Composites Part B 74 (2015) 42–52

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

# Experimental study of bond-slip of GFRP bars in concrete under sustained loads

I. Vilanova, M. Baena*, L. Torres, C. Barris

*Analysis and Advanced Materials for Structural Design (AMADE), Polytechnic School, University of Girona, Campus Montilivi s/n, 17071 Girona, Spain*

ARTICLE INFO

*Article history:*
Received 17 October 2014
Received in revised form
24 December 2014
Accepted 7 January 2015
Available online 13 January 2015

*Keywords:*
A. Glass fibres
B. Debonding
D. Mechanical testing

ABSTRACT

The structural behaviour of reinforced concrete (RC) elements depends heavily on the bond performance between the concrete and the reinforcing material. Bond behaviour under short-term testing has been extensively analysed for steel reinforcement and many studies have been carried out for fibre reinforced polymer (FRP) reinforcement. However, there has only been limited investigation of the long-term effects of this interaction. Several factors can affect the long-term bond behaviour of these elements, the most important being bond length and the immediate and time-dependent properties of reinforcement and concrete (concrete grade, creep, shrinkage and stiffness). This time-dependent behaviour is likely to cause changes and redistributions in bond stresses not properly considered in the limited existing literature. In this experimental study, the bond performance of GFRP RC under sustained load is investigated through pull-out tests. A total of 12 pull-out specimens were tested for a period of between 90 and 130 days. Two concrete strengths (35 MPa and 50 MPa), two bond lengths (5 and 10 times the diameter of the reinforcing bar) and two reinforcing materials (glass fibre reinforced polymer (GFRP) and steel) were used. Experimental results regarding immediate and time-dependent slip are presented and analysed here. In addition, some specimens were instrumented, with internal strain gauges in the reinforcing bar to provide data on the reinforcement strain, thus allowing the distribution of bond stresses and their evolution during sustained loading to be also presented and analysed.



## 1. Introduction

Fibre reinforced polymer (FRP) bars are increasingly being used as an alternative to steel reinforcement for reinforced concrete (RC) elements in corrosive environments or when the effects of electromagnetic fields may be present [1–3]. This has led to an increasing interest in the knowledge of properties and the study of different aspects of behaviour of FRP RC structures [4–14]. The viability of these recently introduced materials largely depends on the effectiveness of the bond between the FRP bar and the concrete. In this regard, pull-out tests are probably one of the tests most extensively used to characterize the behaviour of the interface between the reinforcement and the concrete by means of bond-slip response. In the last two decades, considerable experimental research has gone into investigating the short-term response of FRP-to-concrete interfaces [15–24], with it being generally concluded that the pull-out mechanism of the many existing types of FRP reinforcement differs from that of deformed steel bars and is dependent on even more parameters [20,25].

When analysing time effects on the behaviour of RC elements, concrete creep and shrinkage play a crucial role [26–32]. While creep is associated with sustained stresses, shrinkage may be assumed to be independent of load, but both cause long-term deformations in concrete. For common steel RC no additional long-term effects need to be considered because steel undergoes neither shrinkage nor creep. Few studies have focused on the possible effect of creep in FRP reinforcement. An experimental programme with regard to such an effect in aggressive environments was presented in Ref. [33]. The programme consisted of testing twenty GFRP bars in tension for 417 days at two loading levels (25% and 38% of the ultimate bar tensile strength). The results showed that creep strain in the GFRP bars was less than 5% of the initial strain value. It was also concluded that long-term loading had a minimal effect on the elastic modulus, whilst the effect on residual strength was more dependent on the environmental conditions. A more recent programme was presented in Ref. [34], where GFRP pultruded laminates were tested under a tensile

* Corresponding author. Tel.: +34 972419517; fax: +34 972418098.
*E-mail address:* marta.baena@udg.edu (M. Baena).

http://dx.doi.org/10.1016/j.compositesb.2015.01.006
1359-8368/

sustained load for 500 days. The authors observed that the largest increments in longitudinal stresses due to long-term testing were less than 2%. The components (matrix and reinforcement or polyester resin and glass fibres) were tested separately to check their individual long-term responses. A significant increase in longitudinal strain was observed for the polyester resin while only a negligible increase was obtained for the glass fibres.

The literature dealing with time effect on the bond behaviour of FRP reinforcement and concrete is also limited in extent [35–38]. An experimental study of long-term behaviour of CFRP externally reinforced concrete elements covering three bond lengths and two loading levels was presented in Ref. [35], where the evolution of reinforcement axial stresses and bond stresses under constant tensile load was analysed over 900 days of testing. Results showed a redistribution of bond stresses along the anchorage due to creep deformations at the interface. In respect of internal reinforcement, degradation of the bond between FRP bars and concrete under sustained load was analysed in Ref. [36] through a pull-out testing procedure. The experimental work included four different reinforcing materials as well as different environmental conditions, with pull-out specimens being loaded for one year at different loading levels. Results showed an increase in slip with time, with this increase being dependent on the bar surface treatment and the level of sustained load. A more recent experimental study of the bond behaviour of internal GFRP reinforcement and concrete under sustained loading was presented in Ref. [37]. The pull-out specimens, which combined three different bar diameters, were preloaded until one millimetre of slip was observed at the unloaded end. Following this, the specimens were loaded until slip stabilization. The tests were considered to be acceptable if no increase in slip was observed after 2000 h. To simulate accelerated long-term testing, the tests were conducted at 60 °C, and a design value of bond strength was proposed by the authors based on the experimental data. The long-term effect on steel and GFRP internally reinforced concrete members under tension has been analysed in a study made by the present authors [38]. The experimental programme included three different concrete strengths and two different reinforcing materials. The evolution of reinforcement strains was monitored, and slips and bond stresses were analysed. Results showed that long-term testing caused a reduction in mean bond stress of about 28%, which highlights the importance of analysing and understanding bond behaviour in the long term. Since limited literature exists on this issue, an experimental long-term bond test programme is needed.

This paper presents the results of an experimental campaign consisting of twelve pull-out specimens tested under sustained axial load for a period between 90 and 130 days. The programme included two concrete strengths, two reinforcing materials and two bond lengths. The sustained load level was set at 15% of the ultimate capacity of the GFRP reinforcing bar to ensure it corresponded to the service load range. Experimental results in terms of immediate and time-dependent slip are presented and analysed. Some specimens were instrumented, with internal strain gauges in the reinforcing bar, to provide data on the reinforcement strain, thus allowing the distribution of bond stresses and their evolution during sustained loading to be analysed.

## 2. Experimental programme

### 2.1. Test matrix

The experimental programme was aimed at studying the effect of concrete strength, reinforcing material and bond length on the bond response of pull-out tests under sustained loading. Two different target concrete compressive strengths (35 and 50 MPa), two different bond lengths (equal to $5d_r$ and $10d_r$, with $d_r$ being the nominal diameter of the reinforcing bar) and two reinforcing materials (GFRP and steel) were considered. So that axial stiffness ($EA$) would be similar in all tests, the reinforcement consisted of either a single 16 mm diameter GFRP bar or a single 10 mm diameter steel bar. The combination of these variables gave a total of eight specimens. So that the internal distribution of bond stresses could be analysed, four additional specimens were manufactured that included internal instrumentation of the GFRP reinforcing bar. Thus, the test matrix consisted of twelve pull-out specimens divided into two groups of six specimens each according to concrete grade.

Based on this description, the tested elements are identifiable by the formula CxBRi, with Cx standing for the type of concrete (C1 = 35 MPa, C2 = 50 MPa), B for the bond length (S = $5d_r$, L = $10d_r$), R for the type of reinforcement (F = GFRP, S = Steel), and "i" for the identification of specimens with internally instrumented reinforcement. The test matrix is summarized in Table 1.

All the specimens were cubic (200 mm sides) with a 600 mm bar located in the middle. Before casting, the bond length was appropriately marked, and a plastic tube was positioned to prevent contact along the remaining bar length. Steel housings were glued to the GFRP bars so that the pull-out load could be applied without damaging the bars.

### 2.2. Material properties

Ready-mixed concrete was used to cast the specimens. Compressive strength was determined at the time of loading (35 days after casting) by a standard cylinder test (150 × 300 mm) according to UNE 12390-3 [39]. The average values of the mechanical properties are summarized in Table 2.

In order to determine the characteristics of the GFRP and steel reinforcement, three samples for each material were tested under tension according to UNE ISO 15630-1:2011 [40] and ACI 44.3R-12 [41] respectively. The average values of the mechanical properties of the reinforcing bars are given in Table 3.

### 2.3. Test set-up

Three frames with a double lever system were used to apply a constant tensile load on the pull-out specimens (see Fig. 1). The amplification factor of the mechanical system was 11. In each frame, two pull-out specimens with the same reinforcing bar and concrete grade but of different bond length were connected in series (i.e. specimen C1SS was connected in series with specimen C1LS), which meant that the same load was applied to both

**Table 1**
Test matrix.

| Specimen | Concrete | Bond length, $l_b$ (mm) | Reinforcement | Reinforcement internal instrumentation |
|---|---|---|---|---|
| C1SS | C1 | 50 | Steel | No |
| C1SF | C1 | 80 | GFRP | No |
| C1SFi | C1 | 80 | GFRP | Yes |
| C1LS | C1 | 100 | Steel | No |
| C1LF | C1 | 160 | GFRP | No |
| C1LFi | C1 | 160 | GFRP | Yes |
| C2SS | C2 | 50 | Steel | No |
| C2SF | C2 | 80 | GFRP | No |
| C2SFi | C2 | 80 | GFRP | Yes |
| C2LS | C2 | 100 | Steel | No |
| C2LF | C2 | 160 | GFRP | No |
| C2LFi | C2 | 160 | GFRP | Yes |