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Effects of exposure to saline humidity on bond between GFRP and concrete

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ABSTRACT

Based on extensive experimental program on effects of artificial environmental aging, its effects on strength and bond between outer GFRP reinforcement of RC beams and concrete are described and interpreted. Artificial aging of beams consisted of saline water immersion, salt fogging and cyclic tidal-like action causing degradation on mechanical properties that are reported and examined. Computational modeling of these effects is also preliminarily described, considering post-aged constitutive properties of the component materials and relevant non-linear material properties, to study bond-slip and beam response. Tests to develop a shear Mohr–Coulomb envelope as a rupture criterion on the layers adjacent to the interface are also presented.

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1. Introduction

There are relatively few results available on environmental degradation of the capacity of structural members strengthened with FRP, namely due to changes on bond. The failure mechanisms of beams with outer FRP reinforcement has however been extensively studied [1]. Flexural and shear deformations endured by reinforced concrete (RC) members determine the plate debonding mechanisms. Shear failure and critical diagonal cracking are not considered in this study and attention concentrates on intermediate crack mechanisms. When a small crack reaches a plate, the resulting stress concentration leads to cracking (IC) in the concrete adjacent to the interface. Shear can still be transferred across this crack through aggregate interlock associated with localized forces or stresses normal to the interface. Failure at the interface may also relate to lack of 'aggregate-interlock' that can be measured from pull-tests. Material shear slip can be measured in these tests. Oehlers showed that, when debonding started at the plate end, large stresses normal to the plate/concrete interface develop in the vicinity and are resisted by strict tensile strength of the concrete, instead of 'aggregate-interlock' shear resistance, although interface shear stresses also develop [1].

A meso-scale finite element model for the simulation of interfacial debonding failures in a pull test is described in [2]. Bond-slip laws used to approach the FRP/concrete interface behavior, very often assume bi-linear or exponential laws. Typical bond-slip curves consist of an ascending branch with continuous stiffness degradation till a peak bond stress is reached, followed by a descending branch linear or non-linear until a zero bond stress is attained for a finite value of slip, as illustrated in Fig. 1. Bi-linear laws have the advantage of providing an analytical solution of the problem whereas exponential laws, with non-linear post-peak behavior, approximate with good accuracy the concrete non-linear post-peak behavior. A review of bond strength and bond-slip models is offered in [3]. Non-linear finite element analyses (FEA) of RC beams strengthened in flexure and in shear, simulating various failure modes and including FRP debonding either at the plate end or at intermediate cracks are found in [4]. A finite element (FE) study shows that stresses vary strongly across the adhesive layer [5]. The stresses calculated along the adhesive-to-concrete interface were very different from those along the plate to adhesive interface: near the end of the plate, the interfacial normal stress was confirmed to be tensile along the adhesive–concrete interface, but compressive along the plate–adhesive interface.

Preliminary work was also made in the computational modeling of the GFRP/concrete interface behavior in reference specimens. The computational analysis was based on 2D and 3D modeling and both models led to results with no significant differences. Both models predicted the maximum load and the maximum tensile strength in the GFRP with fairly good accuracy. Maximum bond stress and maximum slip showed larger differences between both models. In any case, the 3D model is closer to the experimental results with relative errors under 18% whereas 37% were found with the 2D model.

Knowledge of environmental physical degradation of strength characteristics is required and has been the object of few publications. Some relevant results are briefly mentioned next. GFRP laminates of epoxy matrix are vulnerable to moisture diffusion [6] because most epoxies absorb between 1% and 7% moisture by weight. Sorption or mass uptake may be due to (i) absorption, associated with capillarity, or (ii) adsorption, a surface phenomenon

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Nomenclature

σ	compressive stress of the interface	f_c	concrete strength
σ_{ult}	ultimate strength of the GFRP laminate	f_{cm}	average concrete strength
σ_x	longitudinal stress	f_{ctm}	average concrete tensile
τ	shear stress	F_{GFRP}	tensile force on the GFRP
$\tau(s)$	bond-slip law	G_f^I	fracture energy of mode I
τ_b	bond stress	G_f^{II}	fracture energy of mode II
τ_m	maximum bond stress	n_P	Popovic's constant
$\Delta\varepsilon$	strain averaged between consecutive gauges	P	external load
ΔL	length between consecutive gauges	P_0	maximum load
$\Delta_{\max}$	maximum displacement measured at maximum load	s	slip between concrete and the GFRP
ε_{ult}	ultimate strain of the GFRP laminate	s_0	maximum slip
ε_r	ultimate strain of the resin	s_m	slip at maximum bond stress
ϕ	internal friction angle at the interface	t_f	GFRP thickness
c	interface cohesion	T_g	vitreous transition temperature
E	Young Modulus	u	displacement perpendicular to the interface bonded surface
E_{cm}	average Young Modulus of concrete		
E_f	Young Modulus of the GFRP	v	displacement parallel to the interface bonded surface
E_r	Young Modulus of the resin		

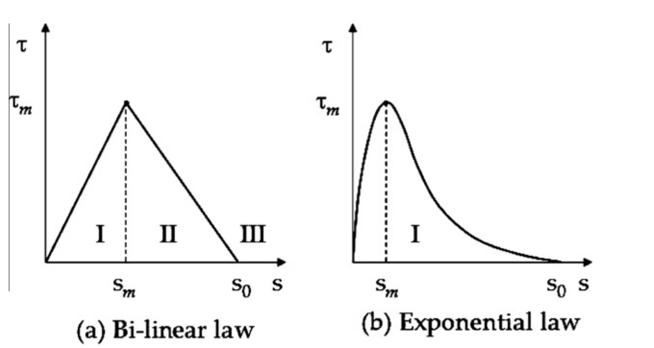
that generates heat and causes swelling. It induces plasticization of the laminates, lowering of the glass transition temperature T_g, and hydrothermal aging associated with chemical phenomena [7].

Moisture sorption affects the mechanical strength of laminates with epoxy matrix [8] and contributes for loss of capacity of RC beams externally strengthened with GFRP. Associated phenomena and increased migration of water into flaws created inside the laminates, especially in the interface with fibers, explain the behavior of glass fiber-reinforced epoxy [8,9].

It has also been shown that "leaching" associated with the diffusion of the alkali ions out of the glass structure into porous water may occur and erode the GFRP reinforcement, a type of degradation more serious for reinforcement rods than external strips [10].

Lowering the vitreous transition temperature of the adhesive, T_g, the bond strength deteriorates, independently of the concrete substrate. Saline tests may, thus, impose a synergetic combined effect on the mechanical properties, depending on the temperature of the water moisture.

Flexural strength of glass composites declines when immersed in seawater for long periods and water absorption has been cited as affecting the Mode I stability of delamination cracks in the



$$\text{I:}\ \tau = \frac{\tau_m}{s_m}\cdot s$$

$$\text{II:}\ \tau = \tau_m \cdot \frac{s_0 - s}{s_0 - s_m}$$

$$G_f = \frac{\tau_m \cdot s_0}{2}$$

$$\text{I:}\ \tau = \tau_m \cdot \frac{s}{s_m} \cdot e^{-\frac{s}{s_m}+1}$$

$$G_f = \tau_m \cdot s_m \cdot e - (s_m + s_0)\cdot \tau_m \cdot e^{\left(\frac{s_0+1}{s_m}\right)}$$

Fig. 1. Bond-slip laws commonly used (based in [3]).

glass/polyester composite [11], a result to be confirmed for epoxy matrices.

Tests simulating tidal effects on eight beams strengthened with FRP submitted to dry/wet cycles, using saline water (15% concentration of NaCl), with half of the specimens pre-cracked showed much earlier degradation of the latter as also found by Spainhour and Thompson [12]. Beaudoin et al. observed negligible effects of tidal cycles on CFRP [13].

Fava et al. imposed artificial aging on beams with external FRP plates and concluded that freeze–thaw cycles reduced bond shear strength, while the beneficial effects of high humidity level characterizing salt spray fog overcame eventual damage due to the chloride solution [14]. Higher deformability of the interface, i.e. high peak slip, appeared to be the major effect found. Other authors [15,16] had already mentioned similar effects.

Tests on the response of beams strengthened with external GFRP laminates under monotonic static load, including some environmental degradation, were also described by the authors [17] with freeze thaw cycles revealing to be more aggressive to the GFRP/concrete interface than salt fog cycles and immersion in 5% of salt water.

Further experimental work and computational modeling are needed and a contribution is described in the sequel. The objectives of this study are twofold: (i) reporting experimental results on effects of saline moisture on GFRP external reinforcement of beams, mainly on bond between the composite and concrete and (ii) presenting numerical models that lead to interpretation and generalization of the experiments.

2. Experimental program

The effects on the mechanical properties of the "materials", i.e. GFRP laminates and concrete, and on the load capacity of structural beams were considered separately. Specific aspects on bond-slip data are treated separately.

The modification of the tensile strength of GFRP laminates was quantified by standard tensile tests in a Zwick universal machine, described below.

2.1. Tensile tests of GFRP laminates

The coupons for tensile tests were made of unidirectional GFRP laminates 1.3 mm thick, 250 mm long and 25 mm wide (SEH51/

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