PROTECTION OF RC ELEMENTS STRENGTHENED WITH CFRP AGAINST HIGH TEMPERATURES

J Aguiar*, University of Minho, Portugal
M Gorski, Silesian University of Technology, Poland
A Camões, University of Minho, Portugal
N Vaz, University of Minho, Portugal
S Majewski, Silesian University of Technology, Poland

Abstract

The strengthening of RC elements with CFRP is a technique that has been acquiring more and more potential. The bond between the CFRP laminates and the concrete support is usually made with epoxy adhesives. However, it is in this part that the integrity of the system can be affected, namely by exposure to high temperatures. In order to evaluate the thermal behaviour, reference RC and CFRP strengthened RC specimens were tested. After cyclical thermal expositions, with temperatures rising between 20°C and 80°C, specimens were subjected to flexural tests. The results demonstrated that the thermal resistance of this strengthened system can not be considered very high. There is a need to find solutions to avoid temperatures near the thermal resistance of the epoxy adhesive. The use of insulation materials can be a good solution to protect the strengthened RC elements. Among tested materials the foamed polyurethane showed the best behaviour.

Keywords: Epoxy resin, temperature, bond, CFRP, durability, protection

1. Introduction

During their service life period, reinforced concrete structures must present good levels of security, durability and functionality. Nevertheless, several problems on design, construction and use can put some of these requirements at risk. The great amount of damaged structures implies the increase of severity in the design codes and in the number of strengthening solutions. The civil engineering structure renewal has received considerable attention over the past few years all over the world. The structures increasing decay are frequently combined with the need for upgrading.

Actually, CFRP sheets and strips are being increasingly used in many structural applications due to their excellent mechanical and corrosion resistance characteristics. But the adhesive strength can be affected by both short-term and long-term environmental exposure. High environmental relative humidity is one of the harmful examples: may reduce epoxy bond strength bellow acceptable levels [1].

The systems that use FRP to externally reinforce concrete structures have polymers in two parts, the saturation resin and the adhesive. The glass transition temperature (T_g) is the temperature above which polymers change from relatively hard and elastic to viscous rubbery materials. Moreover, when the polymer is exposed to humidity, this temperature (T_g) decreases. Because of this fact, some recommendations suggested that FRP systems should not be used at temperatures above their T_g and they recommended that selected materials should have a T_g of at least 20°C above the maximum expected service temperature.

However, in most of existing guidelines, temperature is not considered as a variable in design process. Fib Bulletin 14 [2] limits the guidelines to the division of strengthened structures into two classes: with fire protection and without.

This fact is not synonymous of lack of importance of the temperature variation in the behaviour of the bond. The bonding agent deteriorates quicker than concrete, steel or CFRP as the temperature increase and the characteristics of the adhesive affects the strength of the bond [3].

According to Gamage et al [4] both experimental and finite element results show that the epoxy adhesive temperature should not exceed 70 °C in order to maintain the integrity between the CFRP and concrete at high temperature. These authors also indicate the need for a sound insulation system for CFRP strengthened concrete elements in order to promote higher fire resistance.

2. Experimental program

To verify the influence of temperature in the externally bonded CFRP strengthened for reinforced concrete structures, an experimental research program was defined in order to give simple and comparative results.

2.1 Materials

Two types of concretes were used: a conventional (CC) and a high-performance (HPC) one. The compositions are presented in Table 1 and were produced using CEM I 42.5 R (CC) or CEM I 52.5 R (HPC) Portland cement, natural river sand (maximum aggregate size of 4.76 mm and fineness modulus of 3.21), crushed granite coarse aggregate (maximum aggregate size of 9.53 mm and fineness modulus of 5.82), and a last generation copolymer based superplasticizer.

Conventional concrete was made with a water-cement ratio of 0.60 and slump varied between 80 and 100 mm. High-performance concrete had a water-cement ratio of 0.30 and slump varied between 150 and 180 mm. At the age of 28 days, conventional concrete presented an average compressive strength of 30.0 N/mm^2 and high-performance concrete achieved 90.0 N/mm^2.

Table 1 – Compositions of the concretes

Constituents		CC	HPC
Cement	(kg/m^3)	340 (CEM I 42.5 R)	550 (CEM I 52.5 R)
Sand	(kg/m^3)	869	469
Gravel	(kg/m^3)	865	1158
Water	(l/m^3)	206,4	165
Superplasticizer	(kg/m^3)	-	13,75

So as to evaluate the flexural behaviour, 650x150x100 mm^3 reinforced concrete beams were produced. The amount of steel reinforcement was the same in HPC and in CC beams and it was determined so as to avoid shear failures. The flexural reinforcement steel (f_{syd} = 400 N/mm^2) had 6.0 mm of diameter and the shear reinforcement steel (f_{syd} = 500 N/mm^2) had 3.0 mm of diameter (Figure 1).

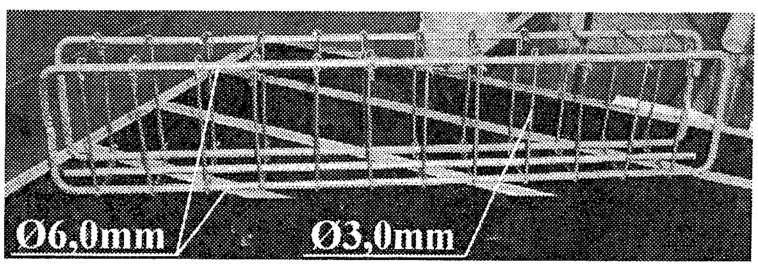

Figure 1 – Steel rebars of the flexural beam specimens.

The beams were kept inside the moulds during the first 24 hours. Afterwards, the specimens were removed and maintained 20 days inside water at a temperature of 20°C. The CFRP strengthening was applied in the beams when they were 28 days old. Before the bond, they remained 7 days at the laboratory room at a temperature of 20°C. The CFRP plates have a tensile resistance of 2800 N/mm^2 and an elasticity modulus of 165000 N/mm^2.

The adhesive used was an epoxy mortar one (Table 2). It was mixed immediately before the application. Resin and hardener were mixed with a reason of 3:1, respectively. They have different colours, so complete mixing can be evaluated after uniform colour has been achieved [5]. This adhesive contains calcareous filler.

Table 2 - Epoxy mortar properties

Density (kg/m^3)	1770
Pot-life – 35 °C (min.)	40
Shrinkage (%)	0.04
Glass Transition Temperature, T_g (°C)	62
Static Young Modulus (N/mm^2)	12800
Thermal Expansion Coefficient – from -10 °C to 40 °C (°C^{-1})	9x10^{-5}

2.2 Bond procedures

To prepare the surface of the hardened concrete, one used a diamond disc, an abrasive disc, air spurt and a soft brush. These resources were important in order to remove laitance, oils and dust. At the same time they give roughness to the extremely smooth surface. The CFRP was cleaned immediately before the application of epoxy adhesive, with the volatile product indicated by the supplier.

It is important to spread the adhesive immediately after mixing, to dissipate the heat and extend its usable life. Adhesive was applied either in concrete and CFRP surfaces [6]. This procedure reduces the risk of forming voids when pressing the CFRP plat against the concrete surface. The producer recommends a joint of 0.5 to 2 mm of thickness.

The specimens subjected to flexural tests were reinforced concrete beams strengthened with CFRP (Figure 2). They were maintained in the laboratory room (20°C) during 7 days after the bonding process. Afterwards, they were submitted to the degradation process.

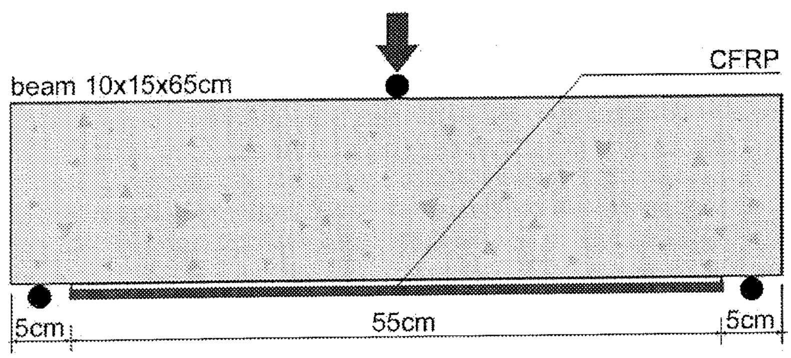

Figure 2 - Flexural test: reinforced concrete beam strengthened with CFRP.

2.3 Degradations

It was established a program of degradations. The glass transition temperature of the epoxy mortar was 62°C, so, one of the temperatures of the thermal exposition was 60°C. It would be equally important to exceed significantly that temperature and know the behaviour at lowers temperatures, such as in a laboratory room and between that and the glass transition temperature. The thermal expositions were based on previous works and on an European standard [7]. The program of degradations is presented on Table 3 and Figure 3. The time by cycle was 6 hours at each temperature. The number of cycles was 50.

Table 3 - Thermal degradations

Degradation	Temperature (°C)	
	Minumum	Maximum
T20	20	20
T40		40
T60		60
T80		80

2.4 Measurement of surface temperature

Aiming to verify the real temperature due to solar exposure in the surface of the adhesive, some measurements were made. A thermocouple was installed in a CFRP strengthened beam into the epoxy adhesive layer and the temperatures were read during a spring day of May in Portugal. Beams were subjected to two different kinds of exposure conditions: protected and unprotected from wind action. In figure 4 one can see the results obtained.

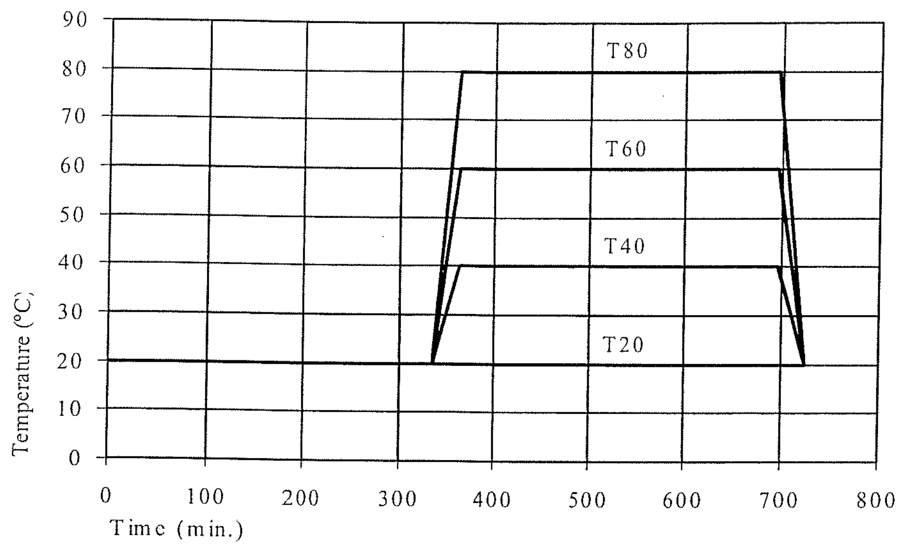

Figure 3 - Variations of temperatures during the thermal degradations.

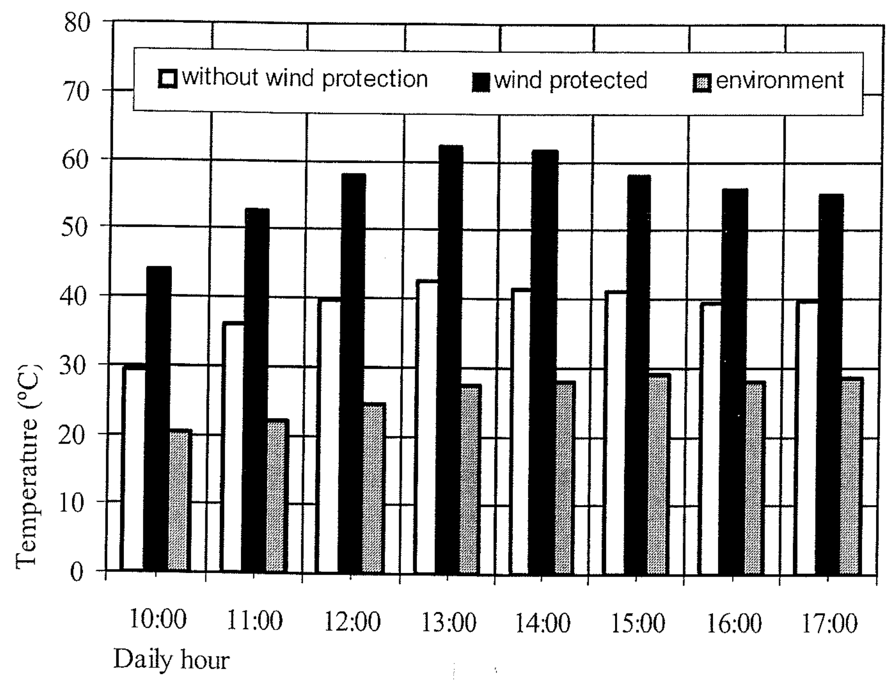

Figure 4 - Variations of temperatures in the adhesive during a spring day of May.

As it can be seen in Figure 4, the solar exposure can imply adhesive temperature that can attain high values, higher than 60 ° C, during a warm and windy spring day of May. Moreover, this proves that the chosen thermal temperatures can reflect real solar exposure conditions.

2.5 Three-point bending tests

The strengthened beams were subjected to three-point bending tests, after the thermal cycle's exposure. The load test was carried out using a controlled system guaranteeing a mid-span deflection increase at a constant rate of 10 μm/s (Figure 5). The test was made with the beams at the maximum temperature of the thermal cycle.

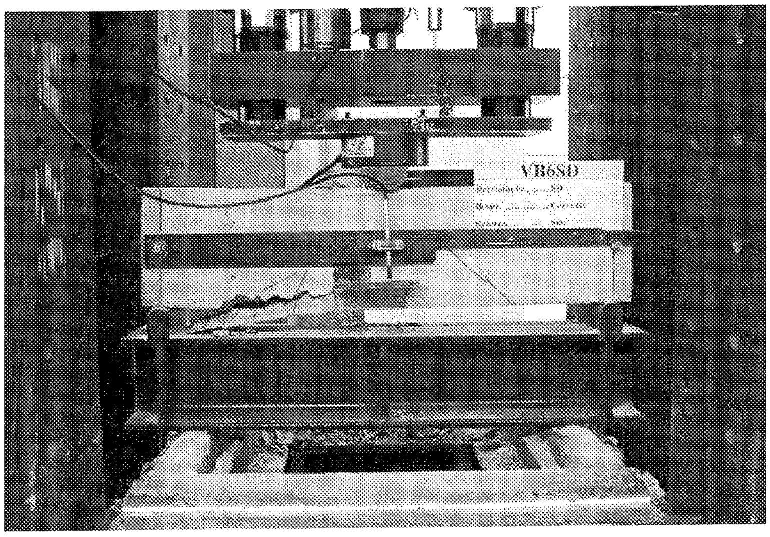

Figure 5 - Three-point bending test.

2.6 Protection

At the end of the experimental work it was tested a protection system in order to avoid temperatures near T_g in the epoxy adhesive. For that three insulation materials currently used in construction were used: rock wool, expanded polystyrene and foamed polyurethane.

The three mentioned materials were used to involve 100 mm edge cubic specimens of concrete strengthened with CFRP (Figure 6). The insulation materials were applied with a thickness of 30 mm and the specimens were subjected to an uniform temperature of 60°C. Regular measurements were done until the temperature stabilise on the epoxy adhesive and in the surface of the insulation material used. During the thermal exposure, the temperatures in the epoxy adhesive were measured with thermal sensors.

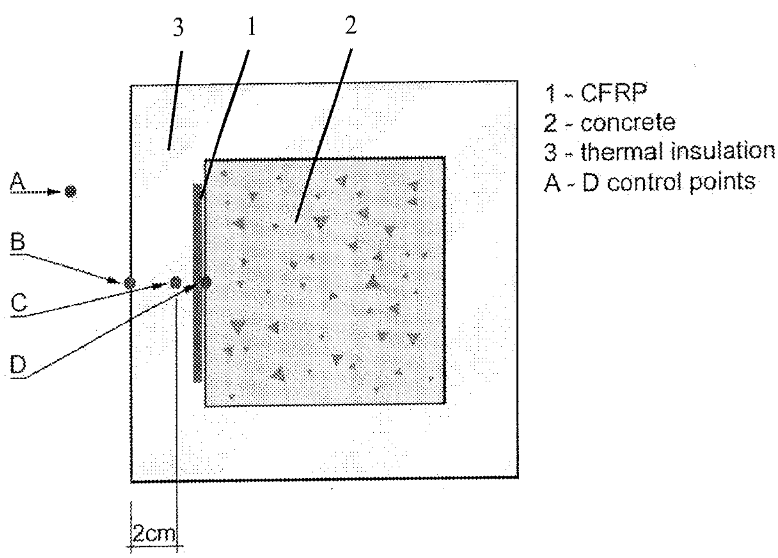

Figure 6 – Schema of thermal protection test.

3. Results

3.1 Three-point bending tests

The evaluation was made taking into account two perspectives: the numerical results and the visual analysis of the behaviour of the beams during and after the final test. In figure 7 one can see the evolution of the maximum resistant bending moments for the different degradations. Beams without CFRP strengthening made with conventional and high-performance concrete are referred as CC and HPC respectively. The abbreviation CC/CFRP and HPC/CFRP represents correspondingly the CFRP strengthened conventional and high-performance reinforced concrete beams. In a previous paper [8] these results were presented with more detail.

The failure types verified in the flexural test are presented in table 4. Observing figures 8 to 10 one can see the different failure type that occurred: flexural failure (flexural), delamination of the concrete cover (delamination) and CFRP debonding (debonding).

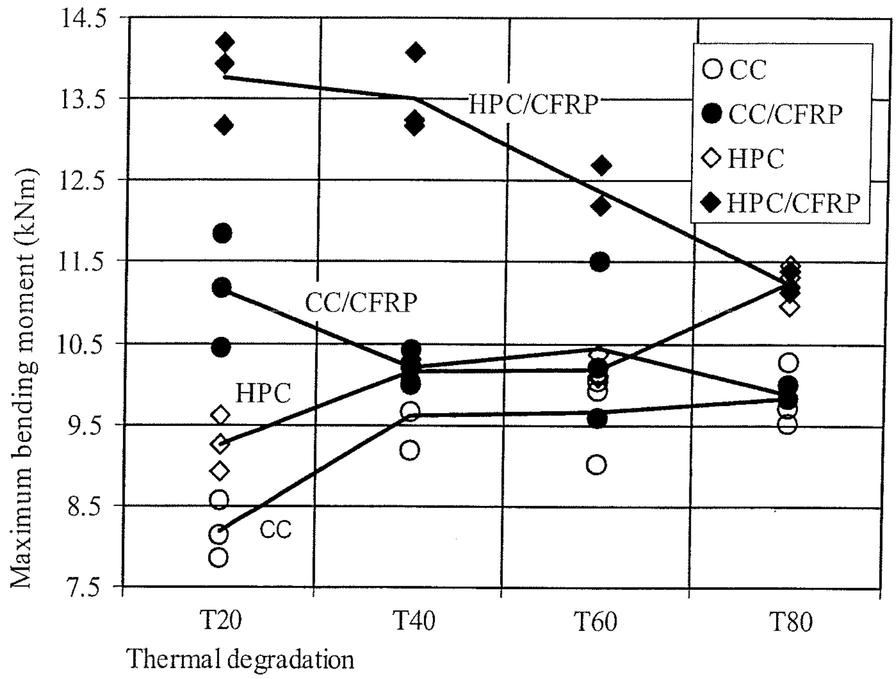

Figure 7 - Evolution of maximum bending moments with temperature, type of concrete and CFRP reinforcement.

Table 4 – Flexural strength failure types.

Thermal Degradation	Failure type			
	CC	CC/CFRP	HPC	HPC/CFRP
T20	Flexural	delamination	flexural	delamination
T40	Flexural	delamination	flexural	delamination
T60	Flexural	delamination and debonding	flexural	delamination and debonding
T80	Flexural	debonding	flexural	debonding

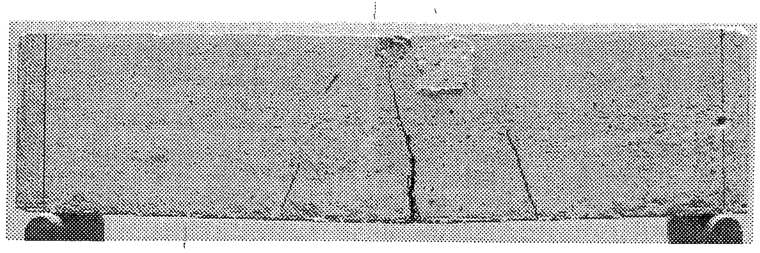

Figure 8 - Flexural failure.

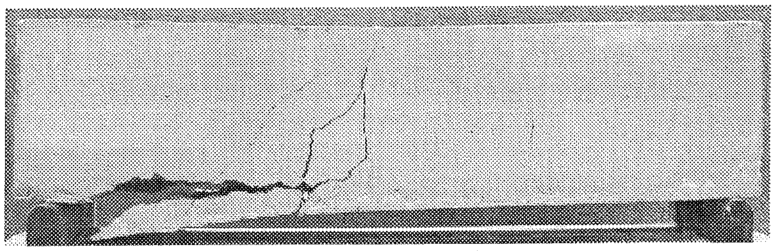

Figure 9 - Delamination of the concrete cover.

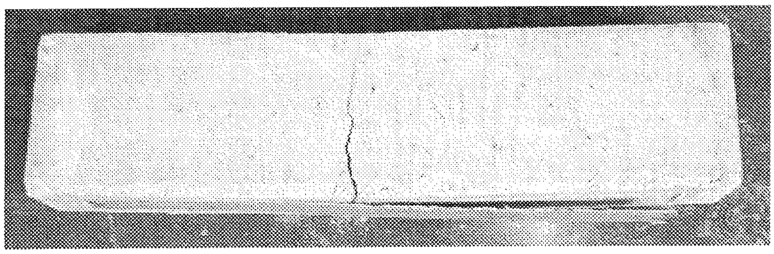

Figure 10 - CFRP debonding.

3.2 Protection

With the protection systems used it was possible to calibrate numerical calculations and extrapolate the results for other temperatures and thicknesses of the insulation materials. This strategy allowed the achievement of the relations presented in figure 11. Observing this figure, it is possible to find the more adequate material and thickness that can give enough protection to avoid that temperature in epoxy resin from going above temperatures not compatible with the thermal resistance of this material.

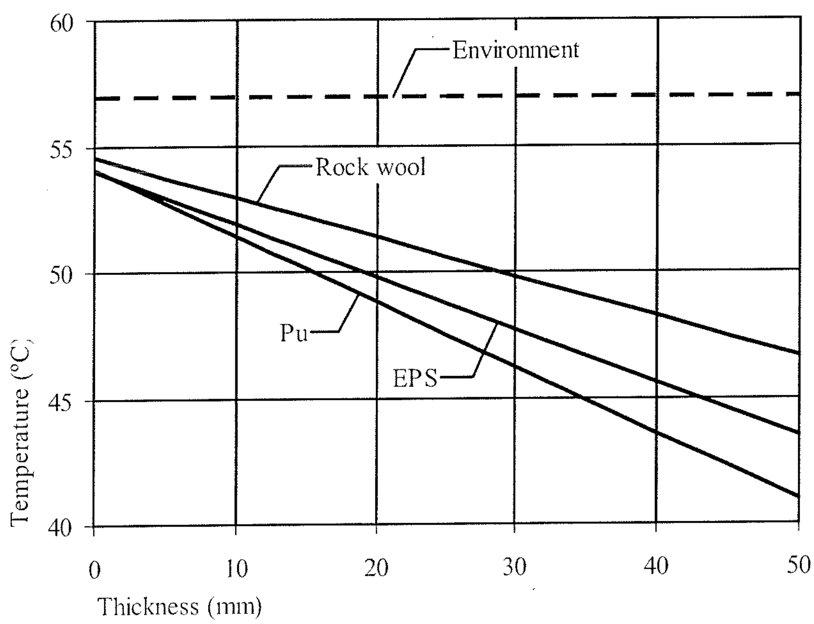

Figure 11 – Variation of temperature in epoxy adhesive with insulation material type and thickness.

4. Analyses of results

4.1 Three-point bending tests

As expected, the increase of the thermal aggressiveness decreases the CFRP reinforcement efficiency. When glass transition temperature of the adhesive was nearly attained (exposition T60) or exceeded (expositions T80), CFRP started debonding.

With the increase of temperature, the bending moment vs. deformation curves (Figure 7) of the strengthened beams become closer to the curves related to the behaviour of the beams without reinforcement. The maximum bending moment gains associated to the presence of CFRP diminished significantly when the temperature increased. For T20, the CFRP strengthening gain (measured by maximum bending moments) was about 35% and 50% for CC and HPC respectively. For T60 reaches only about 10% (CC) and 20% (HPC) and for T80 exposure there was no apparent advantage of using CFRP reinforcement because the maximum bending moments of concrete beams with or without CFRP laminates were similar both for CC and for HPC.

In the series without degradation (T20) and degradation T40, the beams without reinforcement had flexural failure (Figure 8) and the CFRP strengthened beams showed delaminations caused by failure of the covering concrete (Figure 9).

When the aggressiveness of the thermal exposition was near the adhesive T_g (T60), some debondings in the extremities of the CFRP reinforcement were verified. In these situations, particularly for HPC/CFRP beams, debonding occurred at the concrete/adhesive interfaces (Figures 10). In the most severe exposition (T80) and with HPC/CFRP beams, complete debonding of the CFRP reinforcement was verified.

6. Conclusions

The study carried out showed that the temperature effects on CFRP strengthened concrete elements must be taken into account. The epoxy adhesive used to form the bond between CFRP and concrete reveals to be very sensitive to temperature variations. The flexural load capacity of the CFRP reinforced beams decreases with the increase of temperature and the efficiency of the CFRP strengthening tends to vanish. So, based on the results obtained, it is possible to conclude that the epoxy adhesive bond properties deteriorate rapidly with the exposure to high temperatures. This aspect seems to be more relevant because even in solar exposition of a concrete element, it is possible to have temperatures sufficiently high and capable of causing some problems. Therefore, the use of reinforcing systems bonded with epoxies in warm locations needs to be done in a very careful way. It is recommended the selection of epoxies with an elevated T_g of at least 20°C above the maximum environment temperature or to considerer the application of protective insulation systems. The use of foamed polyurethane seems to be the best solution. Design procedures shall be equipped with the system of requirements and solutions reflecting the risk of high temperature influence.

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