specific test setup including the concrete prism size and support conditions [2]. An analysis of a test database containing 525 single shear tests collected from literature shows that most of the FRP to concrete width ratio ranges from 0.10 to 0.75. Only 8 specimens in [2] has a width ratio greater than 0.8 – all of them failed in the concrete prism.

The surface treatment may also contribute to the high bonded strength. In this test, sand blasting was used to remove the top layer of mortar on the concrete prism. Many researchers have observed that the debonding load of a sand blasted surface or water jet treated surface is significantly higher than a surface ground with a stone wheel [3][4]. Also, the concrete surface after sand blasting is very irregular, so more epoxy resin was required to level the surface which may contribute to the enhanced bond strength. The improved performance may also be contributed by the improved epoxy resin penetration into the concrete, as also observed by other researchers [3]. When the concrete surface is treated with sand blasting, the characteristic inclined short cracks near the concrete surface are evident. After failure, a significantly thicker and rough layer of concrete is attached to the plate.

Conclusions

This paper has presented an experimental test programme on both FRP-to-concrete and FRP-to-mortar bonded joints using a single shear pull-off test setup. A total of 18 specimens were tested: 9 concrete and 9 mortar. The failure mode of the FRP-to-mortar bonded joints was the traditional debonding fracture started from the loaded end, whereas the concrete prism failed due to either the splitting of the concrete or the debonding at the interface. The possible reasons for the unusual failure mode were discussed.

Acknowledgement

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References

[1] Chen, J. F., and Teng, J.G., 2001, “Anchorage strength models for FRP and steel plates bonded to concrete,” Journal of Structural Engineering, 2001(7), pp. 784–791.

[2] Yao, J., Teng, J.G., and Chen, J.F., 2005, “Experimental study on FRP-to-concrete bonded joints,” Composites Part B: Engineering, 2005(2), pp. 99–113.

[3] Mazzotti, C., Savoia, M., and Ferracuti, B., 2009, “A new single-shear set-up for stable debonding of FRP – concrete joints,” Construction and Building Materials, 2009(4), pp. 1529–1537.

[4] Toutanji, H., and Ortiz, G., 2001, “The effect of surface preparation on the bond interface between FRP sheets and concrete members,” Composite Structures, 2001(4), pp. 457–462.