Global database of FRP-to-masonry bond strength tests

J. Vaculik, P. Visintin, N.G. Burton

The University of Adelaide, Australia

Abstract

Quantifying the bond strength between fibre-reinforced-polymer (FRP) composites and substrates is essential to the design of FRP retrofit systems. This paper collates a database of 1583 individual tests across 56 published experimental campaigns investigating the FRP-to-masonry bond strength through shear pull-tests. Included in the database is all available information characterizing the test arrangement, geometric and mechanical properties of the constituents, as well as the failure load and failure mode.

© 2018 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).
Value of the data

- Quantification of bond strength is essential to the design of FRP retrofit systems for strengthening structures.
- The database presented collates the results of 1583 bond strength tests from 56 published studies.
- The data can be used as the basis for the calibration of new bond strength design rules.
- The data can be used as a benchmarking dataset for comparing new and existing design rules.

1. Data

Through an extensive literature review, an experimental database of 1583 individual shear pull-tests on masonry specimens was compiled from across 56 published studies [1–56].

1.1. Description of a pull-test

A generic pull-test specimen consists of a fibre-reinforced-polymer (FRP) composite plate adhesively bonded to a substrate prism over a particular lap length. The substrate prism can be either a unit prism consisting of a single brick or block, or a masonry prism consisting of individual units bonded together using mortar joints. Both of these are shown in Fig. 1.

A test is performed by applying an increasing tensile force to the FRP plate until the plate eventually debonds from the prism. Typical debonding failure involves the detachment of the plate along with a layer of the substrate material. Alternate failure modes (other than substrate debonding can include FRP rupture, failure at the adhesive, prism material failure (compression, tension or shear), or a combination of these.

The test results summarised in the compiled database include the maximum load and a description of the observed failure mode. Note that the various possible forms of instrumentation can include the measurement of strain along the plate using strain gauges, slip (displacement) between

![Fig. 1. Generic pull-test specimen and associated geometric definitions for (a) unit prism, and (b) masonry prism.](image-url)
the plate and the prism, or full-field deformation by techniques such as digital image correlation. However, as the focus of the database is the bond strength, these are beyond the scope of the data.

1.2. Scope of tests in the database

1.2.1. Substrate materials

Tested substrate materials include clay brick, limestone, tuff, concrete block, calcium silicate brick, sandstone, and mortar specimens. Data for each test includes the mechanical properties of the substrate material including its compressive and tensile strength. The tensile strength is further subcategorised in terms of the type of test performed as either direct, flexural, splitting, or unspecified.

1.2.2. FRP materials

The database covers both externally-bonded (EB) and near-surface-mounted (NSM) retrofits, as shown in Fig. 2. The different possible reinforcement shapes include EB sheets (a.k.a. fabrics) installed by wet lay-up (see Fig. 2a), and pre-formed rectangular strips and round bars used in NSM applications (Fig. 2b and c).

Composite materials include carbon FRP (CFRP), glass FRP (GFRP), basalt FRP (BFRP), steel-reinforced polymers (SRP), aramid FRP (AFRP), and natural flax FRP. The majority of tests use epoxy adhesive but some also use polyurethane or cementitious adhesive.

![Fig. 2. Cross section and geometric definitions in (a) an externally-bonded retrofit, (b) NSM retrofit using a rectangular strip, and (c) NSM retrofit using a circular rod.](image-url)

![Fig. 3. Alternate test arrangements including: (a) single lap, (b) double lap, and (c) two-block double lap.](image-url)
1.2.3. Test arrangements

Tests within the database are split approximately evenly between single-lap and double-lap arrangements, with the latter being further subcategorised into a single block and a double block variant. Each of these are shown in Fig. 3. Note that for double-lap arrangement the reported ultimate load corresponds to the load in a single lap, $P$ as shown in Fig. 3.

The majority of tests in the database use monotonic loading. However, a small number of tests used cyclic loading comprising separate loading, unloading and reloading phases.

Table 1
Definition of columns within the database.

| Col. | Header                          | Description                                                                 |
|------|---------------------------------|-----------------------------------------------------------------------------|
| 1    | Reference                       | Original reference author and year                                         |
| 2    | Test ID                         | Test identifier                                                             |
| 3    | Substrate Material (Family)     | Substrate material family: ‘Clay Brick’, ‘Limestone’, ‘Tuff’, ‘Sandstone’, ‘Concrete Block’, ‘Calcium Silicate Brick’, or ‘Mortar’ |
| 4    | Substrate Material (Descriptive) | More detailed description of the substrate material. Used also to distinguish between unique substrates reported in the original reference. |
| 5    | fuc (MPa)                       | Compressive strength of substrate unit                                     |
| 6    | fut,dir (MPa)                   | Tensile strength of substrate unit from direct tension test                |
| 7    | fut,flex (MPa)                  | Tensile strength of substrate unit from flexural test                      |
| 8    | fut,split (MPa)                 | Tensile strength of substrate unit from splitting test                     |
| 9    | fut,unspec (MPa)                | Tensile strength of substrate unit from unspecified type of test           |
| 10   | Prism                           | Prism type as either ‘Unit’ (individual unit only) or ‘Masonry’ (units + mortar) |
| 11   | bs (mm)                         | Width of prism                                                              |
| 12   | ts (mm)                         | Depth of prism (perpendicular to bonded face)                              |
| 13   | hs (mm)                         | Height of prism (parallel to FRP axis)                                     |
| 14   | hu (mm)                         | Height of individual unit measured parallel to FRP axis (applies to masonry prisms only) |
| 15   | tj (mm)                         | Thickness of mortar joints measured parallel to FRP axis (applies to masonry prisms only) |
| 16   | Cored Units                     | Denotes whether units are cored                                            |
| 17   | Through Perpends                 | Denotes whether FRP passes through perpend joints                          |
| 18   | Has Precomp                     | Denotes whether specimen has precompression                               |
| 19   | Is Repaired                     | Denotes whether specimen is a previously tested and repaired specimen      |
| 20   | Other Special Features          | Any special features other than those listed in the previous several columns |
| 21   | Laps                            | Number of tested laps. Can be ‘Single’, ‘Double’ or ‘2-Block Double’ (i.e. 4 laps) |
| 22   | FRP Material                    | FRP material: CFRP, GFRP, BFRP, SRP, AFRP or Flax                          |
| 23   | FRP Shape                       | Shape of FRP material: ‘Sheet’ (wet lay-up fabric), ‘Strip’ (rectangular) or ‘Rod’ (round) |
| 24   | FRP Configuration               | Type of retrofit: ‘EB’ (externally-bonded) or ‘NSM’ (near-surface-mounted) |
| 25   | .places (MPa)                   | Ultimate tensile stress of FRP                                             |
| 26   | Ep (MPa)                        | Modulus of elasticity of FRP                                               |
| 27   | bp (mm)                         | Width of FRP plate (in both EB and NSM)                                    |
| 28   | tp (EB) (mm)                    | Thickness of FRP plate (applies to EB only)                                |
| 29   | dp (NSM) (mm)                   | Depth of the FRP plate (applies to NSM only)                               |
| 30   | Lb (mm)                         | Bonded length of plate (along FRP axis)                                    |
| 31   | Lu1 (mm)                        | Unbonded length provided at the loaded end of specimen                     |
| 32   | Adhesive type                   | “Epoxy” or “Cementitious”                                                  |
| 33   | Loading                         | “Monotonic” or “Cyclic”                                                    |
| 34   | Pmax (kN)                       | Failure load                                                                |
| 35   | No. Reps                        | Number of repetitions (denotes whether given Pmax is given as average of multiple) |
| 36   | cov(Pmax)                       | Coefficient of variation in Pmax (applies only to cases where Pmax is given as average of multiple) |
| 37   | Failure Mode                    | Reported failure mode(s): “Substrate Debonding”, “FRP rupture”, “Adhesive failure”, “Prism failure”, or a combination. |
| 38   | Comment                         | Provides comment regarding any provided information that differs from the original paper |
1.3. Data inclusion/exclusion criteria

The database includes only tests conducted under standard conditions, that is, where the plate is bonded directly to the masonry substrate and subjected to quasi-static loading. The data therefore excludes the following:

- Specimens subjected to effects such as temperature and moisture [5,25,29,33,41,46,51,52];
- Tests in which additional anchorage between the FRP and substrate was provided. For example, those with nails, fans or cogs [9,18,24,30,32,55];
- Tests in which the FRP was bonded to plaster instead of directly to the masonry substrate [9,39,42,55,56];
- Non-quasi-static loading conditions such as impulse loads [54]; and
- Plates manufactured from textile-reinforced mortars or fibre-reinforced cementitious mortars.

These exclusion criteria were applied to individual tests, and as such, control specimens found in the aforementioned studies are still included. Note that some studies have intentionally opted not to report the failure load for tests where the mode of failure was not by interfacial debonding—such tests are still included as long as the mode of failure was reported. Additionally, where the same tests were identified to have been reported in multiple sources, they are only included once.

The database also includes tests with the following special conditions, which are specifically identified in the database:

- Tests with confining pre-compression (30 tests) [13,19];
- Curved specimens (10 tests) [18]; and
- Specimens that were repaired after an initial test and re-tested (98 tests) [34,40,50].

1.4. Description of information provided in the database

The compiled database is provided as a CSV (comma separated variable) spreadsheet in Supplementary Material accompanying this article. Table 1 summarises the data provided for each individual pull-test. Note that fields entered as ‘-’ mean that the data is either not relevant to the particular test or that it was not specified in the original paper.

Acknowledgments

The authors gratefully acknowledge the financial support from the ARC through its Discovery Grant Program (DP140102695). The findings and views expressed are those of the authors and not necessarily those of the sponsors.

Transparency document. Supporting information

Transparency data associated with this article can be found in the online version at https://doi.org/10.1016/j.dib.2018.08.111.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.dib.2018.08.111.
[32] M. Fagone, G. Ranocchiai, C. Caggegi, S. Briccoli Bati, M. Cuomo, The efficiency of mechanical anchors in CFRP strengthening of masonry: an experimental analysis, Compos. Part B: Eng. 64 (2014) 1–15.

[33] B. Ghiassi, D.V. Oliveira, P.B. Lourenço, Hygrothermal durability of bond in FRP-strengthened masonry, Mater. Struct./Mater. Constr. 47 (12) (2014) 2039–2050.

[34] A. Kwiecien, Shear bond of composites-to-brick applied with highly deformable, in relation to resin epoxy, interface materials, Mater. Struct./Mater. Constr. 47 (12) (2014) 2005–2020.

[35] H. Maljaee, B. Ghiassi, P.B. Lourenço, D.V. Oliveira, “Bond performance in NSM-strengthened masonry brick.”, in: Proceedings of the 9th National Conference of Experimental Mechanics, 2014.

[36] G. Barbieri, L. Biolzi, M. Bociarelli, S. Cattaneo, Pull out of FRP reinforcement from masonry pillars: experimental and numerical results, Compos. Part B: Eng. 69 (2015) 516–525.

[37] F.G. Carozzi, P. Colombi, C. Poggi, Calibration of end-debonding strength model for FRP-reinforced masonry, Compos. Struct. 120 (2015) 366–377.

[38] F. Ceroni, A. Garofano, M. Pecce, Bond tests on tuff elements externally bonded with FRP materials, Mater. Struct./Mater. Et. Constr. 48 (7) (2015) 2093–2110.

[39] B. Ghiassi, J. Xavier, D.V. Oliveira, A. Kwiecien, P.B. Lourenço, B. Zając, Evaluation of the bond performance in FRP-brick components re-bonded after initial delamination, Compos. Struct. 123 (2015) 271–281.

[40] B. Ghiassi, P.B. Lourenço, D.V. Oliveira, Accelerated hygrothermal aging of bond in FRP-masonry systems, J. Compos. Constr. 19 (3) (2015).

[41] A. Hosseini, D. Mostofinejad, M. Emami, Influence of bonding technique on bond behavior of CFRP-to-clay brick masonry joints: experimental study using particle image velocimetry (PIV), Int. J. Adhes. Adhes. 59 (2015) 27–39.

[42] C. Mazzotti, B. Ferracuti, A. Bellini, Experimental bond tests on masonry panels strengthened by FRP, Compos. Part B: Eng. 80 (2015) 223–237.

[43] C. Mazzotti, B. Ferracuti, A. Bellini, Experimental study on masonry panels strengthened by GFRP: the role of inclination between mortar joints and GFRP sheets, Key Eng. Mater. 624 (2015) 559–566.

[44] M. Panizza, E. Garbin, M.R. Valluzzi, C. Modena, Experimental study of the bond of FRP applied to natural stones and masonry prisms, Key Eng. Mater. 624 (2015) 453–460.

[45] T. Rotunno, L. Rovero, U. Tonietti, S. Briccoli Bati, Experimental study of bond behavior of CFRP-to-brick joints, J. Compos. Constr. 19 (3) (2015).

[46] M.S. Sciolti, M.A. Aiello, M. Frigione, Effect of thermo-hygrometric exposure on FRP, natural stone and their adhesive interface, Compos. Part B: Eng. 80 (2015) 162–176.

[47] O. Anil, C. Durucan, S.W. Din, Experimental study on the stress distribution at the interface between CFRP and three different types of masonry units, Compos. Part B: Eng. 92 (2016) 63–73.

[48] R. Capozucca, V. Ricci, Bond of GFRP strips on modern and historic brickwork masonry, Compos. Struct. 140 (2016) 540–555.

[49] G. de Felice, M.A. Aiello, A. Bellini, F. Ceroni, S. De Santis, E. Garbin, M. Leone, G.P. Lignola, M. Malena, C. Mazzotti, M. Panizza, M.R. Valluzzi, Experimental characterization of composite-to-brick masonry shear bond, Mater. Struct. 49 (7) (2016) 2581–2596.

[50] A. Kwiecien, G. de Felice, D.V. Oliveira, B. Zając, A. Bellini, S. De Santis, B. Ghiassi, G.P. Lignola, P.B. Lourenço, C. Mazzotti, A. Prota, Repair of composite-to-masonry bond using flexible matrix, Mater. Struct./Mater. Constr. 49 (7) (2016) 2563–2580.

[51] H. Maljaee, B. Ghiassi, P.B. Lourenço, D.V. Oliveira, FRP-brick masonry bond degradation under hygrothermal conditions, Compos. Struct. 147 (2016) 143–154.

[52] H. Maljaee, B. Ghiassi, P.B. Lourenço, D.V. Oliveira, Moisture-induced degradation of interfacial bond in FRP-strengthened masonry, Compos. Part B: Eng. 87 (2016) 47–58.

[53] A. Napoli, G. de Felice, S. De Santis, R. Realfonzo, Bond behaviour of Steel Reinforced Polymer strengthening systems, Compos. Struct. 152 (2016) 499–515.

[54] J.M. Pereira, P.B. Lourenço, Experimental bond behaviour of GFRP and masonry bricks under impulsive loading, Mater. Struct./Mater. Constr. 49 (11) (2016) 4799–4811.

[55] F. Ceroni, Bond tests to evaluate the effectiveness of anchoring devices for CFRP sheets epoxy bonded over masonry elements, Compos. Part B: Eng. 113 (2017) 317–330.

[56] F. Ceroni, M. Leone, V. Rizzo, A. Bellini, C. Mazzotti, Influence of mortar joints on the behaviour of FRP materials bonded to different masonry substrates, Eng. Struct. 153 (2017) 550–568.