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CRACK PROPAGATION IN CONCRETE ELEMENTS STRENGTHENED BY GFRP

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ABSTRACT

Fibre Reinforced Polymers (FRP) are a useful alternative to external strengthening with steel plates. Their typical applications are flexural and shear strengthening of reinforced concrete beams and wrapping of columns.
In this paper, a study of crack onset and propagation is reported, in order to improve knowledge of the global behaviour of r.c. beams strengthened by FRP.
The results of an experimental programme based on tensile tests on both unstrengthened and Glass Fibre Reinforced Polymer (GFRP) strengthened concrete specimens are proposed.
Based on Fracture Mechanics, a theoretical study of the stress field around the crack tip, and in particular at the concrete-FRP interface is presented. The Stress Intensity Factor at the interface are evaluated. The results afford an opportunity for some considerations about crack propagation: the first crack always appears in the concrete. Then the crack propagates to the concrete-composite interface. When the shear stress at the interface is low (applied load not high and crack edge displacement not big), the only way where the crack can propagate is into the concrete.

KEYWORDS

Concrete, Fibre Reinforced Polymer, Cracking, Fracture, Strengthening

INTRODUCTION

FRPs were first applied in the mechanical and aeronautical fields of engineering, and in recent years they have spread to civil and structural engineering. FRPs are a useful alternative to traditional steel reinforcement, because of their lightness, corrosion resistance and very high tensile strength. Typical applications are flexural and shear strengthening of reinforced concrete beams [1,2,3] and wrapping of columns [4]. Both experimental and analytical-numerical researches have been performed in order to study the failure mechanisms. The first researches on the FRP application to civil structures involved a macroscopic scale [5],[6]. The principal failure modes found are:

- compression and shear failure of concrete,
- tensile rupture of FRP,
- peeling and debonding of FRP.

This macroscopic approach can give useful information about the global behaviour of concrete elements strengthened with FRP. But, especially in the last case, it is important to investigate the crack onset and propagation in order to follow the local crisis up to the global failure of the concrete element.

EXPERIMENTAL

The final goal is to study the effect of the FRP strengthening applied to the concrete structures in bending. This preliminary experimental programme is aimed at studying the correlation between the crack propagation in the concrete and the crack propagation at the interface.

Testing specimens

For this reason, tensile tests were carried out. In this way a simple case has been

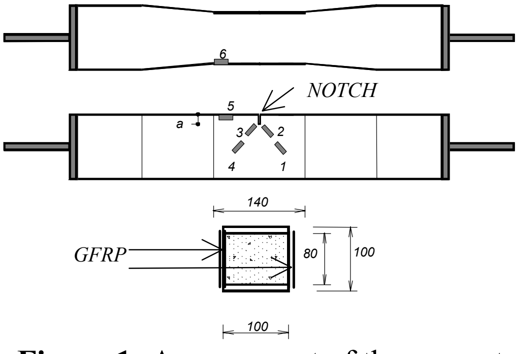


Figure 1: Arrangement of the concrete specimen tested in tension

studied, because the specimen has a very regular geometry and the loading arrangement is well defined. The shape and dimensions of the specimens are sketched in Figure 1. The particular shape was designed in order to have a stress state not disturbed by anchorage effects in the central part of the specimen. GFRP sheets were glued to the plain surfaces, on opposite sides. A notch was milled on one side, under the composite, to establish the crack starting point. Five similar specimens were tested. One plain concrete specimen was tested too.

Test set-up

The test set-up is shown on Figure 1. The specimens were instrumented with electrical strain gauges (ESG), 6 mm long, placed as follows:

- two ESGs on the same section, one on concrete and the other on GFRP (#5 and #6), in order to detect the difference between the strains during testing;
- two ESGs on the concrete (#2 and #3), close to the notch, 45° to the longitudinal axis;
- two ESGs (#1 and #4) as the previous ones, but at 20 mm from the notch.

Two displacement transducers LVDT-5 mm were used to measure of the elongation of the specimen.

Nevertheless, the local measurements supplied by the ESGs appeared to be unable to give sufficient information about the crack propagation direction around the cracking area. For this reason some photoelastic images were taken during the tests. The photoelastic sheet was glued to the concrete, in the area of interest. A digital video-camera was used to record the tests.

Experimental results

Photoelastic images

In figures 2.a and 2.c the most significant pictures from the video-camera are shown. Note the change in strain state during loading. Figure. 2.a shows the propagation of the first crack: an area of strain concentration localised close to the notch can be noted.

With loading increasing, the crack propagates into the concrete to the concrete-GFRP interface, as can be observed in Figure 2.c.

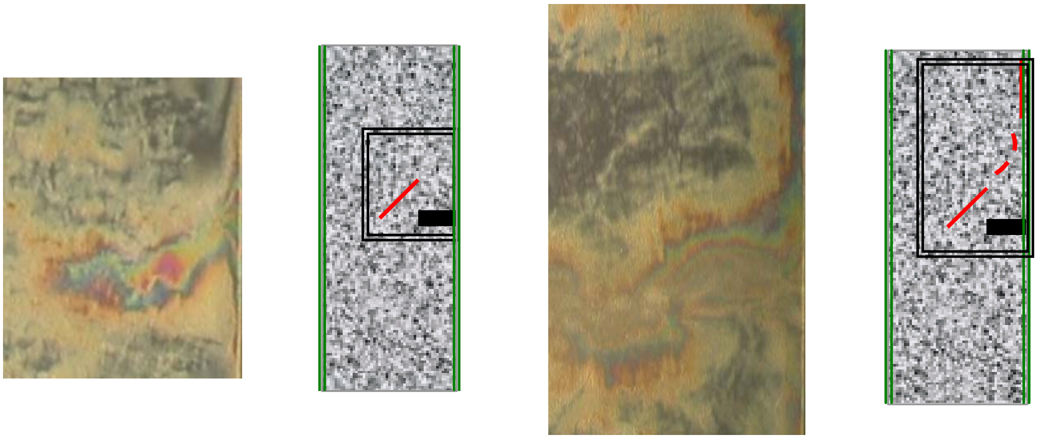
By means of the photoelasticity, it is easy to see the propagation direction: the fracture mode is a mixed mode at the start of the crack. Then, the crack propagates into the concrete towards the concrete-composite interface with mixed mode, too. This propagation mode has also been observed by other researchers [7]. Finally, the crack propagates in the concrete, perpendicular to the loading direction (Figure 2.c).

Strain measurements

In Figure 3 the readings from the two longitudinal strain gauges are plotted vs. load. The strain in the GFRP is higher than in the concrete, after the crack reaches the interface; this is because the concrete cracking causes a stress transfer from the concrete to the composite.

Figure 4 shows the diagonal strain in the concrete from the ESGs placed at +45° and –45° from the axis of the notch.

We can note higher strain values for the ESG #3. This difference can be caused by the strain localisation as pointed out by the photoelastic image (see Figure 2/a).



a: first crack in the concrete | **b:** sketch of the first crack onset | **c:** crack propagation | **d:** sketch of the crack propagation

Figure 2: Photoelasticity

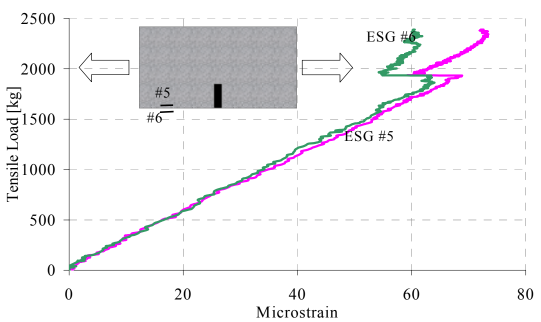


Figure3: Total Load vs. Longitudinal Strain

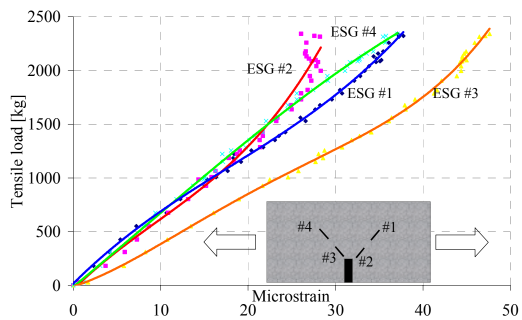


Figure 4: Total Load vs. Diagonal Strain

ANALYTICAL APPROACH

A simple analytical approach is presented, aimed at evaluating the Stress Intensity Factor for this experimental case.

An analogous problem has been analysed in [8] for a cracked beam element in r.c. beams.

In this case, a concentrated load P simulates the behaviour of the GFRP strengthening which hampers the opening of the crack. The existent models based on Fracture Mechanics [9,10] for a simple strip have been used and they are illustrated in Figures 5 and 6, respectively.

For a crack with a distributed tension, the stress intensity factor (SIF) is

$$K_{I\sigma} = \sigma\sqrt{\pi a}F(\xi),$$

where, $K_{I\sigma}$ is the stress intensity factor due to a distributed tension σ and ξ is the normalised crack height[9],

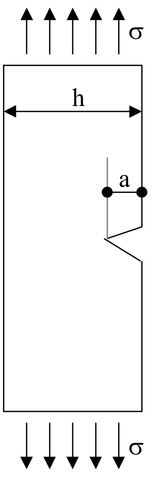


Figure 5: crack with distributed tensile stress

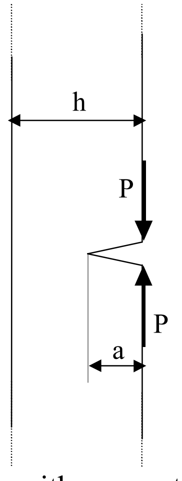


Figure 6: crack with concentrated load

$$F(\xi)=\sqrt{\frac{2}{\pi\xi}tg\frac{\pi\xi}{2}}\frac{0.752+2.02\xi+0.37\left(1-sin\frac{\pi\xi}{2}\right)^3}{\cos\frac{\pi\xi}{2}}.$$

For a crack with a concentrated load the value of the stress intensity factor is

$$K_{IP}=\frac{P}{h^{0.5}b}Y_P(\xi),$$

where K_{IP} is the stress intensity factor due to a concentrated opening load P, h, b are the height and the width of the specimen, respectively, and ξ is the normalised crack height[10],

$$Y_P(\xi)=\frac{3.52}{(1-\xi)^{3/2}}-\frac{4.35}{(1-\xi)^{1/2}}+2.13(1-\xi).$$

So, the final stress intensity factor K_{IT} can be evaluated as

$$K_{IT}=K_{I\sigma}-K_{IP}.$$

For the case under study, the calculated value of K_{IP} is higher than the value of $K_{I\sigma}$. For this experimental test, the load applied to the specimen is not too high to allow the crack propagation at the interface concrete-FRP strengthening. This could happen if the shear stresses reach critical values at the concrete-resin interface.
The crack propagation, as can be seen on the photoelastic images, takes place in the concrete, at the crack tip.

CONCLUSIONS

The first results of this research suggest that the crack propagation in the concrete strengthened by GFRP can be studied by means of Fracture Mechanics. The experimental tests give useful information about both the stress and strain state around the crack and the direction of the crack propagation. The values of SIF can be calculated and they suggest some failure mode of the concrete element strengthened. In particular, if the constraint of strengthening is good, the SIF suggest that the crack can not propagate at the interface and then it propagates around the other tip in the concrete. Research is still in progress in order to apply these preliminary results to the r.c. beams strengthened by FRP in bending, and then to define some correlation between the crack in the concrete and the crisis at the concrete-FRP interface.

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