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SERBESCU, Andreea, GUADAGNINI, Maurizio and PILAKOUTAS, Guadagnini

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Test Standardisation for FRP-to-Concrete Bond Characterisation

Andreea Serbescu
Sheffield Hallam University, Department of Built Environment
Norfolk Building, Sheffield
S1 1WB, UK

Maurizio Guadagnini and Kypros Pilakoutas
University of Sheffield, Department of Civil and Structural Engineering
Mappin Building, Sheffield
S1 3JD, UK

ABSTRACT

Brittle debonding of flexural FRP strengthening systems can occur at relatively low load levels, thus significantly reducing the FRP effectiveness and affecting the overall structural safety. Although various design models against debonding are available in the literature, they lead either unsafe or too conservative predictions. This could mainly be attributed to the lack of standardised methodology for experimental bond characterisation. Accordingly, design models continue to be developed or calibrated based on limited sets of experimental data.

This paper presents an investigation into the suitability of the double shear test setup to become a standardised test and suggests potential improvements. The experimental program in this study comprised a series of 20 double shear specimens and 6 types of FRP systems. The performance of the adopted double shear test set up is analysed in terms of reliability of bond stress-slip data obtained as well as the ease of specimen preparation and testing. In addition, the influence of the roughness of the concrete substrate on bond capacity is also assessed.

INTRODUCTION

The use of Fibre Reinforced Polymer (FRP) Externally Bonded Reinforcement (EBR) is currently the leading structural strengthening solution for reinforced concrete (RC) beams. However, the weakest link is the bonded interface [1] and to date a reliable, safe and economic design approach against debonding does not exist. The prediction ability of the vast amount of models available in the literature relies on the assumed relationship between shear stress and slip at the bonded interface as well as the calibration factors determined from parametric studies. In the absence of a standardised bond test, various studies adopt different test set-ups and use different test parameters, thus hindering the development of widely valid bond models.

Research efforts continue to be directed towards identification of the most reliable testing procedure for both laboratory studies as well as quality control on site applications [2]. Amongst other setups [3], the double-shear test was considered by the current study due to its potential to accurately capture the pure shear stress state at the interface between FRP and concrete as well as the ease of performing the test in universal testing machines available in most structural laboratories. The tests carried out and discussed in this paper formed part of an extensive international Round Robin Test exercise [4].

The main parameters that significantly influence the bond capacity of EBR systems, such as FRP stiffness, concrete tensile strength and effective bond length, are well established [6, 7, 8]. However, the effect of surface finish of the concrete substrate on bond capacity received less consideration in the published experimental studies and it has not been quantified. Most design guidelines include qualitative recommendations on surface preparation. For example, ACI 440-2R, TR 55 or CNR-DT 200 [5, 6, 7] simply recommend the preparation of concrete surface by grinding to ensure a certain roughness degree. However, a high impact preparation, such as bush hammering, may potentially weaken the surface and thus, high levels of roughness are reported by some researchers to adversely affect the concrete surface by inducing microcracks [9]. On the other hand, a too fine grinding of the surface may limit the development of the interfacial bond stress.

EXPERIMENTAL PROGRAM

Specimens and Materials

Each of the 20 specimens tested comprised two concrete prisms of 400mmx150mmx150mm. A bond length of 300mm was chosen for each prism, as recommended by fib 40 [8]. The FRP plates were left un-bonded for 100mm in the central zone so as to avoid any shearing of the concrete corners.

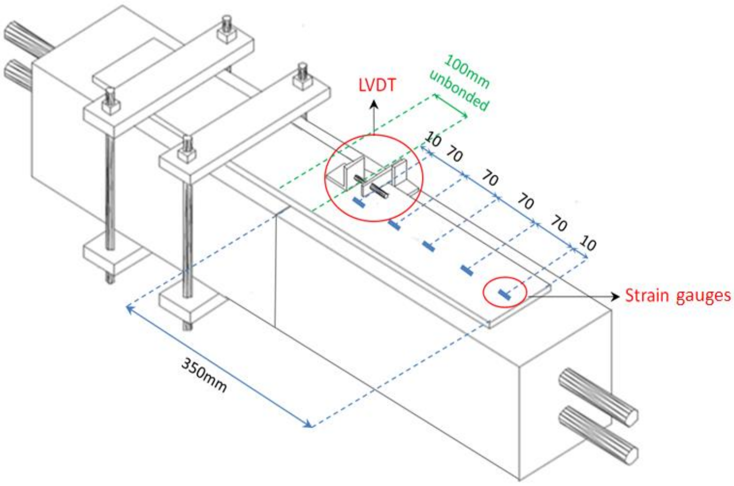

Figure 1. Test set-up and instrumentation

A total of 6 different FRP systems were tested and their properties are shown in Table 1. Three specimens were tested for each test group except for C5 for which only two specimens were tested.

Table 1. FRP Plates

Test Group	FRP Plates					
	Width b_f [mm]	Thickness t_f [mm]	Area A [mm^2]	Strength f_f [MPa]	Modulus E_f [GPa]	Strain ε_u [%]
C1A	100	1.2	120	3100	165	1.7
C1B	100	1.4	140	3100	210	1.3
C1C and C1C-R	60	1.3	78	3100	165	1.7
C3	100	1.2	120	2850	165	-
C4	100	1.4	140	3100	170	1.6
C5	80	1.2	96	2590	200	-

The concrete strength at the time of testing was 27.2 MPa. The structural adhesive used was that recommended by each FRP manufacturer and was applied using a steel template to ensure a uniform thickness of 2mm.

Two degrees of surface roughness were considered. A smooth surface finish (minimally surface preparation) was achieved by simple wire brushing (C1 to C5 specimens). After debonding of the C1C specimens, the FRP plates were completely removed and new ones bonded (specimens C1C-R). A high degree of roughness was achieved for specimens C1C-R as a result of the removal of a thin layer of concrete after plate debonding of specimens C1C. These smooth and rough surface preparation levels correspond to the roughness grades CSP 1 and CSP 3-6 of ICRI, 1997 [10].

Test set up

The tensile load was applied using two 16 mm steel bars protruding from each end of the concrete specimens (Fig. 1). The load was applied by displacement control with a rate of 0.05 mm/min. The displacements and strains at various locations along the sides of the test prisms were measured using LVDTs and strain gauges installed as shown in Fig. 1.

RESULTS AND DISCUSSION

Failure Modes

As expected, all specimens failed primarily due to debonding by shear induced peel-off at the adhesive to concrete interface. A very thin layer of mostly cement paste remained attached to the FRP plate after failure (Fig. 2 left and middle).

Figure 2. Typical peel-off (left), failure appearance of specimens with smooth (middle) and rough (right) surface preparation

Although a similar failure mode was observed for specimens with a rough substrate, C1C-Rs, the debonding in this case propagated deeper and resulted into a thicker concrete layer with exposed aggregates attached to the FRP plate (Fig. 2 right). This was enabled by a better adhesion due to a deeper ingress of the adhesive and greater mechanical interlock after hardening.

Bond Behaviour

The behaviour of all 20 specimens tested in this experimental program was very similar. Thus, for clarity, only the behaviour of specimen C3-2 is discussed in detail herein. Table 2 shows the test results for this specimen alongside the others in the C3 test group, for statistical purposes.

Table 2. C3-specimens

Specimen	Experimental					Calculated Maximum Local		Debonding Load in [%] of Ultimate Load
	Ultimate Load P_{max} [kN]	FRP Strength σ_u [MPa]	FRP Max Strain ε_u [%]	Average Bond Stress τ_m [MPa]	Slip s_{LVDT} [mm]	Bond Stress τ_{max} [MPa]	Slip s_{max} [mm]	
C3-1	17.1	142.7	0.10	0.57	0.27	1.42	0.13	95
C3-2	23.2	193.0	0.14	0.77	0.32	2.00	0.25	90
C3-3	26.4	220.3	0.16	0.88	-	1.79	0.24	80
Mean	22.2	185.3	0.13	0.74	0.30	1.74	0.21	88
St. Dev.	4.7	39.4	0.03	0.16	0.04	0.29	0.07	7.6
COV	0.21	0.21	0.23	0.21	0.12	0.17	0.32	0.09

Local bond stress values were determined by derivation of the strain measurements [11]. For each specimen, debonding was considered to initiate at the load level causing a major shift of the peak local bond stress. As can be seen in Fig. 3 left, debonding for specimen C3-2 initiated at 90% of the maximum applied load; after this load level, debonding quickly propagated and the specimen failed. The maximum local bond stress is reached at the initiation of debonding and it is considered herein as the bond capacity. At each level of the applied load, the tensile force developed in the FRP plate transfers to the concrete along a certain bonded length. Graphically, this transfer length can be identified as the distance from the loaded end to the section at which the local bond stress tends to zero, for each load level (Fig. 3 left). The transfer length corresponding to the maximum local bond stress represents the effective length and relates to the maximum force that can possibly be sustained by the FRP plate. Experimentally, bond stresses reach zero values only at complete detachment of the plate. Thus, the softening branches of bond stress distributions at each load levels were extrapolated to zero and the corresponding transfer length identified. These values are shown in Fig. 3 right alongside the effective length value of 208mm identified as the maximum value of transfer length before the shift of bond stress occurred (Fig. 3 left). As can be seen, the transfer length is relatively constant with load application until debonding initiates (~90%), at which point this length rapidly increases in an unstable manner.

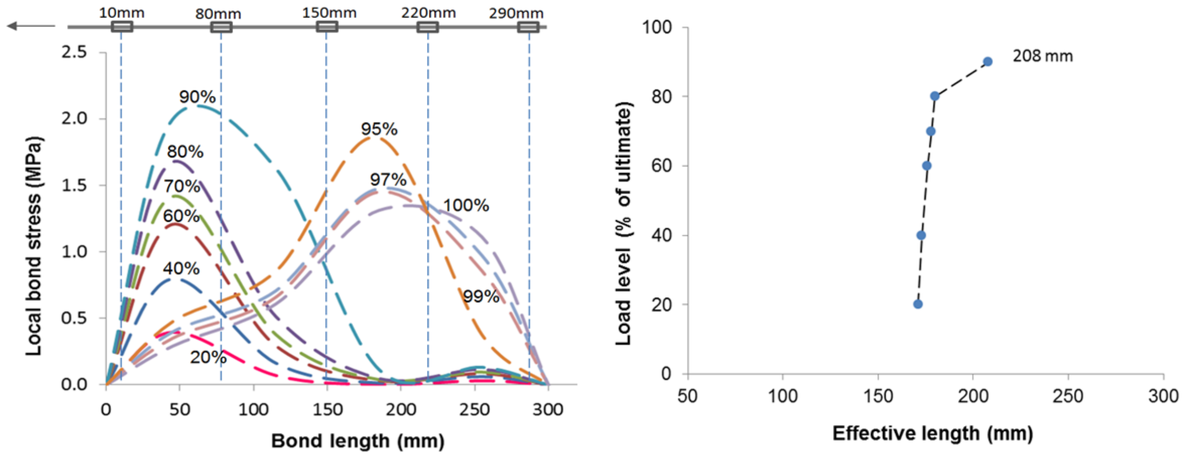

Figure 3. Bond length (left) and effective length (right)

The analytical slip values (s_{SG}) were calculated by integration of the strain measurements [11]. Figure 4 left indicates the location of debonding based on the maximum slip developed. Figure 4 right shows the comparison between the calculated and experimentally measured slip values (s_{LVDT}). As can be seen, the variation of the calculated slip was found to be generally similar to that of the measured slip.

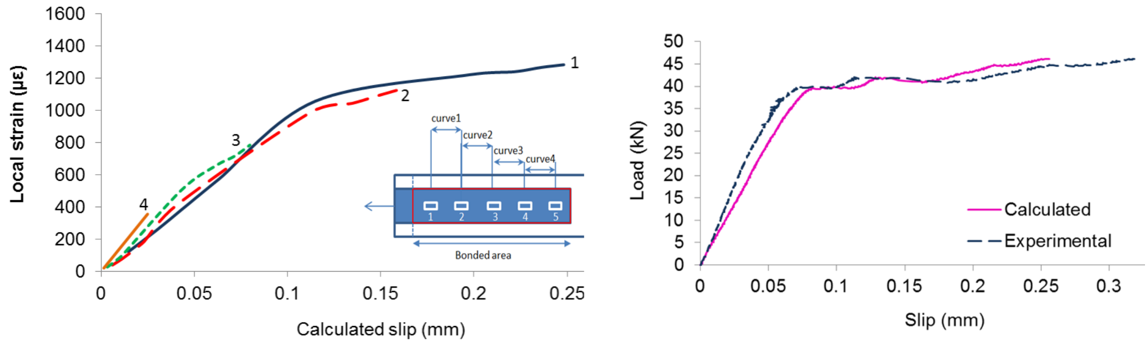

Figure 4. Calculated slip development (left) and calculated vs. measured slip comparison (right)

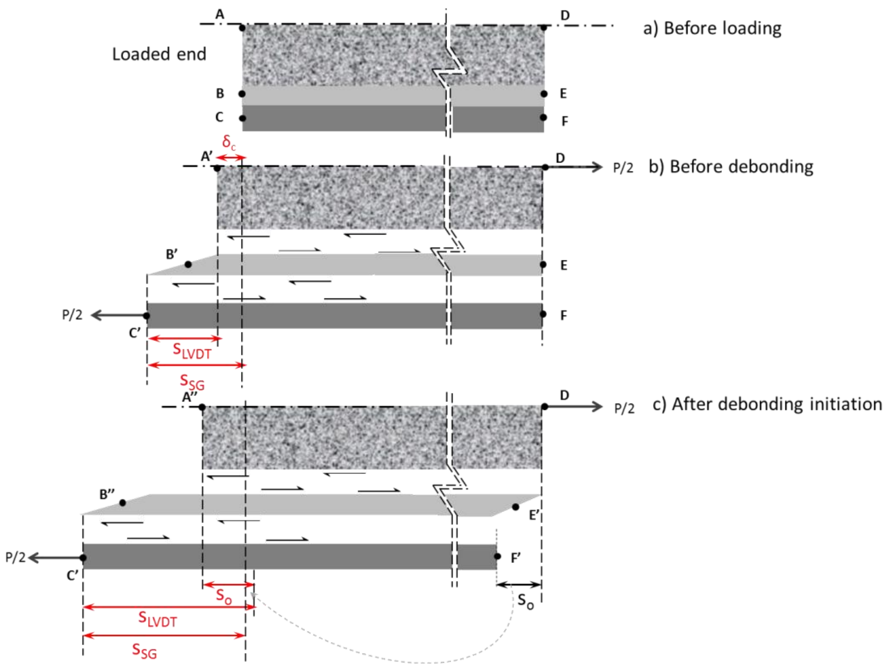

Figure 5. Schematic illustration of the actual deformations

However, as can be seen in Fig. 4 right, the calculated slip is higher at the early stages of loading and lower at the later stages. This can be explained by the fact that at early stages, the elastic extension of the concrete substrate δ_c is not captured by the strain gauges (Fig. 5). On the contrary, close to debonding load, the calculated slip, s_{SG}, becomes lower as the small deformation at the unloaded end s_0 is captured by the transducers. However, bending or uneven substrate stiffness alongside large spacing of strain gauges can also cause differences between measured and calculated values of slip.

Effect of surface preparation on bond capacity

The roughness of the concrete substrate was found to influence significantly the bond capacity. Table 3 and Figure 6 show a comparison between specimens with a smooth surface (C1C-2 and C1C-3) and those with a rough surface (C1C-R-2 and C1C-R-3).

Table 3. C1C and C1C-R specimens

Specimen	Experimental					Calculated Maximum Local		Debonding Load in [%] of Ultimate Load
	Ultimate Load P_{max} [kN]	FRP Strength σ_u [MPa]	FRP Max Strain ε_u [%]	Average Bond Stress τ_m [MPa]	Slip s_{LVDT} [mm]	Bond Stress τ_{max} [MPa]	Slip s_{max} [mm]	
C1C-2	14.92	191.3	0.11	0.83	0.19	2.63	0.19	90
C1C-3	16.23	208.1	0.12	0.90	*0.05*	2.27	0.21	90
C1C-R-2	27.43	352	0.24	1.52	0.36	3.59	0.30	70
C1C-R-3	27.57	354	0.24	1.53	0.30	3.86	0.27	90

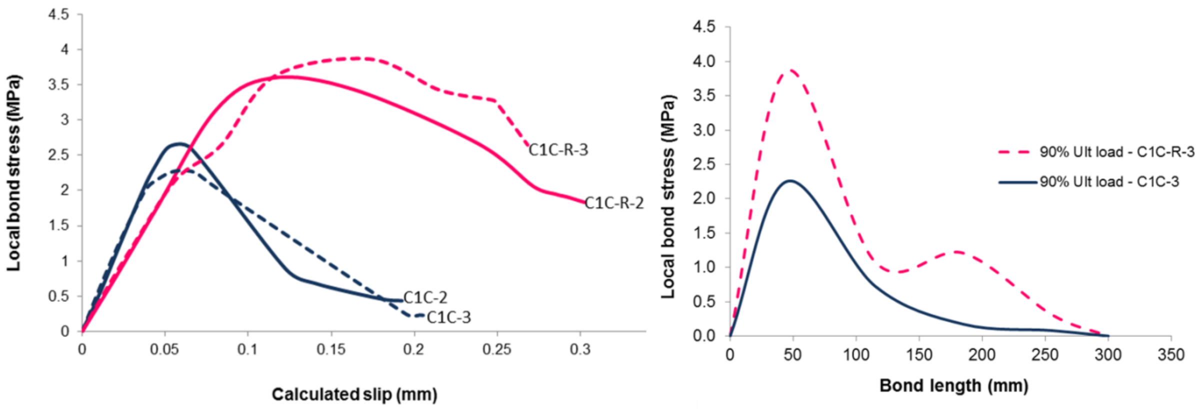

Figure 6. Local bond stress distribution for C1C-3 and C1C-R-3 specimens

It can be seen that the deformation capacity exhibited by specimens with a rough surface finish was almost double of those by specimens with a smooth surface (Fig. 6 left). Furthermore, it can be seen from Fig. 6 right that a rougher substrate enabled the development of almost twice the local maximum bond stress along the bonded length. Comparing the parameters of the bilinear bond stress-slip models shown in Fig. 6 left, it can be seen that, as expected, higher fracture energy (area under the curve) is developed for the specimens with the rougher substrate finish.

Performance of double-shear test set-up

Overall, the double-shear tests appear to represent a reliable tool for the characterizations of bond capacity. However, the performance strongly relies on the perfect alignment of the prisms and embedded steel bars and this was very difficult to ensure. The specimens were also found to be very sensitive to the handling and installation operations. Even small relative movements could induce cracking at the bonded interface and affect the actual test results. It is therefore suggested to cast the prisms on a rigid surface, such as a steel plate, which could be removed after the double-shear specimen is mounted into the testing machine. To reduce the variability of the results and capture more accurately the local bond development, closer spacing of strain gauges could be adopted.

CONCLUSIONS

From the analysis of the results obtained in this experimental program, the following main conclusions are drawn:

The double shear test is a strong candidate for a standardised test to characterise peel-off debonding and carry out parametric studies towards the development of improved design model. However, the test results were found highly sensitive to the alignment of the two individual prisms and embedded steel bars. Misalignment of the steel bars not only may weaken the bonded interface but also result in the tensile load being eccentrically applied and thus lead to inaccurate results. A solution to ensure alignment was suggested. An initial loading rate of 0.1mm/min tried on one of the specimens was found too fast and thus a rate of 0.05mm/min was adopted and recommended for such tests.

The bond strength is significantly affected by the concrete surface preparation, which should be taken into account at the design stage. As expected, higher degree of roughness enables higher bond capacities to be developed. However, it should be noted that severe roughening may instead weaken the surface. On the other hand, the same preparation technique could result in different degrees of surface finish, and more quantitative techniques, such as surface profilometry, can be adopted prior to bonding, as a quality control measure.

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