VIII International Conference on Computational Plasticity
COMPLAS VIII
E. Oñate and D.R.J. Owen (Eds)

# MODELLING OF FAILURE MECHANISMS IN RC BEAMS RETROFITTED WITH FRP IN FLEXURE

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**Key words:** Concrete; FRP delamination; end-peeling; interface stresses; cracking.

**Summary.** *The effectiveness of f.e. analysis on investigating the nonlinear behaviour up to failure of RC beams retrofitted with FRP composites is investigated in this work. Attention is mainly focused on the determination of interfacial stresses at the FRP/concrete interface and on the prediction of middle-span debonding and end-peeling failure mechanisms.*

## 1 INTRODUCTION

The analysis of the failure mechanisms of reinforced-concrete (RC) beams retrofitted with fiber-reinforced-polymers (FRP) which involve end-peeling of the fiber-reinforced composite, FRP debonding or covercrete debonding requires more sophisticated models than those based on the hypothesis that cross sections remain plane after deformation [1]. It has been shown in [2, 3] that a 2D finite-element analysis a RC beam in four-point bending is able to reproduce the experimental results reported in [4], with good agreement, provided that the nonlinear behaviour of concrete, the crack pattern in the beam, the rebar-concrete bond-slip mechanism and the possibility of FRP debonding are adequately accounted for. In particular, a zero-thickness FRP-concrete interface is introduced in [2] and supplemented with a cohesive-zone model.

The present study provides a further step in the use of nonlinear numerical analysis for the investigation on the above mentioned failure mechanisms. In particular, it is shown that the explicit modelling of the crack pattern which develops in the concrete plays a key role in the accuracy of the computed interfaces stresses at the FRP/concrete interface. The ability of the model to predict the initiation of the delamination from the area below the applied force, close to the middlespan and in correspondence of one of the vertical cracks, as well as its propagation is then illustrated. The possibility of deriving the interface parameters entering the cohesive-zone laws used on the FRP/concrete and rebars/concrete interfaces from a suitably determined set of material parameters for the concrete is then discussed.

## 2 NONLINEAR FINITE-ELEMENT MODEL

The simply supported beam in four point bending experimentally studied by White et al. in [4], see figure 2 for beam geometry, steel reinforcement and loading pattern, has been numerically analysed with the nonlinear finite-element model described in [2,3]. Both a control beam, with no FRP reinforcement, and two types of beams, denoted with SB and RB and reinforced with a pultruded CFRP lamina and with a pre-preg CFRP sheet, respectively, have been simulated.

The Menetrey-Willam elastoplastic model has been used for concrete while cohesive-zone models have been adopted to simulate both the bond-slip between steel rebars and concrete and the possible debonding of the FRP reinforcement. The material properties adopted for concrete and steel rebars are those reported in the work by White et al. The paramteres which govern the bond-slip law between rebars and concrete have been chosen on the basis of similar cases reported in the literature, while for those entering the FRP/concrete interface law the indications given in codes of practice have been followed. Details on the constitutive models and the values of material properties can be found in [3].

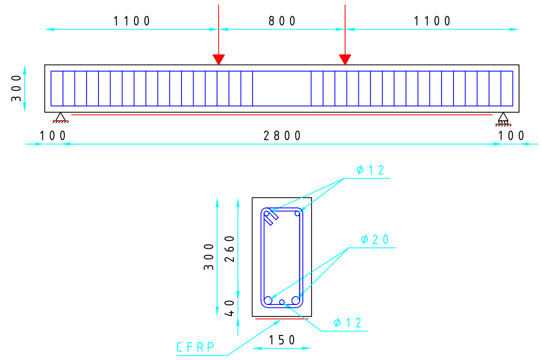

Figure 1: RC beam: geometry and loading.

In the f.e. model, which represents only half of the beam because of symmetry, a crack pattern has been predefined and 14 vertical cracks have been introduced with a spacing of 100 $mm$, a distance approximately the same as that observable from the experimental results reported in [4]. Contact between crack faces has been properly accounted for. The hypotheses of plane strain and of small displacements have been made.

## 3 Interfacial stresses between concrete and FRP

The insertion of localised cracks has a significant effect on the determination of the interfacial stresses at the FRP/concrete interface, what is correctly captured by the nonolinear model developed in [2,3]. This is shown in figure 2, in which the shear stresses at the FRP/concrete interface for a model with localised cracks and those obtained using a smeared crack approach are reported for a load level below delamination initiation and for the reinforced beam RB. The smeared crack concept has been introduced in the finite element model using Oliver's material model, as already done in [5]. The details of the analysis done with this model are reported in [3].

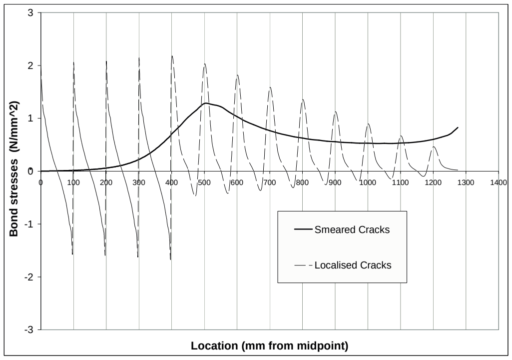

Figure 2: Shear stresses at the FRP/concrete interface for localised and smeared cracks.

In the smeared crack case shear stresses at the interface quickly tend to zero on the left-hand side of the applied force, i.e. in the constant-moment area of the beam. These stresses are smoothly distributed and their value, far from the laminate tips, can be well approximated using Jourawski's approach. This distribution of stresses is very different from that obtained for a beam with localised cracks.

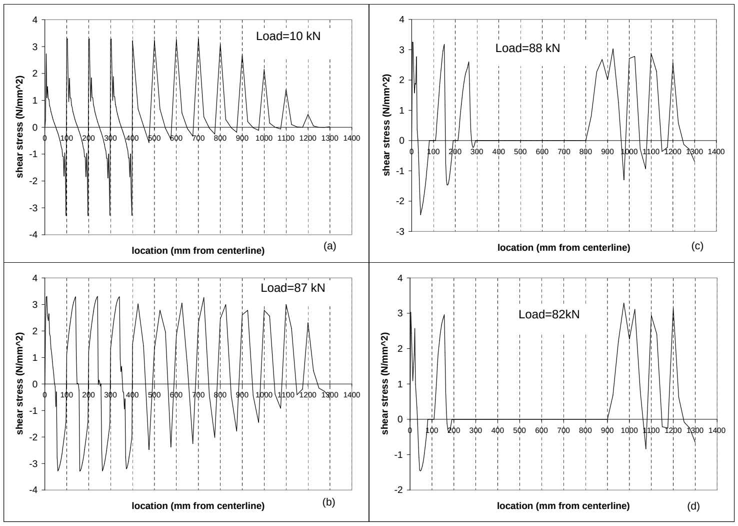

Figure 3: Evolution of the shear stresses at the FRP/concrete interface for the subsequent load levels: (a) $P = 10\,KN$, (b) $P = 87\,KN$, (c) $P = 88\,KN$ and (d) $P = 82\,KN$.

The last set of results presented in figure 3 is a series of diagrams showing the stresses at the FRP/concrete interface in the reinforced beam RB, for several levels of the applied load. It is evident the progressive de-cohesion of the laminate from the concrete face, initiating in the area near to the point of application of the load and leading to almost complete delamination and then to failure. In this case delamination is not triggered in the vicinity of the terminal zones of the laminate. Indeed the shear forces at supports are limited and the stresses generated by crack opening in the span are the critical ones.

Furthermore, it is shown in [3] that the dependence of the Menetrey-Willam criterion on the Lode angle has more influence in the case of a reinforced beam than for the control beam. This is attributed to the fact that shear is the prevalent component of stress at the interface and the the dependence on the Lode angle influences the shape of the deviatoric sections of the yield surface.

In this respect it is worth observing that the assumed interface model is representative of what happens in a finite volume including the bonding material and a layer of concrete, whose thickness is generally estimated as 20-30 mm. Hence, as the boundary between what is concrete and what is interface is somewhat vague, local, refined analyses, accounting for a proper modelling of this layer of damaging concrete and for the coupling between damage and plasticity in the concrete, represent a consistent way for deriving the input interface parameters for the FRP/concrete cohesive-zone law starting from material properties of the concrete. Besides the compressive and tensile strengths, such properties have to include also values of the fracture energies obtained from laboratory experiments like the three-point-bending test.

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