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Effects of thermal cycles on adhesively bonded joints between pultruded GFRP adherends

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A B S T R A C T

This paper presents experimental and numerical investigations about the effects of thermal cycles on adhesively bonded joints between pultruded glass fibre reinforced polymer – unsaturated polyester (GFRP) adherends used in civil engineering structural applications. Single lap bonded joints were produced with two commercial polymeric adhesives – epoxy (EP) and polyurethane (PUR) – and exposed to a mild (Mediterranean) range of thermal variations (−5 °C–40 °C) for up to 350 cycles in a dry condition. The mechanical performance of the adhesively bonded joints was assessed by means of single lap shear tests. Regardless of the inherent differences between both adhesives, results obtained show that the global effect of thermal cycles on the load vs. displacement response of EP-GFRP and PUR-GFRP joints was similar. For both adhesives, thermal cycles caused considerable reduction of joint stiffness and strength, with maximum reductions of 18% and 22% for EP-GFRP joints, respectively, and 19% and 11% for PUR-GFRP joints. The degradation of performance was influenced by post-curing effects, more relevant in the PUR adhesive. Before exposure to thermal cycles, both types of specimens exhibited similar failure mechanisms, which generally (80–90% of cases) involved light fibre tear and fibre tear modes, attesting the effectiveness of the adhesion process and material compatibility. Exposure to thermal cycles did not influence the failure modes of the PUR-GFRP joints; however, EP-GFRP joints became more prone to adhesive failure after being subjected to thermal cycles. Three-dimensional finite element models were used to estimate the magnitude of the internal stresses developed during the thermal cycles. For both types of bonded joints, the numerical results showed a relatively low magnitude of both shear and normal stresses developed due to the mismatch of the coefficients of thermal expansion (CTE) of the adherends and the adhesives. Overall, the results obtained indicate that thermal cycles degrade bonded joints between pultruded GFRP adherends and this degradation seems to be due mostly to detrimental effects on the constituent materials, namely the adhesives; however, for the conditions used in this study, this degradation seems to be compatible with the structural use of this type of joints in civil infrastructure.

1. Introduction

The structural application of fibre reinforced polymer (FRP) composites in civil engineering has presented a continuous increase during the past few decades, for both rehabilitation of existing structures and new construction [1,2]. In particular, pultruded glass fibre reinforced polymer (GFRP) profiles are being used in a growing number of applications, that include structural parts or components of bridges and buildings [3–6].

Pultruded GFRP profiles offer several benefits over traditional materials, such as high specific strength, low self-weight, ease of handling, corrosion resistance and durability in outdoor applications. This makes them particularly well suited for harsh environments, such as waste water facilities, coastal areas and bridges in cold regions, where (corrosive) de-icing salts are frequently used [5]. Despite their higher initial costs, previous studies indicate that comparable life cycle costs and better ecological impact can be obtained compared to conventional solutions [7].

In such applications, GFRP profiles are usually connected by means of bolting and/or adhesive bonding. While mechanical bolting involves drilling operations and often leads to overdesign of GFRP components [8,9], adhesively bonded joints lead to a more uniform load transfer, being more material-adapted, as both the adherends and the adhesive are of a polymeric nature, thus providing better compatibility [4,5]. Some adhesives can also be chosen to increase the ductility of bonded joints [10], namely to guarantee load redistribution in redundant

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structures and/or energy dissipation under seismic loads. In addition to these advantages, sections assembled by means of adhesive bonding may also benefit the construction process by reducing installation times [11].

In spite of their potential benefits, there are concerns about the durability and long-term performance of adhesively bonded joints between GFRP components. In fact, both the adhesives and the adherends can be influenced by environmental conditions, which may affect the stiffness, strength and deformation capacity of bonded joints [12,13].

Temperature variations are among the most important environmental factors that may affect the durability of adhesively bonded joints for civil engineering applications [13–15]. In addition to the detrimental effects caused by exposure to extreme (low and high) temperatures on the constituent materials themselves – the adhesive and the adherends – the concerns with thermal cycles stem also from the thermal deformations of the adherends and the potential dissimilarity between the coefficients of thermal expansion (CTE) of the adherends and the adhesive, which may lead to the development of interfacial internal stresses at the bonded joint and eventually lead to micro-cracks at the interfaces or even premature debonding failure [16].

In what concerns the effects of thermal cycles on polymeric adhesives and GFRP adherends, there is already some information available in the literature. For most typical adhesives used in civil structural applications, previous studies [15,17,18] have shown that internal stresses are developed during thermal cycles: tensile stresses due to thermal expansion can be found when temperature increases, while compression stresses (shrinkage) occur when temperature decreases. Moreover, the cyclic change in stress state and temperature can lead to shrinkage, embrittlement, hardening and microcracking of the adhesives. Regarding pultruded GFRP adherends, earlier work [18–20] has shown that thermal cycles may lead to fibre-matrix interface failure (due to different CTEs of the fibre and the matrix, and the consequent increase of internal stresses), microcracking and matrix hardening. Further degradation may occur when thermal cycles are combined with moisture, due to the development of internal stresses caused by the expansion of the trapped water inside the composite at lower temperatures. Recent studies [20] have also shown that in mild climates the degradation in the physical and mechanical properties of pultruded GFRP profiles is low.

As for adhesive joints, exposure to thermal cycles generally cause a decrease in strength. According to Humfeld and Dillard [21], raising the temperature of the joint induces residual thermal stresses due to the CTE mismatch between the adhesive and the adherends. The higher temperatures facilitate polymer chain mobility and lead to some degree of relaxation of these stresses. However, when cooling the joint, the stress relaxation is reflected in an increased interfacial stress between the substrate and adhesive layer. In addition, the lower temperature reduces the polymer chain mobility, and these tensile stresses cannot be relaxed at the same degree (initial stress state) until the next cycle starts, resulting in accumulating low temperature thermal stresses within each cycle. This cumulative effect repeats each cycle, leading to residual stress increase that can eventually promote failure.

As discussed below, in spite of its importance there is very limited information available about the effects of thermal cycles on the long-term performance of adhesively bonded joints between pultruded GFRP components used in civil engineering applications. Most previous studies on bonded joints between composites refer to different adherend/adhesive systems used in other industries [12,22], or focus on a different combination of substrates, namely FRP-to-concrete (e.g., [23]), FRP-to-metal (e.g., [24,25]) or metal-to-metal (e.g., [14]). To the best of the authors' knowledge the only studies about the effects of thermal cycles on bonded joints between GFRP adherends are the ones by Stazi et al. [12] and Lopez-Anido et al. [26], which are summarized next.

Stazi et al. [12] studied the environmental ageing of joints between pultruded GFRP (glass-vinylester) adherends bonded with six different types of adhesives (two epoxies, one acrylic, one methacrylate, and two polyurethanes). The authors considered single lap and butt joint configurations and subjected them to two types of artificial ageing, one of which comprised hygrothermal cycles, where temperature (and relative humidity) were varied in three stages: (i) 16 h at 40 °C and 100% RH; (ii) 4 h at −40 °C; (iii) 4 h at 70 °C and 50% RH. The specimens were aged for 2 weeks, being exposed to a total of 14 thermal cycles. For most adhesives ultimate loads slightly increased, except for one epoxy (12.5% reduction) and the methacrylate adhesive in the single lap configuration (60% reduction due to premature failure); this generalised increase was attributed to the completion of the polymerization process of the adhesives after the first cycle at high temperatures (w.r.t. the unaged specimens). Joint elongation at failure increased very considerably, while the stiffness of the joints was reduced (70–90%) compared to that of the corresponding unaged specimen; these changes were attributed to the softening of the adhesives, as their glass transition temperature range was reached and exceeded. The failure modes were also largely affected, changing from mixed failure (combination of two or more modes) to mainly adhesive failure (especially in the epoxy adhesives). It is worth noting that the degradation/changes reported in this study were due to the combined effects of thermal cycles and relative humidity.

Lopez-Anido et al. [26] studied the freeze-thaw resistance of single lap bonded joints between GFRP composites (glass-epoxy-based vinylester), produced by VARTM, and an underwater curing epoxy adhesive. After fabrication, specimens were immersed in tap water at 38 °C to allow the epoxy adhesive to cure in an underwater environment. After 2 weeks, the control samples were removed and tested in a dry condition, while the specimens subjected to thermal cycles were removed after 3 weeks. The freeze-thawing exposure consisted of 20 cycles characterised by (i) 8 h at −18 °C, and (ii) 16 h of tap water immersion at 38 °C. The apparent bond strength of the specimens was very sensitive to freezing and thawing, suffering a 43% reduction after exposure. The authors suggested that the reduction in the bond strength was mainly due to increased moisture ingress in voids present in the adhesive layer that resulted from the fabrication process (uneven spreading and absence of proper clamping). The void content was affected during the freezing period due to water expansion, which generated cracks and degraded the epoxy adhesive bond line; the failure mode was also affected, changing from predominantly adhesive to a combination of adhesive and cohesive. Similarly to the previous study, the degradation experienced by the joints was due to several factors: water immersion, thermal cycles, and freeze-thaw.

The two studies reported above, although providing useful information, make it difficult to predict the long-term response of bonded joints between pultruded GFRP components in relatively mild climates, a limitation that is delaying their widespread use [27,28]. Indeed, the extreme temperatures and the thermal amplitude used were quite high compared to normal outdoor exposure in those climates. In addition, the number of cycles considered in both studies was quite limited, taking into account the typical service life of civil engineering structures (generally, 50 years or higher). Finally, it is also worth noting that the durability behaviour of FRP components and joints depends on the following aspects (which varied in those studies): (i) the manufacturing process, (ii) the test protocol, namely the type of conditioning during exposure to thermal cycles (either saturated or dry condition), (iii) the moisture level during mechanical testing, and (iv) the type of adhesive.

In order to obtain a better understanding about the long-term durability of adhesively bonded joints between pultruded GFRP adherends, this paper presents experimental and numerical investigations about the effects of thermal cycles on the mechanical response of single lap bonded joints between pultruded glass-unsaturated polyester laminates. GFRP adherends were bonded with two commercial adhesives – epoxy and polyurethane (the two most frequently used in civil infrastructure) – and were exposed to a mild (Mediterranean) range of thermal variations (−5 °C to 40 °C) for up to 350 cycles, in a dry condition. Single-