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State-of-the-art review and future research directions for FRP-to-masonry bond research: Test methods and techniques for extraction of bond-slip behaviour

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HIGHLIGHTS

- Collates the results of 1583 masonry pull-test results obtained from 56 studies.
- Inconsistency in test arrangements, instrumentation methods, and data processing identified.
- Lack of reported properties hinders the development of a bond model.

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ABSTRACT

The effectiveness of FRP retrofits is heavily reliant on the shear bond that can be developed between the FRP and masonry substrate, which has been the focus of experimental research for almost two decades. This paper collates and critically reviews previous experimental work on the shear bond between FRP composites and masonry substrates, identifying 1583 individual pull-tests across 56 published studies. Whilst the pool of existing data is significant in terms of number of tests, it encompasses a rather narrow range of substrate material, FRP material and retrofit configuration. Most notably, the majority of tests have been undertaken on clay brick substrates, carbon FRPs and externally-bonded retrofits. By contrast, testing of natural stone substrates and near-surface-mounted retrofits has been limited. Significantly, the review identifies considerable inconsistency in the test arrangements, instrumentation methods, and data processing techniques for extracting local bond-slip properties, which has undoubtedly hindered the development of a unified bond model and codifiable design rules. Methods of extracting bond-slip behaviour from test data are critically reviewed, and importantly it is shown through numerical examples that without adequate instrumentation it is not possible to reliably extract this behaviour from standard pull-tests. Finally, suggestions for adequate instrumentation and a framework for undertaking bond-slip behaviour extraction through inverse analysis are presented. Significantly, the experimental database compiled as part of this work-thought to be the largest of its kind to date—is made openly available as an accompanying Data in Brief article with the intent that it will facilitate development of bond-strength models for FRP bonded to masonry.

1. Introduction

Unreinforced masonry construction is particularly susceptible to seismic loading due to its low tensile strength and heavy mass, motivating the need for retrofit. Fibre-reinforced polymer (FRP) composites (hereafter referred to as 'plates') have emerged as a popular means of strengthening masonry structures due to their high strength and stiffness, low weight, and durability [1]. The role of FRP plating is to act as tensile reinforcement which can be used to enhance a wall's capacity against in-plane shear and/or out-of-plane flexure [2–6].

The effectiveness of FRP retrofits is largely controlled by the ability to develop shear load transfer across the FRP-to-masonry bond. The most common experimental technique for studying bond behaviour is via the shear pull-test (hereafter referred to simply as "pull-test"), shown diagrammatically in Fig. 1. This test involves adhesively bonding a FRP composite to the masonry

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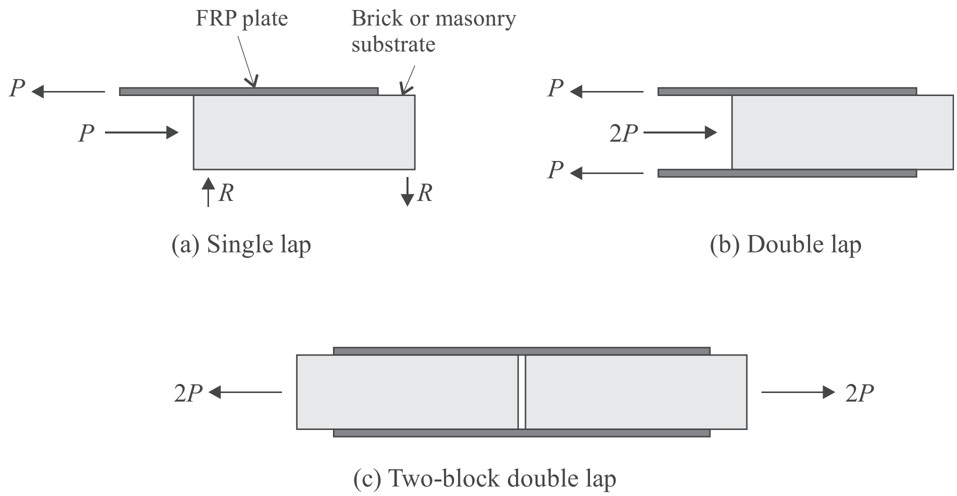

Fig. 1. Various types of pull-test arrangements including (a) single lap, (b) double lap, and (c) two-block double lap. In (a) and (b), the load arrows indicate the more common push-pull variant where the substrate is subjected to compression. In (c), the load arrows indicate the pull-pull variant.

substrate and applying an increasing slip until the plate eventually debonds. To date, pull-tests on masonry substrates have covered a range of:

- Retrofit types, including externally-bonded (EB) and near-surface-mounted (NSM);
- Composite materials, including carbon FRP (CFRP), glass FRP (GFRP), basalt FRP (BFRP), aramid FRP (AFRP), and steel-reinforced polymers (SRP); and
- Substrate materials, including clay brick, concrete block, and various types of natural stone.

Pull-tests can provide insight into the local behaviour of the bond under shear deformation, which is typically characterised in terms a *bond-slip* (τ-δ) model relating shear stress to slip (Fig. 2). The predictive capability of the bond-slip model covers various aspects of retrofit behaviour including the debonding load, required anchorage length, axial strain profile, as well as the global load-slip (P-Δ) behaviour of the system. From a design perspective it is particularly useful to further define the bond-slip behaviour in terms of the mechanical properties of the substrate including its compressive and/or tensile strength. However, while substantial testing has been undertaken to date, there are as-yet no standardised guidelines for performing pull-tests. Consequently, a lack of consistent testing methodology and data analysis technique has to some extent hindered the definition of generalised material

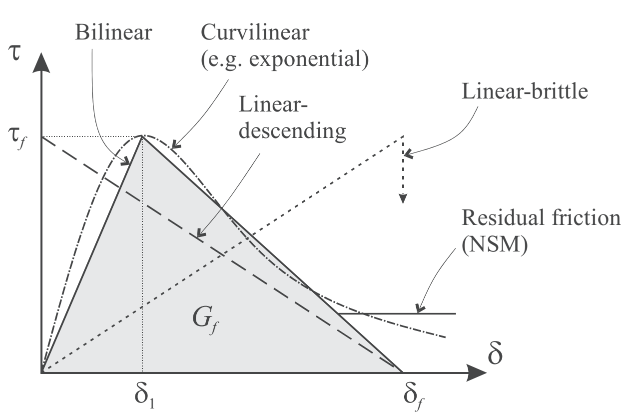

Fig. 2. Commonly used bond-slip models.

models necessary for design guidelines (e.g. [7,8], the discussion of which is the purpose of this paper.

This paper undertakes a state-of-the-art review by bringing together the results of 1583 individual pull-tests from 56 studies, in order to:

1. Identify the scope of previous testing in terms of FRP material properties, masonry material properties, and retrofit types;
2. Discuss the range of common testing methodologies including instrumentation requirements; and
3. Compare and critique the alternative methods of data processing for characterising the local bond-slip behaviour.

This paper is structured as follows. Section 2 describes the underlying mechanics governing FRP retrofits and the general approaches to calibrating bond models. The experimental database collected as part of this work is presented in Section 3 and further discussed in Section 4 in terms of scope of tests and experimental techniques. Recommendations for viable data processing approaches for extracting local bond-slip behaviour are provided in Section 5, and properties extracted from the experimental tests to date are discussed in Section 6.

2. Mechanics of FRP retrofits

2.1. Governing equations

It is commonly accepted that the mechanism of load transfer between FRP reinforcement and brittle substrates is governed by uniaxial shear lap theory, originally proposed by Volkersen [9]. Early works involving application of this theory toward structural retrofit were in the field of concrete which studied the use of adhesively bonded steel and FRP plates [10–12]. The theory has since gained widespread acceptance and formed the foundation for FRP retrofit predictive models in both concrete [13–16] and unreinforced masonry [8,17–26].

The basis of shear lap theory is that stress transfer across the bonded interface is controlled by a fundamental bond-slip law that relates shear stress (τ) to slip (δ) between the two adherents. This law can be represented by a variety of available forms, including those shown in Fig. 2. By enforcing the conditions of force equilibrium and compatibility between the interface slip and elastic deformations of the adherents, the following governing equations are obtained (e.g. [27,28]):