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Extended summary

Evaluation of the durability of reinforced concrete structures bonded with carbon fiber (CFRP) sheets

Curriculum: Architecture, Building and Structures

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Abstract. Civil structures are generally built to last over time. However, several external factors and unexpected events, such as increased load requirement, severe environmental exposure, or natural disasters, can affect their service. Many techniques have been developed to improve the durability of concrete. External bonding of FRP sheets has emerged as a popular method for strengthening conventional materials such as reinforced concrete. In the retrofit application, composites and concrete are bonded together with an adhesive layer between them. The interfaces between the constituent materials in the bonded system introduce a challenging problem in determining the durability of the bonded system.
This paper provides information in the area of short-term durability of concrete beams externally bonded with CFRP sheets. It was intended to study the effect of harsh, wet environmental conditions on the performance of CFRP-bonded reinforced concrete beams and on the interfacial bond between the fiber and the concrete. Modelling of environmental effects on the bond surface between FRP composites and concrete is crucial for the purpose of life prediction of strengthened structures.

Keywords. Carbon Fiber Reinforced Polymers, durability, reinforced concrete, relative humidity.

1 Introduction

Civil structures are generally built to last over time. However, several external factors and unexpected events, such as increased load requirement, severe environmental exposure, or natural disasters, can affect their service. These events may degrade the structures to the point that they can no longer perform their functions efficiently as regards their strength and serviceability, ultimately shortening the intended service lives of the systems.

In some cases, gradual degradation over time can eventually lead to catastrophic failure of structure. Durability may be defined, for both material and structural levels, as the ability to maintain the intended functions for a certain period of time, during which degradation can occur. Many techniques have been developed to improve the durability of concrete.

However, deterioration of concrete cannot be avoided and strengthening and retrofitting existing concrete structures generally become necessary.

External bonding of FRP sheets has emerged as a popular method for strengthening conventional materials such as reinforced concrete.

In the retrofit application, composites and concrete are bonded together with an adhesive layer between them. FRP is one of the widely used composite materials; the use of FRP with concrete represents a multi-material system that can be readily found in civil structure applications. In these applications, substrates are bonded together by an adhesive material, which is usually organic polymer-based.

The interface between the FRP and concrete substrate plays a critical role in this strengthening method by providing effective stress transfer from the existing structures to externally bonded FRP sheets and keeping integrity and durability of the composite performance of FRP-concrete structures.

Existence of the interfaces between the constituent materials in the bonded system introduces a challenging problem in determining the durability of the bonded system.

A considerable amount of research established the successful use of FRP materials for strengthening concrete structures in the aspect of short-term performance. Some research studies have focused on durability of FRP strengthened concrete structures [1, 2].

The problem of durability, understood as the long-term behaviour of buildings which use FRPs with specific structural functions, is one of the aspects which still needs to be extensively studied [3, 4]. However, the limited amount of data concerning the long-term performance of the resins used as bonding agents and the lack of suitable regulations regarding the tests to carry out in order to assess the durability of the structure leads to a certain wariness as regards the reliability of these composites.

The long-term properties of epoxy adhesives and their average life span depend on many factors, including the choice of the raw materials, the conditions in which they are dried, the environment (temperature, humidity, sunlight, pollutants) in which the building is located [5-10]. The bonding agent durability study took into consideration both chemical and physical weathering, since these lead, over time, to changes in the mechanical properties and the durability of the fiber reinforcement [11-13].

The presence of moisture in the composite, in particular, can initiate undesirable structural changes within the matrix, in the fiber reinforcement, at their interface and at matrix/concrete interface. In any case, the result is the reduction of the durability of the FRP reinforcement. Hence, problems pertinent to the role of permeability of polymeric matrices for composites and adhesives in conjunction with the concrete adherent are of prime consideration as the limiting factors of their performance in service. The presence of humidity is probably the most harmful environment that can commonly be encountered by epoxies used as adhesives for civil engineering applications. The sorption of water can greatly influence the physical properties of this thermosetting polymer and its composites. Water may enter a resin either by diffusion or by capillary action through cracks. Once inside, the water may alter the properties of the polymer either in a reversible manner, for example by plasticization, or in an irreversible manner, for example by cracking or crazing [14-16].

To date, accelerated weathering tests carried out on reinforcement systems, have not been confirmed by practical experience and there are no technical regulations which specify the protocols for testing the durability of the fiber reinforcement applied to concrete.

The use of Fibre Reinforced Polymer (FRP) composites is widely gaining appeal in the construction industry due to their many outstanding physical, thermal, chemical and mechanical properties.

These properties make them particularly suitable for rehabilitation. Their lower density is important not only because it adds less weight to the existing structures, but also because of its greater convenience during construction.

Fiber composites offer unique advantages for solving many civil engineering problems in areas where conventional materials fail to provide satisfactory service life. Possess excellent properties, such as high tensile strength and stiffness, light weight, and resistance to corrosion and chemicals.

This paper discusses the results of an experimental research project mainly aimed at assessing the mechanical behaviour of concrete structures (floor and roofing beams) strengthened with carbon fiber reinforced polymers (CFRP) when subjected to changes in relative humidity. The tests were aimed at assessing the concrete-resin adherence strength and the variations in bending strength.

This paper provides information in the area of short-term durability of concrete beams externally bonded with CFRP sheets. It was intended to study the effect of harsh wet environmental conditions on the performance of CFRP-bonded reinforced concrete beams and on the interfacial bond between the fiber and the concrete. Modelling of environmental effects on the bond surface between FRP composites and concrete is crucial for the purpose of life prediction of strengthened structures.

2 Experimental procedure

2.1 Choice of materials and analysis of the environmental conditions

This experimental study was designed so as to analyse and assess the durability of the fiber reinforced structure, understood as the average lifespan predicted for the concrete-composite combination, subsequent to variations in relative humidity.

Small beams reinforced concrete measuring 80 x 80 mmq and with a total length of 1000 mm, were obtained. The small size elements made up by reinforced concrete studied in this research, they the beams of a floor or a covering existing historic buildings in the early decades of the 900.

Before bonding the CFRP sheets to the tension side, the concrete surface was smoothened, cleaned, and completely dried before the epoxy was applied.

After the preparation of surfaces to strengthen, two coats of primer *Kimicover FIX* were applied. A layer of epoxy resin *Kimitech EP-TX* was applied, mixing the two components carefully and applying the product evenly using a metal spreader. While the resin is still wet, the fabric was laid on it and pressed lightly with a suitable metal roller to improve adhesion and prevent the formation of dangerous air bubbles. While still wet the fabric was impregnated with *Kimitech EP-IN* liquid resin.

The same of tests were performed in this study: using concrete specimens, concrete reinforced with CFRP specimens, concrete reinforced with CFRP and plastered specimens, in order to evaluate how the layer of external plaster acts or less as protection against the high levels of relative humidity present in the environment.

By the analysis of the average monthly values of relative humidity in different climate zones in Italy and considering the values found inside housing, the following relative humidity ranges were chosen: R.H.= 65 % ÷ 90 %.

Half of the specimens were left to environmental conditions. These specimens were used as control tests. The others were placed in a specially constructed environmental chamber and were exposed to relative humidity higher than 90 %.

2.2 Test methods

All specimens were stored at room temperature for three weeks before the beginning of the test campaign, to allow polymerization of the epoxy adhesive to proceed.

After the cycle of hygrometric stress the specimens were subjected to the following mechanical trials to determine any possible reduction in strength and stiffness consequent to the treatment undergone:

- static bending tests on four load control points to determine bending strength. The four load control points consist of two support points and two load points, the latter being obtained by placing metal structure between the load piston and the specimen of concrete. The test was monitored with three centesimal resolution displacement transducers. Subsequently mechanical bending tests were performed so as to better clarify, in terms of strength stiffness, the mechanical behaviour of the fiber reinforced concrete specimens compared with not fiber-reinforced concrete specimens;
- adhesion tests using a single modulus of rupture cycle in order to assess adhesion to the base and the type of fracture found in the concrete-CFRP specimen. In order to determine the strain profiles along the bonded interface during the adhesion test as well as the load transfer length, specimens were instrumented by two strain gages glued to the surface of the composite material;
- adhesive bond characterizations were carried-out at room temperature by pull-off tests according to EN 1542 European standard. Pull-off test is used primarily to check the level of quality of the application of the composite material, or the homogeneity of the entire operation of reinforcement, both before and after the hygrometric treatment in which the specimens were subjected. A partial core was first drilled around the test zone, with an approximate depth of 4 mm within the concrete substrate. A cylindrical steel body of diameter 50 mm was then glued to the test zone using an epoxy adhesive. Finally, a tensile loading was applied to the steel body by mean of a dynamometer device, until debonding occurred. The adhesive bond strength or pull-off strength (MPa) was simply deduced by dividing the failure load (N) by the cross sectional area of the steel body (mm^2).

3 Experimental results and discussion

Seen that the specimens were not reinforced to shear stress, as often happens in existing buildings in which the structural elements are often equipped with a poor transverse resistant reinforcement, is important to emphasize the different mode of failure of the specimens unreinforced and fiber-reinforced emerged during the bending test. Indeed, while the failures of unreinforced specimens occurred in bending with or without crushing of the compressed concrete; in fiber-reinforced specimens with and without plaster on the surface, the break is of shear the brittle type.

The analysis of the experimental data showed an increase 77.8 % in tensile strength between untreated unreinforced specimens and untreated fiber-reinforced. On the other hand, treated fiber-reinforced specimens showed an increase of 44.4 % in comparison to treated unreinforced specimens.

The situation is different for the presence of plaster. In this case the increase of the load at break between unreinforced specimens and plastered fiber-reinforced specimens, is of 62.6 % for the untreated samples and of 48.9 % for treated specimens at high values of relative humidity.

In fact, it is difficult to compare the results found between samples with and without reinforcement, given the different failure modes of the same. It was therefore necessary to try to compare results between similar samples. Indeed, in the case of shear type breaking of the specimens followed by subsequent delamination of the reinforcing woven, it is evident a loss of load of 17 % by comparing untreated and treated reinforced specimens. The loss breaking load is up to 12 % in the case of rupture of the specimens only for shear.

Analysing the results of both untreated and treated reinforced specimens covered with plaster, it is clear that the plaster surface attenuates the actions due to adverse environmental conditions on exposed specimens before carrying out the mechanical tests. Only the presence of plaster leads to better performance, since it reduces the absorption of water by the substrate, being a so-called sacrificial surface.

4 FEM analysis

A mathematical model of finite elements was created in order to evaluate different failure modes of the unreinforced and fiber-reinforced specimens, the difficulty of comparing the obtained results and to understand the activity of reinforcement before the application of the maximum load during the bending test. The modeling was carried out using ANSYS software.

By modeling we tried to determine and compare the results found with the experimental laboratory, by appropriately varying some parameters.

The aim was to understand what was going on in the linear elastic phase during the initiation of cracks, prior to the plasticization of the section of reinforced concrete. Such a model will also be used to optimize the second experimental phase expected, perhaps extending the results throughout the plastic field, up to rupture of the element itself. Surely, through the application of analytical modeling to the second step of mechanical tests, the results of the two experimental phases will be better interpreted and compared with each other.

5 Conclusion

Based on the informations from the literature on the effects of relative humidity on fiber-reinforced systems, research has been carried out in the short run and long run (3 and 12 months respectively).

In this paper, the first step of tests and the relative analysis after 3 months under high relative humidity was carried out.

In the first phase of this research, the effect of water content on the fiber-reinforced systems was assessed. In the second phase, the effects of one year ageing on these systems, will be evaluated by varying the temperature in wet environment.

In conclusion, it is important to evidence that, when the structure is in on very aggressive environment, the use of an external protective cladding (i.e. plaster) can be an optimal solution. In this last case, repeated inspections and maintenance operations are also needed for prolong durability of the structure.

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