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Experimental Study on the Concrete Surface Preparation Influence to the Tensile and Shear Bond Strength of Synthetic Wraps

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Abstract

Synthetic sheets are increasing in popularity due to its ease in application, and very high tensile strength characteristics. Previous studies on the utilization of wraps for concrete flexural members resulted in a shear-bond loss in the sheets-to-concrete interface. Although the preparation of concrete surface prior to wrap attachment was in accordance with the product manual, the result was not optimal. Improving the bond could result in an increase of the member's load carrying capacity, so that the capacity of the FRP warp could be optimized. To obtain the most effective surface preparation method, two sets of tests were conducted; firstly to study the tensile-bond behavior, and secondly to investigate the shear-bond response. Four concrete surface preparation methods were explored, consisting of grove configurations with respect to the line of loading. In this research, an independent tensile and shear behavior was assumed. It was found that the commonly used surface preparation was sufficient in tensile, but could lead to de-bonding in shear. The research also concluded that all four proposed methods enhanced the shear-bond; the choice of method is thus influenced by economic aspects, time and application ease. The shear-bond testing method as proposed by the *fib* code needs to be perfected, since a variation in errors was detected.

Keywords: FRP; shear-bond; tensile-bond; surface preparation

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1. Introduction

After the Aceh tsunami in North Sumatra in 2004, and earthquakes in the Yogyakarta area in Central Java in 2006, the provision for earthquake resisting elements were drastically revised. For flexural members, the revision lead to a much higher capacity demand, thus leaving all beams designed based on the old code inadequate. An experimental study was conducted to explore the possibility of enhancing the beam's performance by improving the tensile strength using fiber reinforced polymers in combinations with the application of u-shaped shear confinement [1]. It was found that the method significantly increased the load carrying capacity of the beam. The T-section beam with a length of 2.50 meters subjected to a concentrated load at midpoint, had a 45% increase in bending moment capacity as compared to an identical member without the FRP reinforcement.

On close observation it was shown that the failure was characterized by shear de-bonding between the FRP and the concrete surface, resulting in large beam deformations at midpoint. The strain recordings showed that prior to failure of the beam, the tensile steel reinforcement yielded. This behavior is typical for under-reinforced members in flexure. Assuming a perfect bond, the failure mode should theoretically be either due to concrete crushing in compression, or tensile fracture in the FRP. The optimum capacity of the section was thus not reached. A better bond performance between the FRP and the concrete surface would result in a higher moment capacity, resulting in an optimization in FRP use, impacting both economical as well as environmental aspects positively.

This research is focused on studying the concrete-surface preparation methods for FRP wraps. The research is based on the assumption of independent shear and tension bond behavior. Two testing methods were explored, direct tension and direct shear.

2. Surface preparations

The concrete surface preparation method prior to attaching the synthetic wraps, as mandated by the FRP producer, was by grinding the surface to a depth of 4 mm, followed by sandblasting. This method resulted in shear de-bonding of the FRP to the concrete [1]. The wrap used in this research was a high strength black carbon fiber, embedded in a white thermoplastic heat-set fiber resin, attached to the concrete by a tri-methyl-hexane and epichloro-hydrin epoxy resin. Studies showed that the method of surface preparation, type of bonding agent and bond dimension strongly influences the bond between FRP and concrete [2, 3]. Based on this knowledge, four methods to enhance the both shear-bond and tensile-bond were introduced. The surface preparations were conducted by applying groves in the concrete surface on the designated 4 mm grinded surface. The groves had a depth and width of 2 mm and 0.5 mm respectively, and a distance of 10 mm apart. The groves' configurations were perpendicular (code T); diagonal (code D); crossed (code C) and parallel (code L) to the line of tensile load (Fig. 1).

The aim of this study was to compare the individual shear- and tensile-bond failure behaviors of each surface treatment. The standardized treatment as mandated by the FRP producer was designated as type N, and functioned as controlling element. The application of groves was based on the main idea to enlarge the bonding agent's contact area to the concrete, and to enhance the strain-flow distance by re-direct its path.

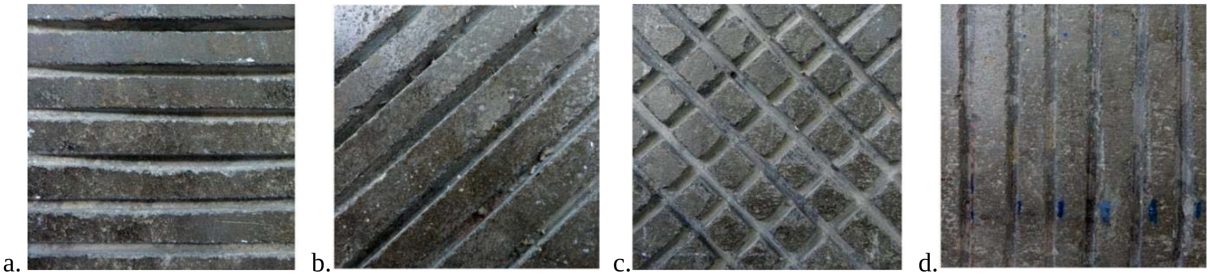

Fig. 1. Concrete surface preparations; (a) Perpendicular (T); (b) Diagonal (D); (c) Crosses (C); (d) Parallel (L).

3. Experimental research

3.1. Shear-bond behavior

Shear-bond test methods for FRP are limited; research work on FRP in shear is mostly applied to FRP plates having a much higher rigidity as compared to sheets or wraps [4, 5, 6, 7, 8, 9]. Since the FRP sheets have significantly less stiffness as compared to FRP plates, the typical one-face-tensile, and the one-face and double-face-push tests as introduced by the majority of researchers, was not applicable. The effect of misalignment would heavily influence the outcome [10]. Considering all aspect, a modification of the test method based the *fib*-CEB technical specifications [2, 11] was chosen (Fig 2).

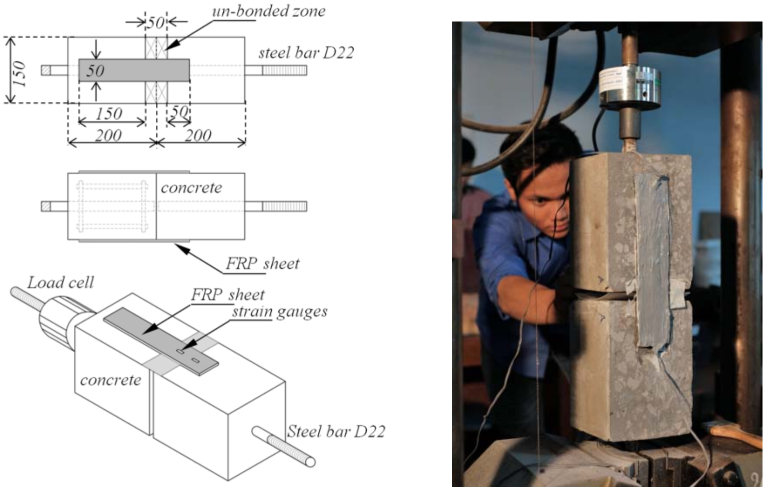

Fig. 2. Shear test set up and specimen preparation.

Instead of using steel clamps as was advised by the *fib*-CEB, a smaller bond area measuring only 50 by 50 mm was designed to localize bond failure. The opposite contact areas were made larger, measuring 50 by 150 mm. An un-bonded zone 50 mm in width was designated to prevent premature spalling due to high stress concentrations in the concrete corner. This un-bonded area was bridged by a two-ply FRP composite attached by an epoxy layer at the interface. The epoxy resin was also applied the exposed face of the FRP. The D22 steel bar dimension; its development length and the concrete reinforcements were carefully designed to ensure failure in the bond. Six specimens were prepared for each surface treatment, and standardized cylinders sized 150 by 300 mm were produced to monitor the 28th day's concrete compression strength. The strength was recorded as 55.60 MPa.

At the age of 28 days, the groves were applied to the concrete surface using a circular diamond saw, and sandblasted to clean the groves of small particles. The FRP sheet was applied using the epoxy-resin and cured for seven days. Upon testing, the specimen was placed in a wooden frame to prevent secondary strains in the bonded and un-bonded FRP area. The specimen was further placed within the gripping jaws of the Universal Testing Machine, and the D22 steel bars clamed. A direct tensile force with a loading rate of 1.5 kN/sec was applied to these steel bars. The load increment, the failure load, and the strain response in the strain gauge, were recorded. Additionally, the strain in the un-bonded FRP was measured using strain gauges attached to the FRP surface prior to the application of the epoxy resin (Fig. 2). The specimens were designated S_T, S_D, S_C, S_L and S_N based on the surface preparation type. All specimens S_T, S_D, S_C and S_L failed due to concrete-shear failure; the S_N specimen failed in de-bonding between the epoxy-resin and the concrete (Figures 3a and 3b)

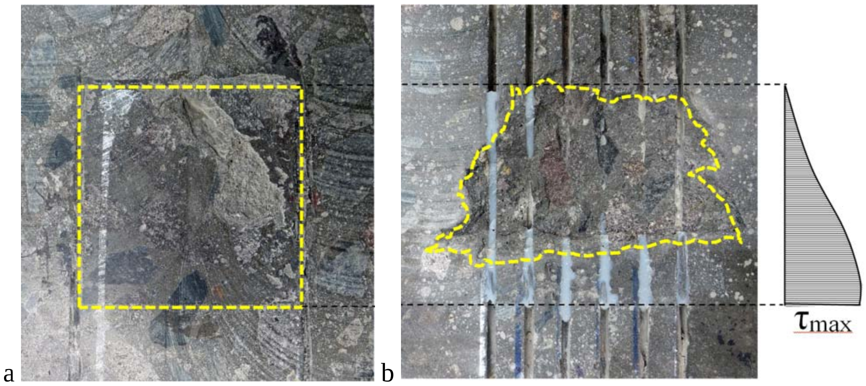

Fig. 3. Shear-bond and concrete-shear failure; (a) De-bonding failure; (b) Concrete-shear failure.

3.2. Shear bond strength

All specimens S_T, S_D. S_C and S_L failed due to concrete shear-cracking, while the S_N specimens failed in the shear-bond mode between the FRP and the concrete. Except for the predicted pattern as seen in Fig. 3, spalling occurred in the concrete at the un-bounded area. This was due to the high stresses in the vicinity of the border between the FRP and the concrete, and the stress-flow propagation in the direction outward of the maximum shear stresses (Fig. 4).

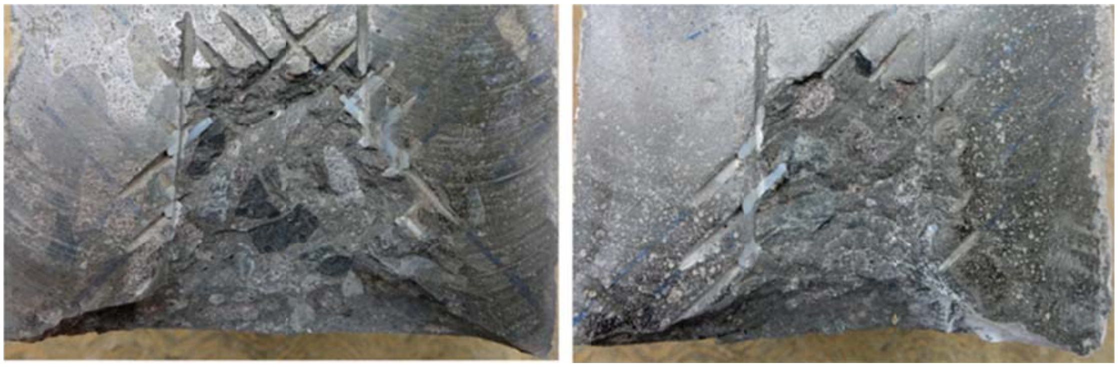

Fig. 4. Concrete spalling due to high shear-stress concentrations.

The S_N specimen failing in shear-bond had a significantly lower failure stress as compared to S_T, S_D. S_C and S_L. The shear-bond strength was calculated to be 5.24 N/mm^2, compared to the concrete-shear strength of 8.12 N/mm^2. This concrete-shear strength closely approaches the concrete-shear capacity as predicted by the ACI code that for a 55.60 MPa concrete strength is 7.46 N/mm^2. The report on the single-lap shear test performed on the FRP-to-FRP bond using the exact same material resulted in average shear-bond strength of 16.6 MPa [12]. If a good bond is produced between the FRP and concrete, consequently the failure mode should be due to concrete-shear.

A closer observation to the strain response in the un-bonded and bonded FRP section recorded by the strain gauges showed that the bonded FRP had a much higher stiffness as compared to the un-bonded FRP (Fig. 5). The un-bonded FRP section had a material stiffness of 63 kN/mm with a Young’s modulus of 57 GPa. The bonded FRP had a material stiffness of 90 kN/mm in combination with a Young’s modulus of 67 GPa. The composite FRP-resin double play generally resulted in a higher elastic modulus as compared to the Young’s modulus of 55 GPa resulted from single-ply FRP-resin specimens [12]. The double layered FRP and the additional epoxy-resin treatment added 4% to the initial stiffness of the material. The Young’s modulus was determined based on a 0.13 mm FRP thickness, and a 0.50 mm thickness of the epoxy resin layers. The tensile load was also assumed to be distributed equally to the two bond faces.

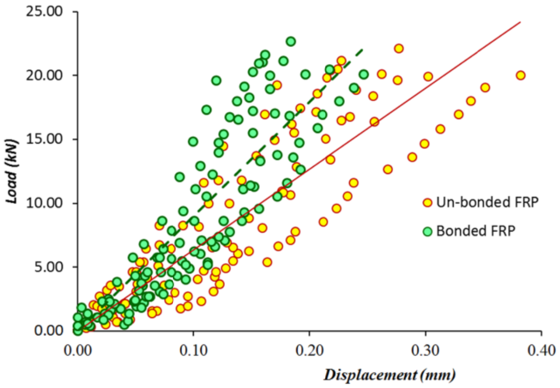

Fig. 5. Stress-strain behavior of bonded and un-bonded FRP wraps

3.3. Direct tensile behavior

To test the response in direct tension, an experimental model was constructed that targets only the bond area between the FRP and concrete. The Dyna Proceq haftprufer pull-off tester Z16 having a pull-out capacity of 16 kN and an accuracy level of less than 2% with a stroke of 3.5 mm, was used.

The concrete surface was prepared in the same manner as the shear specimens, and denoted as T_T, T_D. T_C, T_L and T_N. The synthetic sheet was attached to the concrete surface and the specimens were tested after seven days curing. Upon testing, a cylinder with a diameter of 50 mm was core-drilled in the concrete surface, creating a cone inside the slab. The aluminum test disc was attached to the FRP with resin, and connected to the pull-off tester through the draw-bolt. This draw bolt had a conical head to ensure a concentric tension force. The specimen was tested till failure, and the load recorded (Fig 6).

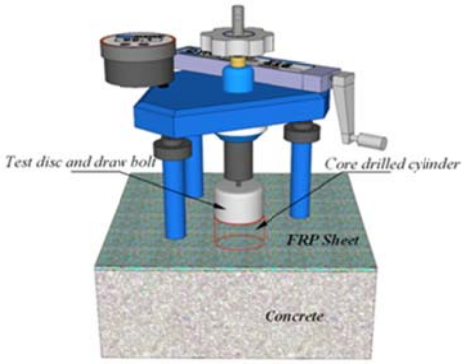

Fig. 6. Direct tensile testing method.

3.4. Tensile bond strength

All but one of the T_N specimens failed in tensile-bond mode. All other surface treatments resulted in concrete failure due to tension. The tensile-bond failure resulted in a stress of 1.29 N/mm^2, compared to the concrete-tensile strength measured to be 3.20 MPa. This value was taken as average of all the data. The concrete tensile strength as calculated from the *fib*-CEB model code 2010 predicted a tensile strength of 3.84 MPa, which is very close to the test results. The cracking pattern was easily distinguishable from the tensile-bond failure, since the concrete failure surface showed a clear breaking mode in the interface between the aggregate and the mortar (Fig 7).

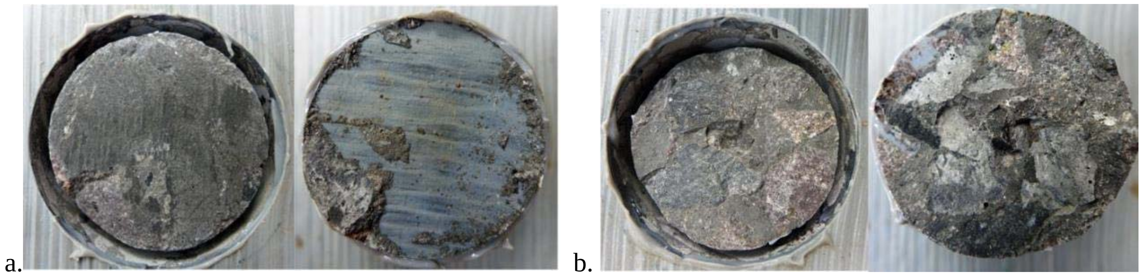

Fig. 7. (a) De-bonding in tension; (b) Mortar tension failure.

4. Analysis and discussion

The tensile behavior is less sensitive to surface preparation methods as compared to the behavior in shear. All test specimens expect one failed in the same mode, i.e. in the interface between aggregates and mortar. The tensile test data standard deviation was 0.72 as compared to 4.79 for the shear data, suggesting a much higher accuracy level for this experiment. The standardized equipment used for testing produced an almost perfect centric force, resulting in a uniform stress in the bond and concrete.

The fact that only one specimen in tension failed de-bonding mode suggested that the treatment by removing 4 mm of the surface, followed by sandblasting, is sufficient to maintain a perfect bond between the FRP sheet and the concrete. Any additional surface preparation is unnecessary, since all specimens failed in concrete tensile cracking. For members in bending, the tensile-bond contribution to the moment capacity is also negligible.

As for shear, the SN type specimen failed in de-bonding, underlined by the substantial lower failure stress reaching only 65% of the concrete shear-strength. All other surface treatments failed due to concrete-shear cracking. Whiles all tensile tests demonstrated a perfect circular failure section perpendicular to the applied load, the shear-bond tests showed a large variation in failure modes. Observed modes were: fracture in the un-bonded and bonded FRP sheets, partial de-bonding followed by concrete failure, and spalling. The failure surface areas were also non-uniform, suggesting that the testing method does not always produce a concentric load in the element. Errors observed during testing were: twisting of the steel bars at the starting of load application; flaws in the un-bonded FRP area due the manufacturing process; and non-uniformly distributed load to the both sides of the FRP. The method introduced by Irshidat and Al-Saleh [13] might overcome the unequal force distribution to the two test areas. This double shear test was directly applied to the bonded area through the FRP hooped around a cylindrical roller, resulting in more uniform force distribution in the both adjacent bond areas.

The shear-stress distribution, unlike tension, has a parabolic function and increases near the edge of the area. These high stresses resulted in spalling of concrete in the concrete edge, influencing the measured load magnitude at failure [14].

Contradictory to the tensile-bond, it was proven that a concrete surface grinding of 4 mm is insufficient to ensure that a perfect bonding in shear. This finding underlined the test results of Tudjono et al. in 2015 [1]. However, all four surface treatments resulted in the same failure mode, cracking of concrete in shear.

5. Conclusion

The introduced test methods to evaluate the tensile and shear-bond of FRP sheets were proven usable. The tensile test method was far more thorough when compared to the tensile testing method, based on comparison of the data’s standard deviation, and observing the variations in failure modes.

The tensile tests concluded that the commonly used surface preparation method of grinding a 4 mm layer from the concrete surface is sufficient to ensure a concrete-tensile failure in the FRP reinforcement. As for the shear-bond, it is concluded with certainty that additional surface preparations are mandatory to ensure an optimal performance in shear. The 4 mm grinding method generally resulted in de-bonding between the epoxy resin and concrete. Since all surface preparation, the perpendicular, diagonal, crossed and parallel groves all resulted in concrete-shear failure, it can be concluded that all methods are evenly effective. The choice on the surface preparation method is thus based on the consideration which application method yields in the easiest technique in combination with the least labor costs and execution time. These factors will influence the effectiveness of the method. The evaluation on the load distribution to the both testing faces showed that eccentric loading is of major concern; the method as introduced by the proposed *fib*-CEB code therefore requires the necessary evaluation and probable re-adjustments to minimize the load distribution imperfections during testing.

The stiffness response of the FRP when applied in multiple layers alters the stiffness behavior of the element. Care has to be taken when constructing a reinforcing system with multi FRP layers, since a brittle failure could be induced when a substantial number of FRP plies is used to increase the strength.

A next step is to investigate the depth, distance and width of the groves with respect to the concrete strength. A correlation between concrete strength and method could then be established and serve as guidance for applications in the field. A better bond performance will generally lead to an optimization in material usage; both the FRP and epoxy resins are chemical products which use should be controlled, if not minimized, to reduce the negative impact on the environment.

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