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Debonding resistance of FRP-to-clay brick masonry joints

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ABSTRACT

Debonding at the FRP-to-masonry interface has been identified as the preferred failure mechanism in fibre-reinforced polymer (FRP) retrofitted masonry as it allows for some redistribution of forces. The results of 14 FRP-to-masonry bond tests are presented, where the FRP was near surface mounted (NSM) to stack-bonded clay brick masonry. These tests were conducted to investigate the effect that variables such as cyclic loading and FRP strip dimensions have on the debonding resistance of a NSM FRP-to-masonry joint. These results were then incorporated into a large database of FRP retrofitted masonry pull test results by various researchers over the past 10 years. The database includes results for both externally bonded (EB) and NSM retrofitting techniques. From this database, local bond–slip parameters such as the maximum interface shear stress, τ_{max}, and the maximum slip, δ_{max}, were investigated to determine correlations between these values and masonry material properties. Further, 15 existing concrete and masonry bond strength (maximum load at the FRP-to-substrate interface) models in the literature were assessed for their use with masonry by comparing these models against the results in the pull test database. Based on the comparative statistics of the test-to-predicted bond strength it is concluded that a new FRP-to-masonry bond model is required which gives more accurate predictions. Results include a discussion on the global load–slip response and FRP-to-masonry interface behaviour.

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1. Introduction and background

Unreinforced masonry (URM) structures constitute both a significant portion of the world's heritage buildings and a significant component of the modern residential building stock, and are particularly susceptible to damage from out-of-plane loads such as those generated by earthquakes [1]. Over the past decade or so, the use of near surface mounted (NSM) fibre reinforced polymers (FRPs) has gained much attention as a promising new seismic strengthening technique [2–6]. The NSM FRP retrofitting technique (i.e. inserting FRP strips into grooves cut into the surface of a wall) provides significant advantages over externally bonded (EB) FRP such as improved aesthetics, reduced surface preparation and better protection from UV exposure and vandalism. Importantly, NSM FRP debonds at higher strains than EB FRP and thus leads to more efficient use of the FRP material [7]. When using the NSM technique, the most efficient cross-section is a thin rectangular strip as its benefits, in terms of efficiency and construction time, are superior to those of other shapes such as bars [8].

Some of the common out-of-plane failure mechanisms of FRP strengthened masonry walls include sliding of the masonry units, flexural-shear cracking, FRP rupture, FRP debonding, punching shear and crushing of brick in compression [9–14]. Among these debonding mechanisms, intermediate crack (IC) debonding governs the increase in moment capacity and sectional ductility. IC debonding involves progressive detachment of the NSM FRP strip which initiates at the location of intermediate flexural or flexural-shear cracks when the strip is subjected to large tension stress. If the FRP is perfectly attached to the masonry then theoretically the FRP strip requires infinite strain capacity in order to bridge the intercepting cracks. As such strain levels are not possible, debonding cracks will occur at the FRP-to-substrate interface and gradually propagate towards the strip ends [15,16] as long as the debonding strain is lower than the tensile rupture strain for the FRP.

IC debonding may be further divided into two types: (i) associated with the presence of a single crack in a member; and, (ii) where multiple cracks are distributed along the length of a member [17,18]. The stress state at the interface for type (i) (refer Fig. 1a) can be idealised using a pull test where a tensile force (P) is applied to the FRP strip causing a slip (Δ) at the crack face as shown in Fig. 1(b). The resulting P–Δ response is referred to as the global load–slip response which depends on the interfacial bond characteristics between the FRP and the surrounding masonry substrate such as the interface shear stress, τ and the local interface slip, δ. The local τ–δ response is known as the local bond–slip behaviour. Pull tests are a useful and relatively inexpensive testing procedure

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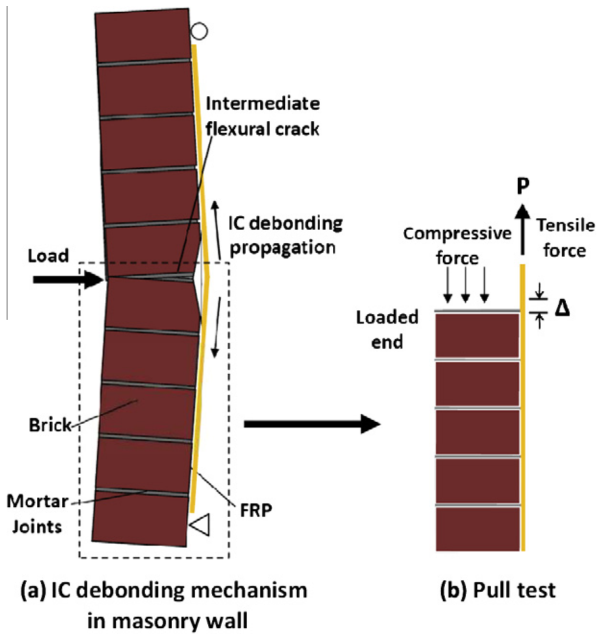

Fig. 1. Pull test simulating IC debonding.

that can be used to investigate the interface τ–δ behaviour as well as to determine the critical bond length, L_{eff}, the strain in the FRP strip at the onset of debonding, ε_{db}, and other factors impacting the bond strength. Furthermore, the debonding resistance obtained from FRP-plated pull tests is a lower bound to the IC debonding resistance in beams due to effects of moment and crack distribution [17–20]. Hence, to understand the behaviour of a FRP-strengthened URM wall subjected to out-of-plane loading, the FRP-to-masonry joint behaviour must be understood first [18,19,6,5].

Due to material similarity between concrete and masonry, such as low tensile strength and brittleness, the debonding mechanisms for retrofitted masonry have been shown to be similar to those of retrofitted reinforced concrete (RC) members (Fig. 2). Moreover, factors affecting the FRP-to-concrete bonded joint behaviour similarly influence FRP-to-masonry bonded joint behaviour [19,6]. The use of FRP to improve the flexural resistance of RC members is now well established (e.g. [21,15]). Hence, the research on the debonding mechanisms in plated RC structures has been used as a starting point for research on FRP retrofitted masonry structures.

A large database of pull test results is presented, reporting previously published data for masonry retrofitted with FRP strips. The derivation of analytical models to determine the IC debonding resistance of bonded joints is also presented. Empirical relationships for key parameters such as the fracture energy, G_f, and shear stress–slip (denoted as local bond–slip) relationship, τ–δ, are investigated. Whilst the application of NSM FRP strips appears to be a particularly viable retrofitting technique (Dizhur et al. [22]), limited research has previously been conducted on the application of this retrofitting technique to masonry structures. For example, of the 223 FRP-to-masonry pull tests available in the open literature, NSM tests account for only about 25% of the total. Hence, to add to the relatively small existing NSM database, 14 new pull tests on clay brick masonry prisms retrofitted with NSM carbon FRP strips were conducted. These experimental tests are reported below.

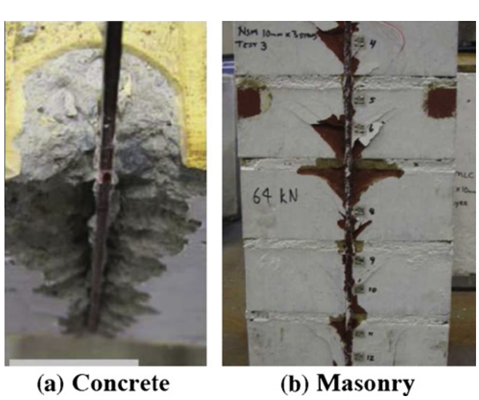

Fig. 2. Debonding failure in pull test specimen.

2. New pull test data

As part of ongoing research at the University of Adelaide 14 NSM carbon FRP-to-masonry pull tests were conducted. Different variables that affect the bond behaviour of FRP-to-masonry joints were considered such as FRP strip cross-section and loading type.

2.1. Material properties

Clay brick units with nominal dimensions of 230 × 110 × 76 mm were used. The mortar used to construct the pull-test specimens consisted of Portland cement, hydrated lime and sand, combined in a ratio of 1:1:6 by volume. Material tests were conducted in accordance with Standards Australia [23,24] to determine the quality of the masonry and to quantify any material parameters that are required for development of the empirical model. The mean value of the flexural tensile strength of the brick unit, f_{ut} and the modulus of elasticity of the masonry, E_m, were 3.41 MPa and 10.7 GPa, respectively. The ultimate tensile strength of the FRP, f_{rupt}, and Young's modulus of the FRP, E_p, provided by the manufacturer were 2700 MPa and 165 GPa, respectively.

2.2. Test setup and specimen details

Fig. 3 shows the test setup and instrumentation details. Each pull test prism consisted of a five brick stack, with 10 mm mortar bed joints and an FRP-to-masonry bonded length of 420 mm. The groove for the NSM strip was cut using a diamond blade saw and then filled with an epoxy adhesive. The strip was cleaned with acetone to remove any foreign substances before being inserted into to the epoxy-filled groove and allowed to cure for 7 days. The FRP strip was positioned flush with masonry surface as shown in Fig. 3 for all specimens. A layer of quick drying paste was applied to the top and bottom surfaces of the masonry prism to ensure that the load was transferred evenly using a manually controlled hydraulic ram. A solid steel plate with a small gap for the FRP to pass through was placed onto the top surface (loaded end) of the specimen. This restraining plate was used to apply approximately 1kN of pre-compression to settle the specimen at the early stages of loading. Once the specimen was in place, a monotonic tensile load was applied in displacement control using an Avery testing machine at a constant rate of approximately 2.5 kN per minute until failure, with 0.5 mm per minute as an upper bound for displacement rate. For cyclic loading, one cycle of load consisted of increasing the load monotonically until the target load (displacement) was reached, then reducing the load to zero. Thus, the NSM strips of FRP were only loaded in tension. Each cyclic specimen was subjected to three cycles of load for each target displacement.

Each test specimen had two strain gauges glued on the FRP strips and positioned 25 mm away from the top brick unit at the

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