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Temperature effects on the shear capacity of external bonded fiber reinforced polymer on concrete

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HIGHLIGHTS

- External bonded fiber reinforced polymer to concrete interface.
- Shear strength.
- Finite element modelling.
- Coupled effect of shear stress and temperature.
- Local bond slip model.

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ABSTRACT

The use of Fibre Reinforced Polymer (FRP) for the strengthening of concrete structures involves their exposure to temperature variations. This paper investigates the combined effect of the temperature and mechanical loads on FRP-concrete bonds. The investigation refers to a double lap shear test conducted in a controlled temperature chamber with temperature ranging from −40 °C to 120 °C. Both experimental and theoretical analyses are performed. The experimental results demonstrate (i) a decrease of the failure loads for temperatures higher than the Tg (40 °C) of the adhesive matrix, (ii) an increase of the failure loads for temperatures lower than Tg which, however, decreases for very low temperatures (lower than −20 °C), and (iii) the cohesive failure modes for temperatures ranging from −40 °C to 40 °C to de-cohesive failure modes for temperatures above 40 °C. Analytical and finite element analysis helps to illuminate the experimental results and indicates that the difference in the coefficient of thermal expansions, as well as the mechanical loads, have an impact on the stress/strain distribution. Finally, the finite element model was used to analyse the typical solar radiation effects (during summer and winter days) on the reinforced systems. The cyclic variations of stress due to the sun thermal effects highlight the need of using an adhesive matrix with a high fatigue limit for FRP reinforcement.

1. Introduction

For many years, intensive research has investigated the properties of externally bonded fiber reinforced polymers (FRP) systems used for the strengthening of reinforced concrete structures. Reviews of these studies can be found in [1,2,3]. Many of these studies adopted the single or the double lap joint test setup to characterize a spectrum of effects, including the manufacturing process, size, interfacial stresses, anchorage conditions, and many others [4,5]. Different tests have demonstrated that the FRP stiffness is not the only parameter influencing the delamination effect. Other parameters, such as the presence of cracks, the stiffness of the substrate and the stiffness of the bonding resin, can also play an important role in delamination. It is also essential to have a better understanding on how the FRP and adhesive matrix together influence debonding through their geometries and mechanical properties.

Another aspect that plays a critical role in the behaviour of the FRP strengthened element is the combined effect of the mechanical load and the temperature change. A detailed experimental demonstration of this effect is discussed in Klamer et al. [6,7], Gao and Dai [8–10], Hosseini and Mostofinejad [11] and Ferrier et al. [12]. An analytical study of this issue is presented by Ruocci [13], Costa [14] and Rabinovitch [15]. These studies have shown that the interfacial failure in the layered structure is affected by both high and low temperatures. The effect is observed in the range of tempera-

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ture where the adhesive or resin material reveals stable mechanical behaviour as well as in the range where this critical component reveals a reduction in mechanical properties. In both cases, interfacial failure is observed under normal realistic service conditions. This observation draws attention to the characterization of the temperature dependency of the mechanical properties of the adhesive/resin as well as to the assessment of the impact of this dependency on the behaviour of the layered structure. Considering that result, this paper follows the research initiated in [12] and moves forward towards the understanding of the behaviour of the layered structural element under the combined effect of load and temperature changes. Previous work [12] mainly experimental was not able to distinguish the effect of temperature on mechanical change and the effect of internal stress due to temperature. Objective is to clarify this issue thanks to FEM modelling and also to observe real temperature effect due to real temperature variation.

In the present paper, complementary experiments are proposed to further investigate the influence of the FRP properties and the effect of the adhesive joint characteristics on the strength of the concrete/FRP interface.

Mechanical tests were conducted using a specific shear loading configuration, which is described in Section 2. Two different series of FRP-strengthened Reinforced Concrete specimens were characterized. The parameters of interest for the FRP system were

- The nature of the fibres - either dry or pultruded
- The type of manufacturing process used in the FRP strengthening of the RC samples, either the wet lay-up (system 1) process or the bonding of pultruded laminates (system 2)
- Young's modulus and thickness of the FRP reinforcement
- The value of the glass transition temperature of the two tested specimens

Additionally, for a selected FRP system, several temperature tests of the epoxy adhesive were investigated (i.e., −40 °C to 80 °C for a wet lay-up system and −20 °C to 120 °C for bonded laminate). The aim was to evaluate the effect of such conditions on both the Carbon Fiber Reinforced Polymer mechanical properties and the strength of the concrete/FRP adhesive bond.

Experimental data obtained through the mechanical tests were analysed according to the shear stress/slip curve method [3]. Changes in the shear stress versus the sliding results were compared for the different sets of the specimens' test temperature, thus providing comparative data on the shear strength, slip value, and peak shear stress. The effects of the previously cited parameters were then discussed based on these results.

The paper takes two more steps towards achieving this goal.

First, it presents the experimental analysis. This section develops and performs an analysis on the experiments conducted on the adhesive/resin. The FRP and double lap shear tests were in the range of −40 °C to 80 °C [15].

Second, it presents the theoretical analysis. This section develops and performs an analysis on the results of an analytical model [16] and the finite element approach. These approaches highlight the coupled effects of the mechanical and thermal loads on the shear behaviour of the system "concrete/resin/FRP" assembly and on its mode of failure. In the last section of this second part, the finite element model is used to analyse typical sun thermal effects (summer and winter days) on the reinforced systems.

2. Experimental analysis

2.1. Materials characterisation

2.1.1. Tests on the resin/adhesive and FRP specimens

The measured properties of the two considered FRP systems at the reference temperature of 20 °C are listed in Table 1 and Table 2.

Table 1
Characteristics properties of the CFRP, system 1.

		Epoxy resin	CFRP
Tensile strength	[MPa]	20	825
Tensile modulus	[MPa]	3200	97 000
Ultimate strain	[%]	2.3	0.85
Glass transition temperature	[°C]	76	–
Coefficient of thermal expansion (CTE)	[1/°C]	35.10^{-6}	$1 * 10^{-6}$

Table 2
Characteristics properties of the epoxy paste and laminate, system 2.

		Epoxy resin	CFRP
Tensile strength	[MPa]	29.5	2900
Tensile modulus	[MPa]	4940	160000
Glass transition temperature	[°C]	58	–
Ultimate strain	[%]	0.6	1.3
Coefficient of thermal expansion (CTE)	[1/°C]	$25\ 10^{-6}$	$1 * 10^{-6}$

Table 3
Results of the tensile test on the adhesive used for the wet lay-up (system 1) and bonding (system 2).

	Temperature (°C)	Strength S1 (MPa)	Young's modulus S1 (MPa)
System 1	−30	12.83	9562.33
	20	20.17	3626.33
	40	21.90	2482.33
	50	11.40	1045.50
	60	10.17	574.67
	80	2.00	183.33
System 2	−20	12.8	11475
	20	24.6	4352
	40	21.9	2979
	50	11.4	1236
	80	10.2	690
	100	2	220

Tensile tests were done on the polymer matrix of two samples according to standard ISO527 (Table 3). The tests were conducted in a special controlled temperature chamber, which accommodates the specimen and the test set-up. Three specimens were analysed for each temperature and were placed in the thermal chamber for 30 min before testing. As shown in Fig. 1-a, b, for the two matrix systems, an increase in the temperature (−30 °C to 80 °C) leads to a decrease in the Young's modulus. There is a significant decrease between the temperatures in the range of −30 °C to 25 °C. However, the strength significantly increases from low temperatures up to a maximum of approximately 25 °C. Beyond this temperature, the strength decreases with increasing temperature. These experimental results clearly show that the ultimate stress and modulus of the resin/adhesive depend strongly on the temperature. For all specimen the Poison ratio measured is nearby 0.3. Therefore, the shear behaviour of the "concrete/resin/FRP" system also depends on the temperature. These effects are investigated in the following section.

2.1.2. Tests to determine the coefficient of thermal expansion of the resin

Further analysis has revealed that the coefficient of thermal expansion (CTE) of the resin also depends on the temperature. The CTE variations of the two epoxy systems were measured using the dilatometry testing procedure according to ASTM Test Method E 228 [17].

To determine the CTE, one measures the displacement and temperature of samples loaded by a thermal cycle. The main technique used to determine the CTE was the dilatometry technique coupled with a thermomechanical (strain gage) analysis. In this study, the polymer CTE is measured from −40 °C to 100 °C. As shown in Fig. 1-c, the CTE values vary from $60 * 10^{-6}$ 1/°C (in the range of −40 °C to 40 °C) to $29 * 10^{-6}$ 1/°C at 40 °C and above for the polymer of system 1 and from $46 * 10^{-6}$ 1/°C (in the range of −40 °C to 50 °C) to $6 * 10^{-6}$ 1/°C at 50 °C and above for the polymer of system 2.

Both the epoxy systems exhibited different thermal behaviours which depend on the temperature value (Fig. 1-c).

2.2. Double lap shear test

A brief literature study reveals several techniques to characterize adhesively bonded joints under shear loading. The single-lap shear test is well-known but can induce a bending stress at the edges of the adhesive joint, which might