Finite element analysis of flexural cracking behavior of RC structures, strengthened by externally bonded CFRP

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Abstract :

FE simulation of damage and crack initiation and propagation in RC structure, externally strengthened by CFRP will be presented. Constitutive law, based on the model of Mazars will be used for the simulation of the non-linear concrete behavior. In the proposed incremental procedure the regions, affected by damage will be remeshed at each step and the initial mesh will be refined. The numerical results will be compared with experimental results obtained by the authors for CFRP strengthened RC beam subjected to a bending.

Mots clefs: FE simulation, nonlocal damage, crack initiation, crack propagation

Introduction

A numerical simulation of the mechanical behavior of a Reinforce Concrete beam, subjected to flexion and strengthened by adhesively bonded composite material is presented in this study. Casting composite material enhance the mechanical performances of the RC structure, but the failure mode which provokes the global failure changes from the flexural I-mode crack in concrete to interfacial crack at the concrete/composite material interface.

The interface crack trajectory follows the path requiring the least amount of energy. Theoretically the interface fracture can occur either in the substrates (concrete, composite material) either in the adhesive layer or in the interfaces (steel/concrete, concrete/adhesive, adhesive/composite material). In the experimental part of our study we observed an interface meso-crack initiation and propagation ate the concrete cover. We focus on the modeling of concrete behavior, taking into account the contribution of the other components of the strengthened system (steel, adhesive, composite material).

1. Solution description and background

The constitutive models are formulated in the meso-scale. Nonlinear material models are defined for the structure components which have non-linear behavior: concrete, steel. An accurate explicit 3D modeling of the structure is also proposed

The behavior of a Reinforced Concrete structure is simulated in a numerical semi-analytical procedure based on the commercial FEM code ANSYS. The concrete response being strongly path-dependant [1], the structure behavior is obtained in an incremental solution. The driving parameter is the applied load (Fig. 1). In the solution module the components of the strain and stress tensors are evaluated in a non-linear FEM analysis. Nonlinear static analysis for the current load step is performed and the components of the strain and stress tensor are evaluated.

The stress-strain relationship is described trough predefined constitutive laws, chosen after consideration of the experimental data obtained in mechanical tests. Failure criteria are also defined for the different materials. Thus, a bilinear isotropic hardening is used to model the steel behavior. The non linear concrete response is simulated in the framework of the continuous damage mechanics with definition of a scalar damage variable, affecting the elasticity modulus. A material model, assuming isotropic damage is used [2]

$$\overline{E} = E.(1-D) \text{ with } D_{c,t} = 1 - \frac{\varepsilon_{D_0}\left(1-A_{c,t}\right)}{\varepsilon_{eqv}} - \frac{A_{c,t}}{\exp\left(B_{c,t}(\varepsilon_{eqv} - \varepsilon_{D_0})\right)} \quad (1)$$

and spectral strain decomposition:

$$\langle \varepsilon_i \rangle = \varepsilon_i \text{ Si } \varepsilon_i \geq 0\,,\ \langle \varepsilon_i \rangle = 0 \text{ si } \varepsilon_i < 0 \quad \varepsilon_{eqv} = \sqrt{\sum_1^3 \langle \varepsilon_i \rangle^2}\ . \quad (2)$$

The composite material behavior is assumed to be linear elastic till rupture as the material anisotropy is taken into account in the identification of the rigidity tensor components, the behavior of the adhesive layer is assumed to be linear elastic and isotropic.

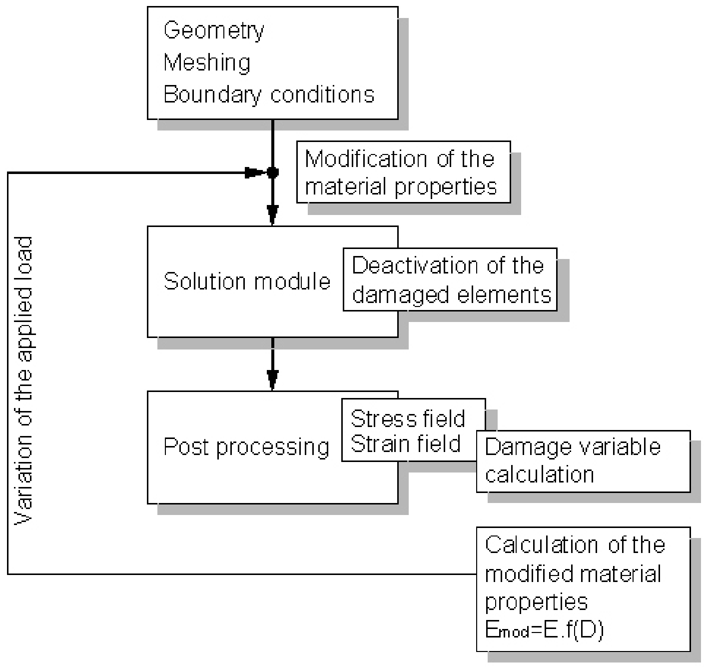


Fig. 1: Semi-Analytical procedure

In the post-processing module, the failure criteria are verified for each finite element. The result data is stored into arrays in order to modify in the subsequent increment the material properties of the finite elements in which damage accumulation takes places. The finite elements in which failure is detected are deactivated before performing the next increment solution.

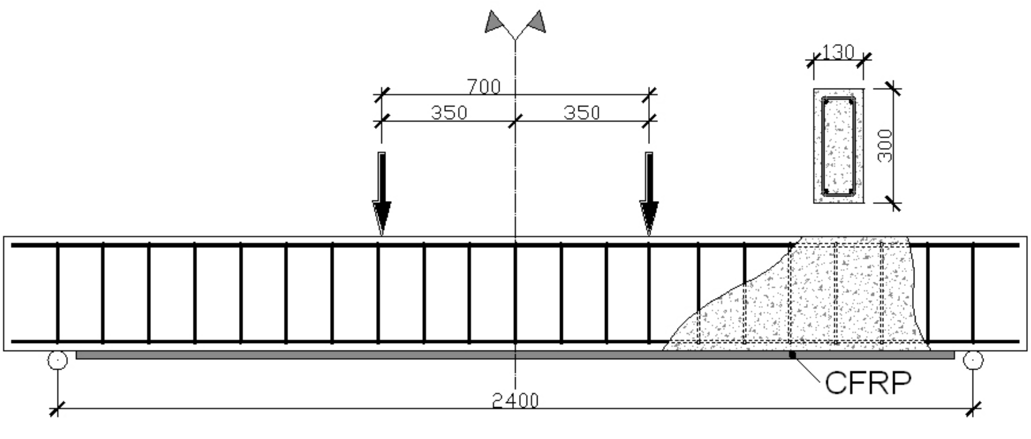


Fig. 2: Reinforced Concrete Beam Geometry

1.1 Structure geometry

Before applying the procedure described here-before, the structure geometry has to be defined.
A 2400mm spam RC beam with cross section 130mm x 300m (Fig. 2) is modeled. The beam is reinforced with 8mm diameter steel rebars and 6mm diameter stirrups. All existing planes of symmetry are used and symmetry boundary conditions are applied.

1.2 Identification of the mechanical parameters

Table 1: Mechanical parameters for steel material model

$f_y(MPa)$	$f_u(MPa)$	$\varepsilon_y(\%)$	$\varepsilon_u(\%)$	$E_0(MPa)$	$E_1(MPa)$	ν
500	580	0.237	10	210700	815	0.28

Table 2: Mechanical parameters for concrete material model

$E_0(MPa)$	$f_{c,28}(MPa)$	A_c	B_c	$f_{t,28}(MPa)$	A_t	B_t	ε_{D0}
29000	30	1.39	1538	3.6	0.8	12000	2.10^{-5}

Table 3: Mechanical parameters for CFRP material model

$E_{11}(GPa)$	$E_{22}(GPa)$	ν_{12}	ν_{23}	$E_{22}(GPa)$
238.6	27.8	0.35	0.18	4.86

Table 4: Mechanical parameters for adhesive material model

$E(MPa)$	ν
7050	0.39

Along with the material models constitutive laws are formulated for steel- concrete interface. According to previous researches [3] and our experimental data no failure is observed in the adhesive layer. In the present study failure criteria is not formulated for the concrete- composite material interface

1.2.1 Steel- concrete interface:

A Coulomb model function is chosen to model the behavior of the steel-concrete interface [4] (Fig. 3):

$$f(\tau,\sigma) = \tau - |\sigma_n|.tg\theta - c\,, \qquad (3)$$

where τ is the tangential bond stress, c- cohesion, θ- friction angle.

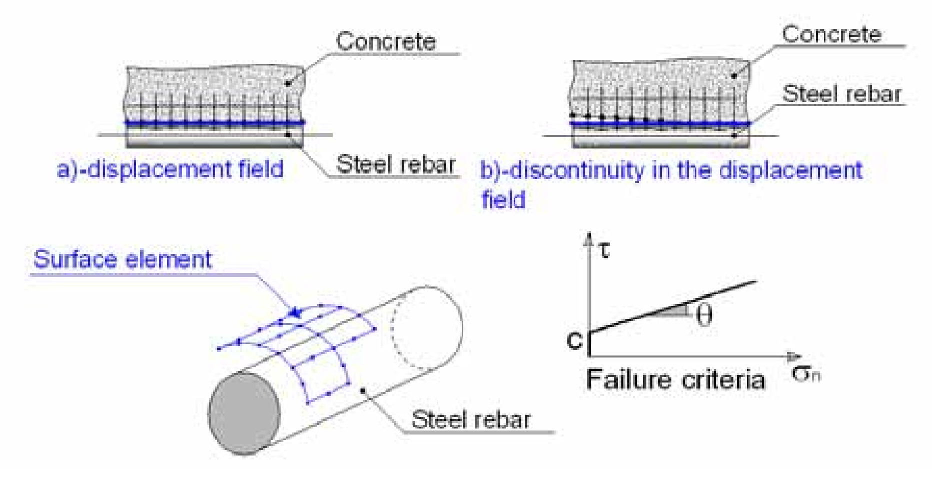


Fig. 3: Concrete interface

According the experimental data [5], [6], [7] the following values are used: $c = 5MPa$ and $\theta = 10^0$.

1.3 Delocalization of the Damage variable

The non local state can be considered trough the delocalization of damage variable. Thus the assumption can be made that the mechanical state at the considered "source point" affects the mechanical state in the small portion of matter around the "source point". Furthermore the hypothesis can be formulated that the "impact" on a current point depends on the distance between the "source" and the current point in the framework of the representative volume element. Using this approach, the variable $W(x)$, evaluated in current point x, is "smeared" on the volume around the point: $W(x) = W_0.F$, where W_0 is a normalization factor, F can be the Gauss distribution function $F*$ or bell-shaped function $F**$ [8]:

$$F* = \exp\left(-\|x\|^2 / 2\delta_c^2\right) \text{ and } F** = \left\langle 1 - \|x\|^2 / 2\delta'^2_c \right\rangle^2 \quad (4)$$

x -distance between the source point and the current point, δ_c - internal length of the medium. The correlation between fracture mechanics and damage mechanics gives the order of magnitude of the internal length of the concrete [9]: $\delta_c = 2.10^{-1}$ m.

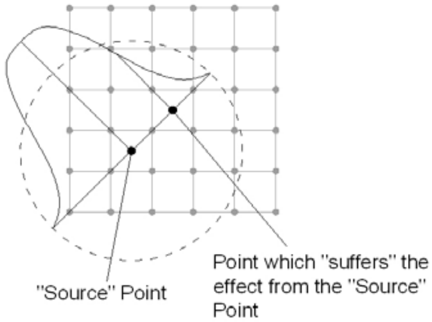


Fig. 4: Delocalization of the damage variable

In this study the following function is used (Fig. 4):

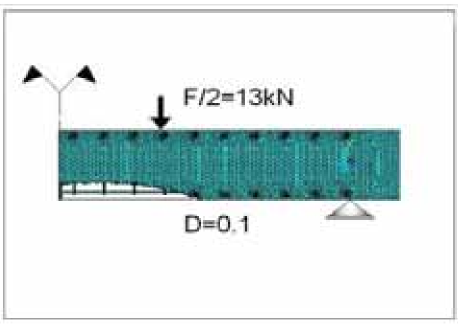
$$F*** = C.\exp\left[-\left(\delta^2 / \delta^2 - |x|^2\right)\right] \text{if } |x| \le \varepsilon \text{ and } F*** = 0 \text{ if } |x| \le \varepsilon \quad (5)$$

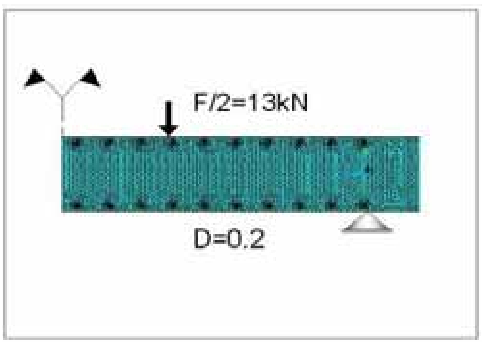
The normalizing factor W_0 is evaluated with respect of the condition:

$$\int_V W_0 F*** \, dx = 1 \quad (6)$$

2. Numerical results

The proposed numerical procedure can be used for both quantitative and qualitative simulation of a reinforced concrete member mechanical behavior. The procedure offers the possibility to follow the damage initiation and propagation in the concrete with the applied load increase (Fig. 5), what is its qualitative aspect.





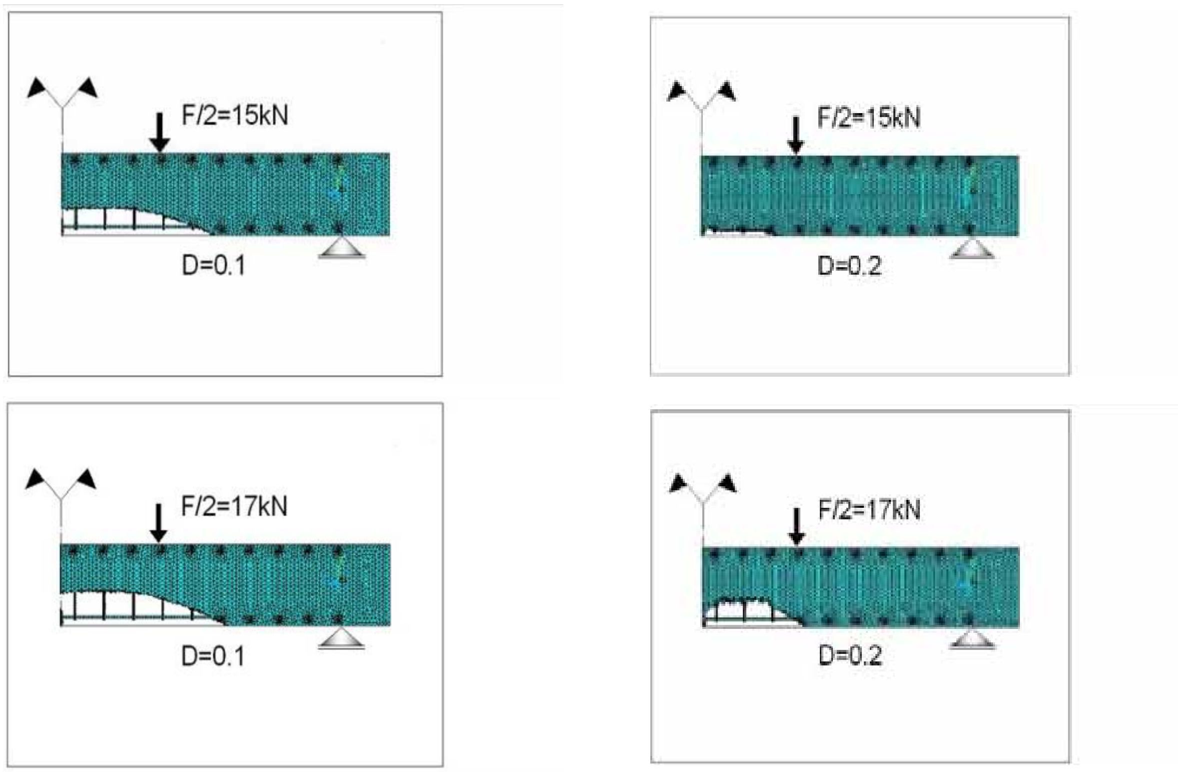


Fig. 5:Initiation and propagation of damaged zones with the applied load increase

A monitoring of the global and of the local response of the structure can be provided for all the load history. The numerically obtained results are close to the experimental data (Fig. 6). At (Fig. 7) is illustrated the increase in rigidity of the strengthened system with the increase of the number of reinforcing layers.

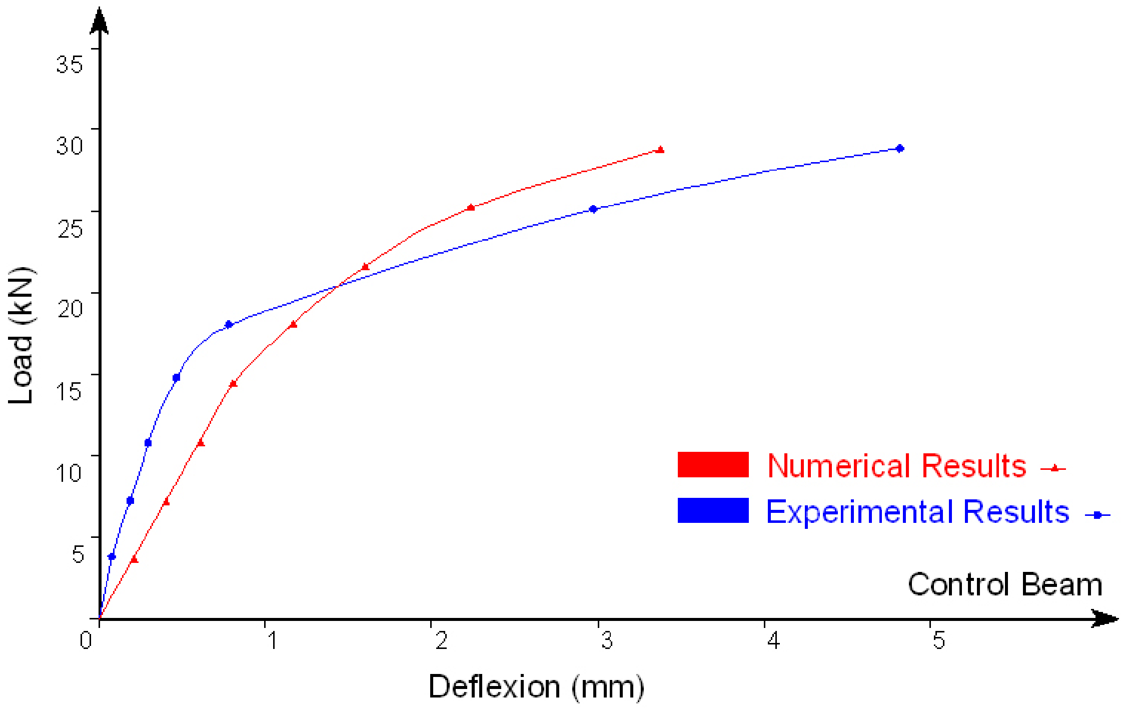


Fig. 6: Comparison between the experimentally and numerically obtained load- deflection beam response

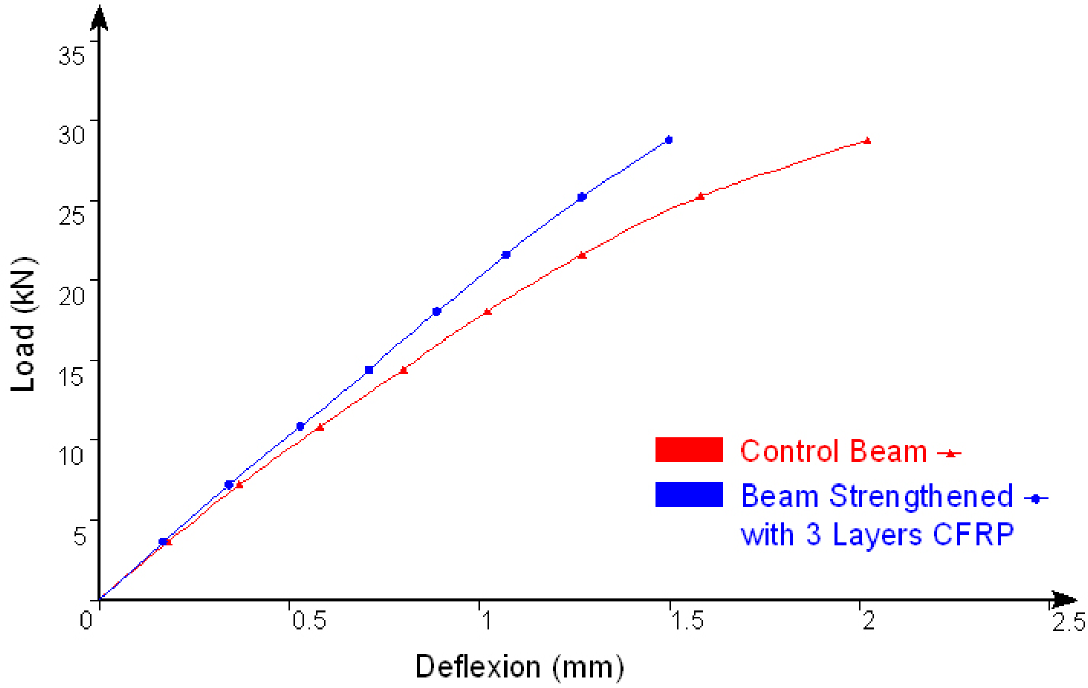


Fig. 7: Gain of rigidity after casting 3 layers CFRP

Conclusion

A semi-analytical procedure aiming the simulation of the mechanical behavior of a RC beam strengthened by externally bonded composite material is presented in this paper. Unlike the existing models, non-linear behavior of materials is simulated. Explicit geometry modeling enables the interface zone definition. In order to introduce the mechanical problem consideration in the framework of the non-local state a delocalization of the damage variable is performed. For more accurate simulation of the structure behavior the implementation of an anisotropic damage model for concrete can be anticipated in future research works.

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