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Pullout strength of NSM CFRP strips bonded to vintage clay brick masonry

D. Dizhur [a,*], M.C. Griffith [b,1], J.M. Ingham [a,2]

[a] Department of Civil and Environmental Engineering, The University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
[b] School of Civil, Environmental and Mining Engineering, The University of Adelaide, Engineering North N136, North Terrace Campus, Australia

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ABSTRACT

The frequently observed inadequate seismic performance of unreinforced masonry (URM) buildings necessitates the development of cost effective minimally-invasive seismic improvement techniques for this type of construction. One promising solution is use of the near surface mounted (NSM) technique to incorporate fibre reinforced polymers (FRP) strips as longitudinal reinforcement. In particular, the NSM technique provides several advantages over externally bonded (EB) FRP as a seismic improvement technique including significantly higher axial strain at debonding, minimal negative impact upon the aesthetics of the structure, reduced installation time, and superior protection from fire and the environment, thus providing a cost effective and minimally-invasive option for seismically strengthening URM buildings. An experimental program consisting of 39 pull tests was conducted using NSM carbon (C)FRP strips bonded to vintage solid clay brick masonry, to provide data with which to validate the accuracy of existing predictive FRP-to-masonry bond models. Based on experimental findings, a variation of an existing analytical FRP-to-masonry bond model is proposed and the effects of geometric variation of the NSM groove and the reinforcing CFRP strip are discussed.

1. Background

It is well known and was once again highlighted during the 2010 M7.1 Darfield (New Zealand) earthquake [1] and subsequent 2011 M6.3 aftershock [2], that unreinforced masonry (URM) construction often has insufficient strength to resist lateral earthquake forces in high and moderate seismic zones [3–5]. One of the most critical deficiencies of URM buildings is the lack of wall–diaphragm connections, but once added, it is the out-of-plane bending failure mechanism and subsequent wall collapse that poses the greatest risk to both the building's occupants and to passers-by [6]. To mitigate this risk, various seismic improvement techniques have been developed over the decades. One such established technique for strengthening and increasing the ductility capacity of URM walls subjected to earthquake loading is the use of fibre reinforced polymer (FRP) material. Externally bonded (EB) FRP sheets or plates [7,8] and, more recently, near-surface mounted (NSM) FRP bars or strips are the two FRP application techniques that are commonly used. Using the NSM strip technique provides several advantages over the EB technique, including significantly higher axial strain at debonding, minimal negative impact upon the aesthetics of the structure, reduced installation time, and superior protection from fire and the environment [9,10], thus providing a cost effective and minimally-invasive option for seismically strengthening URM buildings. It is typically assumed that a horizontal crack at approximately wall mid-height will initially develop at a low level of out-of-plane loading applied to a vertically-spanning URM wall [11]. Hence, because vertical bending of URM walls is typically critical, the application of vertically oriented strengthening elements to improve the vertical bending capacity of such walls is most appropriate [12].

Accurately predicting the strength of the bond between an NSM FRP strip and the substrate material is essential to ensure the effectiveness of the NSM CFRP strengthening. The intermediate crack (IC) debonding mechanism [13] governs the increase in moment capacity and ductility of structural sections strengthened using NSM FRP, and is considered to be the most critical of the commonly observed debonding mechanisms. A good understanding of FRP-to-concrete bond behaviour and the IC debonding mechanism has been achieved from extensive previous research, as reported by Stone et al. [14] and Hassan and Rizkalla [15], with reliable

* Corresponding author. Tel.: +64 9 373 7599x84521, mobile: +64 21 1581 895; fax: +64 9 373 7462.
E-mail addresses: ddiz001@aucklanduni.ac.nz (D. Dizhur), michael.griffith@adelaide.edu.au (M.C. Griffith), j.ingham@auckland.ac.nz (J.M. Ingham).
[1] Tel.: +61 8 8313 4316.
[2] Tel.: +64 9 373 7599x87803.

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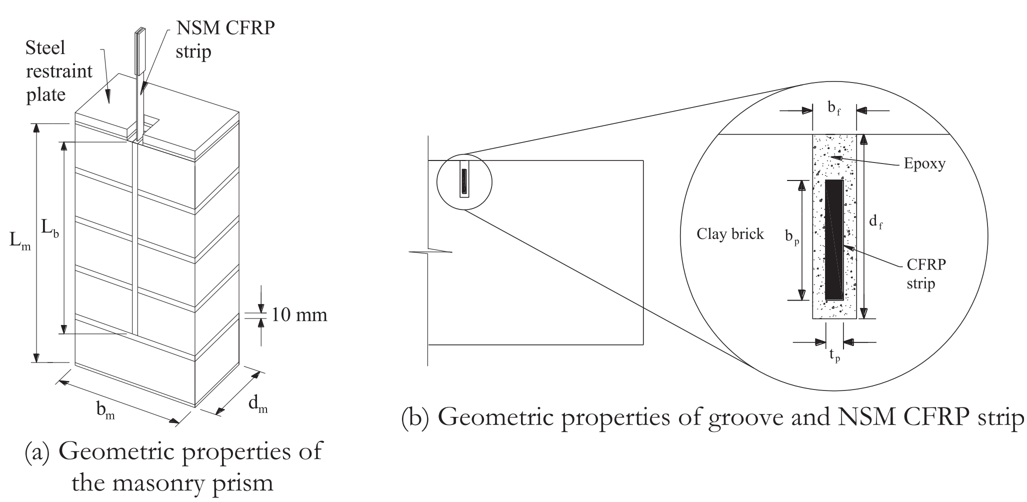
analytical predictive models for the IC debonding resistance also having being established [16]. Initial experimental validation of the use of NSM FRP as a technique for seismic improvement of masonry focused on strengthening modern URM and involved simulation of the IC debonding failure mechanism using simple monotonic pull tests [9,17–19]. The observed failure modes are categorised as: (i) IC debonding failure, where cracking propagated in the masonry; (ii) Sliding failure, where failure occurred at the CFRP strip–adhesive interface. (iii) Rupture of the CFRP strip. Subsequently, analytical models to predict the bond behaviour of modern masonry-to-FRP were developed. However, the advances in the clay brick manufacturing process such us the firing temperature, the use of chemical additives and stricter in place quality controls change the physical and mechanical properties of clay brick masonry when compared to clay bricks manufactured using traditional manufacturing processes approximately 100 years ago [20]. Hence, applicability of the developed models to the bond formed between NSM FRP and vintage clay brick masonry requires further validation.

The strength of the FRP-to-masonry bond depends on the following parameters [10]: the groove and the strip dimensions (see Fig. 1), the tensile and shear strength of masonry and groove filler, the level of preparation of the groove substrate and the position of the FRP strip within the member being strengthened. Previously conducted research was undertaken using a variety of test setups, with the most common procedures including small-scale simple block pull tests [10,21], beam tests [15,22] and full scale walls loaded out-of-plane [7,12]. Although beam tests and full scale wall tests are typically considered to provide better representation of how the IC debonding mechanism develops during an earthquake, these test methods are both time consuming and expensive to prepare and undertake. Previous small-scale experimental pull tests considering the FRP to masonry bond behaviour [9,17–19] included a limited range of brick strength (brick modulus of rupture strength ranging from 3.41 MPa to 3.57 MPa) and a limited variation of geometric parameters, and therefore further research is warranted.

A companion study to the research conducted by Petersen et al. [9], Willis et al. [18] and Kashyap et al. [17] is reported here, that entailed the use of small-scale monotonic pull tests. This test method was adopted as it permitted a greater number of tests and a wider range of variables to be considered in comparison to the testing of masonry beams or full-scale walls. As no standard testing procedure currently exists pertaining to the method of testing, a large number of different experimental test setups have previously been adopted by various researchers studying the bond strength of FRP-to-concrete and FRP-to-masonry joints. During previous experimental and numerical studies on the bond strength of FRP-to-concrete joints, it was shown that the variation in test setup used can result in substantial differences in the produced test results [23]. The near-end supported single shear pull test setup appears to be the most popular test setup due to its simplicity and proven reliability [24]. It is recognised that this type of single shear pull test setup, that is near-end supported with the masonry in compression, does not necessarily accurately represent a URM wall loaded out-of-plane, where the zone containing the NSM CFRP strip is in tension. However, due to the simplicity and reliability of this test setup and the ability to make direct comparison to the aforementioned studies previously conducted by other [9,17,18] the near-end supported single shear pull test setup was selected for the experimental study reported herein. The experimental study reported here consisted of 39 pull-test prisms and the aim of the experimental study was also to investigate the influence of the brick compressive strength and geometric parameters of the FRP strip and the cut groove on the FRP-to-masonry bond. Also, the aim of the experimental study was to acquire experimental



(a) Geometric properties of the masonry prism

(b) Geometric properties of groove and NSM CFRP strip

Fig. 1. Prism geometrical detailing.

Table 1
Masonry material properties.

Brick group	Origin and year built	f'_b (N/mm^2)	n	f'_m (N/mm^2)	n	f'_j (N/mm^2)	n	f'_{rup} (N/mm^2)	n	E_b (N/mm^2)	n
A	Auckland, 1930s	35.8 (0.21)	10	–		15.0 (0.11)	6	3.8 (0.14)	8	9600 (0.35)	6
B	Auckland, 1940s	17.1 (0.15)	10	7.79 (0.14)	3			2.6 (0.26)	11	6200 (0.29)	4
C	Auckland, pre-1930s	21.5 (0.25)	8	–				3.4 (0.24)	9	3600 (0.42)	5
D	Auckland, 1910	16.0 (0.11)	6	–				2.5 (0.35)	4	3000 (0.38)	10
E	Gisborne, 1906	15.7 (0.21)	8	–				1.9 (0.36)	9	2700 (0.32)	10
F	Wellington, 1884	8.9 (0.18)	9	–				1.2 (0.29)	5	1000 (0.47)	9

Note: n – sample size; () – coefficient of variation (CoV).