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EXPERIMENTAL INVESTIGATION ON BONDING CARBON FIBER REINFORCED POLYMERIC PLATES TO CONCRETE SUBSTRATE

BY

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Abstract. Various researches have been carried out in the recent past years with the aim of demonstrating the feasibility of strengthening structures by means of composite materials. Thus, the use of externally bonded fiber reinforced polymeric composites (FRP), composite system for strengthening concrete structures became one of the most common application of FRP composites in civil engineering and has received a great amount of research attention. Bond behaviour between FRP and concrete has emerged as a major issue, being essential in shear and flexural applications. A great deal of the success of externally reinforced elements depends on the surface preparation, thus appropriate specifications regarding this matter will be also presented.

The experimental work consists in testing concrete specimens strengthened with different types of carbon fiber reinforced polymeric (CFRP) plates and subjected to double shear test. The empirical results obtained during the tests provide an adequate characterization of the interfacial region regarding bond strength, the bond – slip behaviour, as well as the types of failure.

Key words: bond strength; CFRP; concrete; double shear test; failure modes.

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1. Introduction

Concrete is one of the most utilized construction materials, as a result of its many advantages that it has, such as low cost, long service life (when properly mixed, placed and cured), ease of construction and high compressive strength. Thus, modern civilization relies upon the continuing performance of a wide variety of concrete or reinforced concrete (RC) structures, ranging from apartment buildings to bridges. However, numerous concrete structures suffer important degadations and damages due to environmental exposure or extraordinary overload or have insufficient strength because of defective construction, increased service load requirements, or updated codes, fiber reinforced polymer (FRP) composites strengthening becoming nowadays a commonly accepted and widespread technique (Rizkalla & Nanni, 2003; Triantafillou, 2007).

Modern practice in civil and structural engineering involves strengthening concrete structures by externally bonded FRP composite materials. This type of reinforcing system has a significant number of advantages, such as lightness, noncorrosive, nonmagnetic, strong and highly versatile, FRP products being, in certain cases, the ideal materials for structural strengthening and rehabilitation (Oprişan *et al.*, 2009; Cozmanciuc *et al.*, 2009, 2011).

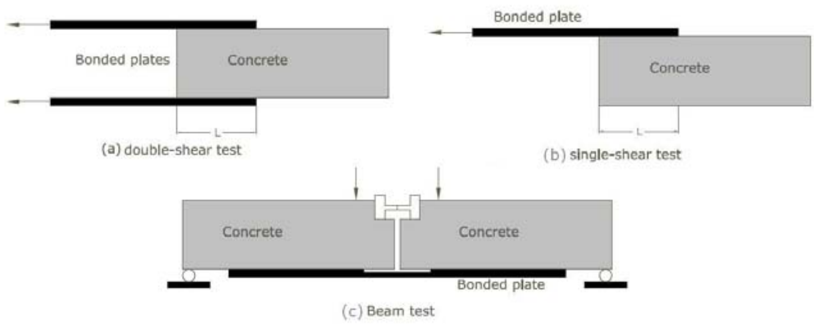

Fig. 1 – Bond test set-ups.

The two general types of applications of externally bonded FRP hybrid systems for concrete structures are known as contact-critical and bond-critical. In contact-critical applications load is transferred between FRP and concrete by contact stress (pressure) across the interface, as in passive column confinement. In bond-critical applications load is transferred by shear stress as well as peeling-stress, as in flexural and shear reinforcements for beams (Mirmiran *et al.*, 2004). Therefore the existing experimental work has been carried out using several set-ups, including single shear test (Yao *et al.*, 2005; Aiello & Leone, 2008; Resende *et al.*, 2007), double shear tests (Aiello & Leone, 2008; Aiello & Sciolti, 2006; Xiao *et al.*, 2004) and beam tests (Aprilew *et al.*, 2001) (Fig. 1).

Adhesive bonding plays an important role in providing effective stress transfer from the FRP to the substrate as well as in securing the integrity and durability of the FRP strengthened elements. For a maximum efficiency, non-uniform stress distribution should be reduced in order to avoid bond failure, which always begins at the maximum stress point (Oltean *et al*., 2009). Therefore, proper procedures for preparing the concrete surface and installing the FRP material should be followed.

This paper deals with the study of bond between CFRP plates and concrete. In this matter an experimental investigation was carried out aiming to determine an appropriate assessment of the interfacial region.

2. Specimen Properties and Experimental Set-up

2.1. Concrete

For the experimental program a single batch of concrete blocks with dimensions of 150 × 150 × 400 mm were realized from a concrete mix having a maximum aggregate size of 16 mm.

The concrete blocks were poured using a special designed steel mould, which was conceived to encase two concrete prisms that were separated by a thin metal plate (Fig. 2). Two steel bars were embedded into each prism. These bars do not connect the two concrete prisms, which means that the two prisms will be only connected through the bonded FRP surface reinforcement. The length of the protruding part of the steel bars has been chosen in order to guarantee the clamping in the tensile testing machine (Țăranu *et al.*, 2010).

Table 1
Properties of the Concrete Batch

Property	Concrete batch
Density, [kg/m^3]	2,350
Slump, [mm]	120
$f_{c,\text{cub}}$, [N/mm^2]	34.68
$f_{c,\text{cyl}}$, [N/mm^2]	31.37
E_c, [N/mm^2]	32,000

The target concrete cylinder strength is $f_{c,\text{cyl}}$ = 30 N/mm^2, thus the concrete mix was conceived in order to satisfy this requirement. The properties of the fresh and hardened concrete are presented in Table 1. The mechanical properties were determined on three specimens, namely the compressive strength was determined on three cylinders (150 × 300 mm) and on three cubes (150 × 150 × 150 mm).

Fig. 2 – Specimen mould.

2.2. Composite Plates

Three types of CFRP laminates were used at the current experiment, having the dimensions of 100 × 700 mm and a thickness smaller than 1.5 mm.

The main characteristics of the CFRP reinforcement were provided by the producer and listed in Table 2.

Table 2
CFRP Laminates Used

CFRP plate / Property	Sika Carbodur S1012	Sika Carbodur M1014	CFK 150/2000
Manufacturer	Sika	Sika	S&P Clever Reinforcement AG
Dimensions, [mm]	1.2 × 100 × 700	1.4 × 100 × 700	1.2 × 100 × 700
Modulus of elasticity, [N/mm^2]	165,000	210,000	165,000
Tensile strength N/mm^2	3,100	3,200	1,000
Elongation at break %	>1.7	>1.35	>0.60

2.3 Bonding Operation

Substrate surfaces are full of surprises, often they contain components that are very different from the bulk material, thus the behaviour of the hybrid system heavily depends on a good substrate and the preparation of its surface (Oltean *et al*., 2009).

Concrete surface preparation is a critical parameter in the bond performance of adhesives applied to concrete. Proper surface preparation provides a dry surface to avoid the presence of dirt, dust, oil and grease. Even moisture can absorb onto the surface of the substrate or onto the freshly applied adhesive to form a weak boundary layer (Ganga *et al*., 2007, Hollaway & Teng, 2008). Thus, the concrete surface was abraded and the grinding dust was removed (Fig. 3).

Fig. 3 – Preparation of the concrete surface.

Although bonding fibre reinforced polymeric composites to the concrete substrate is a relatively simple technique, the proper installation of the FRP composites is essential to ensure the adequate performance of the hybrid system. The CFRP reinforcement was bonded on two opposite sides of the concrete specimen, taking into account the application procedures as provided by the manufacturer. The CFRP plates were left un-bonded over a central zone of 100 mm, where the two concrete prisms connect each other (Fig. 4).

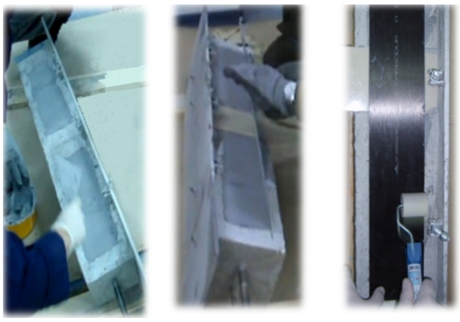

Fig. 4 – Bonding CFRP plates.

Sufficient pressure was applied with rollers to ensure a uniform adhesive layer and to expel any entrapped air. A good practical guide on spread is to observe the appearance and amount of squeeze out of adhesive when pressure is applied to the joint. If sufficient adhesive has been spread and pressure is then applied within permissible time limits a thin line of droplets of adhesive will be visible along all exposed joint edges. Absence of such squeeze out indicates insufficient spread or a too long delay before pressure application. Excessive adhesive running down the edges of the joints indicates that an excess has been spread, that the adhesive is too dilute or that pressure has been applied before the adhesive developed sufficient tack (Oltean *et al*., 2009).

2.4. Instrumentation and Loading Procedure

The proposed test set-up is shown schematically in Fig. 5, and detailed drawings of the instrumentation and positioning of the LVDTs and strain gages are illustrated in Fig. 6. The relative displacements between CFRP reinforcing laminates and concrete were recorded with LVDTs, placed on each monitored side, at the location of the transition between the central un-bonded and the bonded zone. Whereas, five strain gages were applied directly on the FRP reinforcement at 10, 80, 150, 220 and 290 mm from the end of the concrete prism.

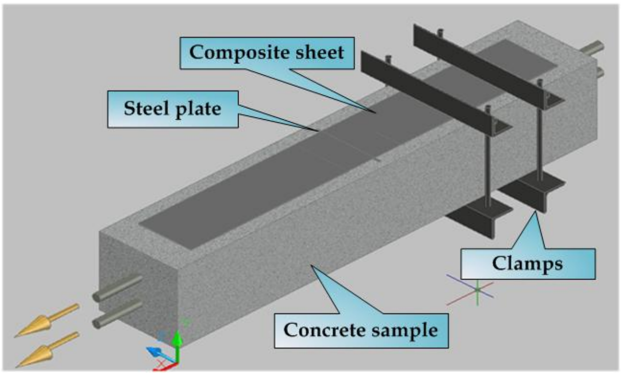

Fig. 5 – Specimen configuration.

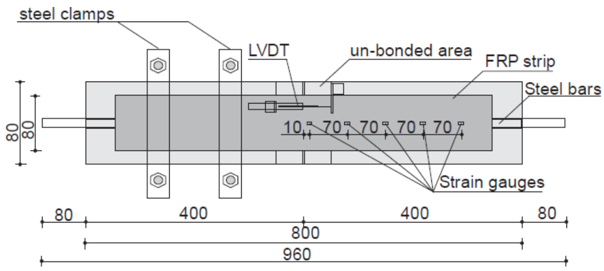

Fig. 6 – Specimen instrumentation.

Tests were carried out using a universal testing machine of 3,000 kN. The rate of loading (displacement rate or load rate) is preferred to be constant during the test. A displacement rate of 0.1 mm/min or a loading rate of 6 kN/min is proposed (Mathhys & Palmieri, 2008).

3. Experimental Results

In this section, on the basis of the performed tests, the influence of the investigated parameters on bond performance between FRP sheets and concrete has been analysed. The results are always reported in terms of the load taken per bond interface.

The double shear tests that have been performed on the prepared specimens are marked as follows: C1 for Sika Carbodur S1012, C2 for Sika Carbodur M1014 and C3 for CFK 150/2000 bonded plates. Tests were performed on three specimens of the same type, using an epoxy adhesive, namely Sikadur 30.

The average experimental results obtained for each set of specimens in terms of maximum load ($N_{fa,\max}$), ultimate strength (σ_u), tensile factor (σ_u/f_f), ultimate strain (ε_u) and maximum slip recorded by LVDTs (s_{LVDT}) are summarized in Table 3.

Table 3
Experimental Results

Specimen	C1	C2	C3
$N_{fa,\max}$, [kN]	46.2	57.8	57.15
σ_u , [MPa]	385.2	412.96	476.25
σ_u/f_f, [MPa]	12.43	13.32	–
ε_u , [%]	0.124	0.12	0.138
s_{LVDT} , [mm]	0.16	0.24	0.49

Debonding of the CFRP sheets from the concrete surface represents the most common failure mode (Oltean *et al*., 2010, 2011). The failure was initiated due to shearing of the concrete just beneath the adhesive layer. Beacause shear strength of concrete is proportional to tensile strength, the value of the ultimate bond strength will be proportional to tensile strength. Failure had a brittle manner, typical for concrete specimens with laterally attached CFRP bonded sheets (Fig. 7).

Fig. 7 – Typical failure mode.

From the measured strain profiles along the joint, it is possible to compute the mean shear stress distribution (Aiello & Leone, 2008; Bizindavyi

& Neale, 1999). Given two consecutive strain readings, ε_i and ε_{i+1}, at positions i and $i + 1$, the laminate thickness, t_f , its modulus of elasticity, E_f, and the distance, Δx_i , between the considered gages, one can determinate the average shear stress, $\tau(x)$, between two consecutive strain gages as follows:

$$\tau(x) = E_f t_f \frac{\Delta\varepsilon_i}{\Delta x_i}. \quad (1)$$

Through the integration of the strain along the bonded length one can compute the slip between CFRP reinforcement and concrete. On the basis of strain compatibility in the infinitesimal range, dx, of the CFRP–concrete interface, and neglecting the concrete strain, the following equation can be written:

$$s(x) = s(0) + \int_0^{L_b} \varepsilon_f \mathrm{d}x , \quad (2)$$

where $s(x)$ is the slip along the bong length, $s(0)$ – the slip at the loaded end, ε_f – the strain in the CFRP reinforcement.

The comparison between specimens reinforced with different CFRP plates, in terms of bond stress *versus* slip, is reported in Fig. 8. All curves are characterized by a linear behavior.

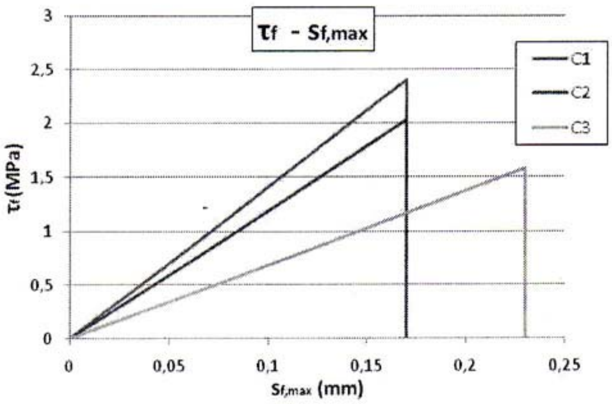

Fig. 8 – Bond *vs*. slip diagram.

4. Conclusions

The reported experimental program were based on double shear test. Debonding of the FRP strips from the surface of the concrete substrate represents the most common failure mode in all studied cases. The failure at the interface occurred in the substrate and had a brittle manner. Therefore it can be stated that the shear strength capacity of the substrate material is a major parameter of the interface region behavior.

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INVESTIGAŢII EXPERIMENTALE PRIVIND ADEZIUNEA LAMELELOR DIN FIBRE POLIMERICE ARMATE CU FIBRE DE CARBON LA SUBSTRATUL DE BETON

(Rezumat)

Numeroase cercetări realizate în ultimii ani au avut ca scop demonstrarea fezabilităţii consolidării structurilor cu ajutorul materialelor compozite. Astfel, utilizarea sistemelor cu materiale compozite polimerice armate cu fibre (CPAF) aplicate la exterior a devenit una dintre cele mai uzuale aplicaţii în ingineria civilă şi s-a bucurat de atenţia cercetătorilor. Conlucrarea dintre compozitele CPAF şi beton a devenit o problemă majoră, fiind esenţială la solicitările de forfecare şi incovoiere. O mare parte parte a performanţelor elementelor armate la exterior depinde de pregătirea suprafeţei, astfel specificaţiile corespunzătoare cu privire la acest aspect vor fi de asemenea prezentate.

Programul experimental constă în testarea probelor de beton consolidate cu diferite tipuri lamele din fibre polimerice armate cu fibre de carbon (CPAFC) şi încercarea acestora la întindere prin dublă forfecare. Rezultatele experimentale obţinute în timpul testării oferă o caracterizare adecvată a regiunii de interfaţă în ceea ce priveşte rezistenţa îmbinării, caracterul curbei tensiuni tangenţiale *vs.* lunecare, precum şi modurile de cedare