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Durability of GFRP-concrete adhesively bonded connections: Experimental and numerical studies

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ABSTRACT

In order to overcome the main mechanical drawbacks of GFRP profiles, namely their high deformability and proneness to instability phenomena, several GFRP-concrete hybrid solutions comprising bonded connections with epoxy adhesive have been proposed. Although being able to provide almost full interaction at the GFRP-concrete interface(s) (at least in the short-term), there is very little information about the durability of such connection systems, which raises concerns about the long-term performance of hybrid structural solutions. This paper presents experimental and numerical investigations on the durability of adhesively bonded connections between pultruded GFRP profiles and steel fibre reinforced self-compacting concrete (SFRSCC). GFRP-SFRSCC specimens were first subjected to accelerated ageing, involving thermal and wet-dry cycles, and then subjected to push-out tests. The accelerated ageing did not have significant influence on the strength of the GFRP-SFRSCC connection; however, it had a very deleterious effect on its stiffness. The numerical study included the development of finite element models of the specimens tested. Using bi-linear bond-slip laws, it was possible to simulate the test results with good accuracy. In the final part of the paper, the influence of the interface stiffness reduction on the deformability of a real hybrid structure (the São Silvestre footbridge) is analysed. Although the stiffness of the GFRP-SFRSCC interface is considerably reduced by the ageing processes, this results in a very small increase of the overall mid-span deflections of the footbridge.

1. Introduction

Fibre reinforced polymer (FRP) materials are being increasingly considered as an alternative to traditional materials for civil engineering structural applications, due to their high strength, low self-weight, ease of installation, electromagnetic transparency and good chemical and corrosion resistance [1–3]. With low maintenance requirements, these materials offer a promising alternative for the development of more durable and sustainable structures [4].

Pultruded glass-fibre reinforced polymer (GFRP) profiles combine the above mentioned advantages with moderately low manufacturing costs. However, GFRP profiles present low elasticity and shear moduli, being relatively deformable and prone to instability phenomena.

To overcome those limitations, several hybrid structural solutions have been proposed (*e.g.* [5–12]), combining GFRP profiles with concrete elements. In some hybrid solutions, adhesively bonded (epoxy) connections are used to enhance the composite action, thus preventing the occurrence of interconnection slip at the GFRP-concrete interface(s) [10]. In some cases, adhesive bonding is complemented with mechanical connection systems, which generally provide a negligible contribution to the stiffness (*e.g.* [5–9]), but can act as a redundant ("backup") connection in case of adhesive failure or long-term degradation. An example of such a hybrid system is the São Silvestre footbridge [13–18], which comprises two pultruded GFRP girders adhesively bonded (with epoxy) and bolted to a very thin deck made of steel-fibre reinforced self-compacting concrete (SFRSCC).

Although adhesively bonded connections have been proved to provide virtually full interaction in the short-term, little is known about the durability of such connection systems, namely when subjected to environmental degradation agents, thus raising concerns about their long-term performance. This paper presents experimental and numerical investigations on the durability of adhesively bonded connections between GFRP pultruded profiles and SFRSCC slabs. The main goal was to assess the influence of (i) thermal cycles, likely to be found in outdoor applications, and (ii) wet-dry cycles, on the stiffness and strength of the GFRP-SFRSCC interface. To that end, GFRP-SFRSCC specimens were subjected to thermal and wet-dry cycles for up to 32 weeks and then subjected to push-out tests. Alongside the experimental study,

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numerical models were developed in order to simulate the push-out tests, in particular to derive (calibrate) time-dependent bond-slip laws representative of the GFRP-SFRSCC connection and of its time-dependent degradation. In the final part of the paper, the effects of the interface degradation on the full-scale structural response of the São Silvestre footbridge are analysed.

2. Literature review

As mentioned, there are very few studies about the durability and long-term mechanical performance of adhesively bonded connections between pultruded GFRP profiles and concrete members, namely when subjected to thermal and wet-dry cycles. The literature review presented in this section summarizes the main findings reported in previous studies about the durability of (i) the constituent materials and (ii) GFRP-concrete (SFRSCC) interfaces subjected to those environmental agents.

2.1. Constituent materials

2.1.1. Effects of thermal cycles

For the temperature range that is likely to be found in outdoor applications, previous studies have shown that thermal cycles have (very) limited deleterious effects on the mechanical properties of pultruded GFRP materials. Indeed, in spite of the differences between the thermal expansion coefficients of the fibres and the polymer matrix, thermal cycles may even lead to improvements in the material properties due to post-curing effects on the matrix. As an example, Sousa et al. [19] subjected pultruded glass-polyester profiles (similar to those used in the present study) to 190 dry thermal cycles between −5°C and 40 °C. Relatively low changes were measured in the mechanical properties of the GFRP material, with maximum reductions of the longitudinal tensile strength and elasticity modulus of −13.1% and −14.7%, respectively. Grammatikos et al. [20] tested similar pultruded glass-polyester profiles exposed to 300 dry and wet (soaked) thermal cycles, between −10 °C and 20 °C. In this case, after dry thermal cycles the longitudinal tensile strength and modulus even increased by 12% and 10%, respectively; in opposition, for wet thermal cycles reductions of respectively −13% and −4% were reported and attributed to a higher degree of induced microcracking within the matrix material, particularly at the fibre-matrix interface, caused by the additional expansion of the absorbed water during the formation of ice crystals.

Regarding epoxy adhesive, Yagoubi et al. [21] subjected epoxy (used in aircraft applications) specimens up to 3000 thermal cycles between −40 °C and 70 °C with relative humidity (*RH*) ranging from ≈0% to 90%, for the lower and higher temperatures, respectively. The authors reported little effects of the accelerated ageing on the mechanical properties of the adhesive, namely on the indentation modulus and the hardness. On the other hand, the same authors reported a decrease in the glass transition temperature (T_g) after 250 cycles, which seemed to stabilize as the ageing process continued. Silva et al. [22] tested the tensile properties of the epoxy adhesive used in the current experiments after being subjected to 120 and 240 thermal cycles between -15 °C and 60 °C, each cycle lasting 24 h; they reported increases in the strength and elasticity modulus up to 33% and 7%, respectively, after 240 cycles. These results are in accordance with the findings of Moussa et al. [23]: the authors heated epoxy adhesives to temperatures slightly above their glass transition temperature (T_g) and then cooled them to ambient temperature; although the epoxy specimens were not subjected to thermal cycles, their strength and stiffness increased and this was attributed to the post curing of the resin.

To the authors' best knowledge there are no studies on the effects of thermal cycles on the mechanical properties of SFRSCC. Unlike polymeric materials, such as GFRP and epoxy adhesives, cementitious materials in general and self-compacting concrete (SCC) in particular do not seem to suffer significant deleterious effects caused by service temperatures [24–26]. In fact, studies on the high temperature behaviour of SCCs indicate little degradation of their mechanical properties for temperatures up to 100 °C [25,27].

2.1.2. Effects of wet-dry cycles

Thermosetting resins, including polyester (that comprises the matrix of the GFRP profiles used in this study) and epoxy, are susceptible to swelling, plasticization and hydrolysis when subjected to water [28,29]. These physical and chemical degradation phenomena, which can be either reversible or permanent and result from complex reaction/diffusion processes [30,31], are known to cause reductions in their stiffness, strength and toughness related properties [3,21,32].

Borges [33] tested the tensile properties of GFRP pultruded material (similar to that used in this study) in dry state after being subjected to water immersion at 20 °C for up to 24 weeks, obtaining low variations in terms of strength (ranging from −7.3% to −7.5%) and elasticity modulus in tension (+1.1% to −4.5%). The author assessed also the effects of water immersion on the flexural and interlaminar shear properties of the material, and obtained variations of the same order of magnitude. In opposition, Cabral-Fonseca et al. [3] reported higher reductions on those mechanical properties, particularly regarding strength (in average -10.6% and -2.7%, for strength and elasticity modulus, respectively) when the same material was subjected to similar ageing conditions but tested in saturated conditions (highlighting the relevance of reversible degradation); in that regard, Quino et al. [32] have shown that particular care must be taken when deriving material properties of wet composites due to non-uniform moisture absorption.

Silva et al. [22] subjected specimens of epoxy adhesive (the same used in the current experiments) to 240 and 480 days of immersion in (i) pure water, (ii) salt water (3.5% NaCl) and (iii) wet-dry cycles in salt water (3.5% NaCl), testing their mechanical tensile properties afterwards. The three ageing processes had a deleterious effect on the mechanical response of the specimens with a degradation of the tensile strength ranging from -21% (wet-dry cycles) to -38% (pure water immersion). A similar effect was observed for the elasticity modulus with reductions ranging from −22% (wet-dry cycles) to -47% (pure water immersion). These results show the impact of the deleterious effects of plasticization and hydrolysis phenomena in the mechanical response of these resins.

The exposure of steel fibre reinforced concrete (SFRC) to moisture may lead to fibre corrosion, potentially hindering its durability, a problem that has been addressed by several authors in the last few years. Balouch et al. [34] subjected SFRC to salt-fog/dry cycles (1 week wet and 1 week dry during 3 months), showing that for water-to-cement ratios (W/C) under 0.5 (similar to that used in the present study, *cf.* Section 3), the minimum cover to avoid corrosion of SFRC is under 0.2 mm. Granju et al. [35] exposed previously cracked SFRC to salt-fog/dry cycles up to 1 year, reporting light (or no) fibre corrosion for crack widths under 0.5 mm, except for the fibres within the first 2 to 3 mm of the concrete external surface. Furthermore, no deleterious effects were observed in the material strength, which actually increased after the accelerated ageing process, an effect the authors attributed to the roughening of the surface of the lightly corroded steel fibres, thus enhancing their bond to the concrete matrix. This phenomenon was confirmed by Frazão et al. [36], who performed fibre pull-out tests on SFRSCC specimens subjected to 10 days of immersion in salt water, reporting an increase of the pull-out strength with the increase of fibre corrosion.

2.2. Pultruded GFRP - concrete interfaces

Although there are several studies on the durability of GFRP-concrete interfaces, they generally focus on GFRP fabrics for externally bonded reinforcement (*e.g.* [37,38]). In fact, to the authors' best knowledge, only a single study has been reported on the durability of pultruded GFRP-concrete interfaces by Mendes et al. [39]. The authors