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NONLINEAR FINITE ELEMENT ANALYSIS OF FRP STRENGTHENED RC BEAMS

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A simple, accurate and efficient finite element model is developed in ANSYS for numerical modelling of the nonlinear structural behavior of FRP strengthened RC beams under static loading in this paper. Geometric nonlinearity and material non-linear properties of concrete and steel rebar are accounted for this model. Concrete and steel reinforcement are modelled using Solid 65 element and Link 180 element, and FRP and adhesive are modelled using Shell 181element and Solid 45 element. Concrete is modelled using Nitereka and Neal's model for compression, and isotropic and linear elastic model before cracking with strength gradually reducing to zero after cracking for tension. For steel reinforcement, the elastic perfectly plastic material model is used. FRPs are assumed to be linearly elastic until rupture and epoxy is assumed to be linearly elastic. The new FE model is validated by comparing the computed results with those obtained from experimental studies.

Keywords: Concrete beam, Fibre reinforced polymer (FRP), Finite element model, Nonlinearity.

1 INTRODUCTION

Steel rebar-reinforced concrete (RC) structures are subjected to structural deterioration which might be caused by environmental factors, defects on design and construction, and extreme loadings such as earthquake, hurricane, impact explosion, fire, etc., and thus might be need to be retrofitted during their service life. FRPs have many superior characteristics such as ease of application on site, high strength to weight ratio, immunity to corrosion, good durability and fatigue resistance, and have been used as a strengthening material to retrofitting RC structures (Hollaway and Leeming 1999).

In recent decades, many experimental and numerical researches have been conducted to investigate the structural behaviour of FRP strengthened RC beams, and finite element models have been developed and employed for nonlinear finite element analysis of FRP strengthened RC beams. For example, Hashemi *et al.* (2007) conducted finite element analyses of FRP strengthened RC beams under four-point loading. The concrete, steel reinforcement and FRP were modelled using Solid65, Link8 and Solid 45 element respectively, and material properties of concrete, steel reinforcement and FRP were modelled using a linearly elastic-perfectly plastic model, elastic-perfectly plastic model, linear model up to the failure respectively. The concrete in tension was modelled as linearly elastic until the maximum tensile strength after which cracks and strength gradually reduces to zero. Sudarraja *et al.* (2008) analysed the structural behaviour of FRP strengthened RC beams under four-point loading using ANSYS. In the modelling, the concrete was modelled using the Macgregor and Wight's (1992) material model for compression and linear elastic model until crack with the strength gradually reducing to zero after cracking for tension. For steel reinforcement, the elastic- perfectly plastic material model was used. Molina *et al.* (2011) claimed that it was necessary to model the epoxy adhesive because it could be susceptible to damage. However most of the finite element models developed in the existing literatures didn't consider the effect of adhesive layer, leading to inaccurate prediction of the structural behaviour.

In this paper, a simple finite element model which can model the structural response of FRP strengthened RC beams under static loading efficiently and accurately is developed. Both geometric nonlinearity and material nonlinear properties are accounted for in this model. In this model, concrete, steel rebar, FRP and adhesive are modelled using Solid 65, Link 180, Shell 181 and Solid 45 elements respectively. Concrete is modelled using Nitereka and Neal's model (1991) for compression, isotropic and linear elastic model before cracking with strength gradually reducing to zero after cracking for tension. For steel reinforcement, the elastic-perfectly plastic material model is used. FRPs are assumed to be linearly elastic until rupture and epoxy is assumed to be linearly elastic. The developed FE model is validated by comparing the computed results with those obtained from different experimental studies available in literature.

2 FINITE ELEMENT MODEL

The Solid 65 element, which is a three-dimensional (3D) solid element, is used to represent the concrete. The element is defined by eight nodes having three translational (translation in the x, y and z directions) degrees of freedom at each node. This element is capable of modelling concrete cracking in tension and crushing in compression. The 2-node LINK 180, with three DOFs (translation in the x, y and z directions) is used to model the reinforcing steel rebar. The FRP strips are smeared as thin plates and four-node SHELL181 element with six degrees of freedom at each node, i.e. translations in the x, y, and z directions, and rotations about the x, y, and z axes is used for modelling the FRP plate. The epoxy adhesive layer is modeled using SOLID45 element, which is a solid element with eight nodes having three degrees of freedom at each node, i.e. translations in the x, y, and z directions.

3 MATERIAL MODEL

Concrete is a quasi-brittle material with different behavior in tension and compression. The compressive behavior of concrete is modelled using the nonlinear stress-strain relationship by Nitereka and Neal (1991), which consists of an ascending curve and linear descending branch as shown in Figure 1(a) and Eq. (1)

$$\sigma_c = f_c\left[\frac{\varepsilon_c}{\varepsilon_0}\left(2-\frac{\varepsilon_c}{\varepsilon_0}\right)\right]\text{for}(\varepsilon \le \varepsilon_0)$$

$$\sigma_c = f_c\left[1 - 0.15 \times \left(\frac{\varepsilon_c - \varepsilon_0}{\varepsilon_{cu} - \varepsilon_0}\right)\right] \text{for}(\varepsilon_0 \leq \varepsilon \leq \varepsilon_{cu}) \tag{1}$$

where f_c is the compressive strength of the concrete and ε_{cu} is the ultimate compressive strain of the concrete. The corresponding compressive strain ε_0 at the compressive strength is calculated by the equation proposed by Coronado and Lopez (2006) as in which E_c is the Young's modulus of concrete.

$$\varepsilon_0 = 1.71 \times (f_c/E_c) \tag{2}$$

For concrete in tension, the stress-strain curve is assumed to be isotropic and linearly elastic up to maximum tensile strength after which concrete cracks and strength gradually reduces to zero as shown in Figure 1(b). T_c is the multiplier for the amount of tensile stress relaxation whose default value is 0.6 in ANSYS.

The input data required in ANSYS to describe the material properties of concrete are: Poisson's ratio (ν), elastic modulus (E_c), uniaxial compressive stress (σ_{cu}), uniaxial tensile stress (f_t), shear transfer coefficient (β_t). The value of β_t can vary from zero to one. A value of zero refers to smooth crack whereas one refers to rough crack. These factors are used to determine how much shear force can be transferred across open or closed crack. For this model, closed crack is assumed as one and open crack is assumed as 0.3.

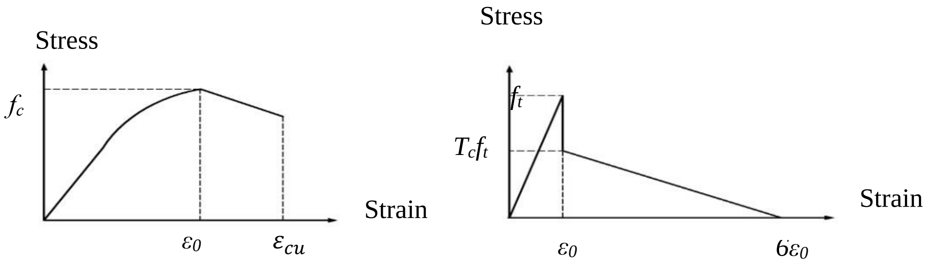


Figure 1. Stress-strain relationship of concrete: (a) compression (Nitereka and Neal 1991); (b) Tension (ANSYS13.0).

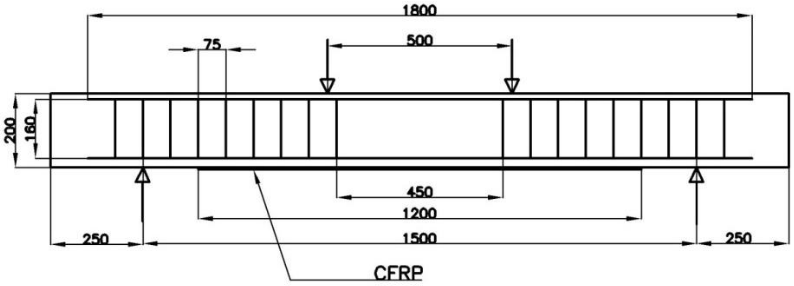
The reinforcing steel is assumed to be elastic-perfectly plastic in tension and compression. FRPs are assumed to be linearly elastic until rupture, and epoxy is assumed to be linearly elastic.

4 NUMERICAL VALIDATION

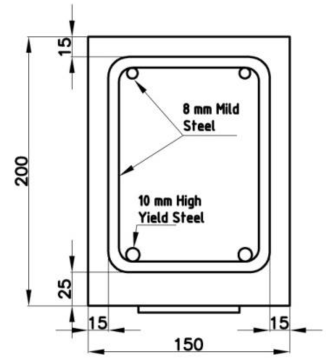
A FRP strengthened RC beam is analysed using the developed FE model and the computed load-central deflection relationship is compared to that obtained from the experimental study.

4.1 A CFRP Strengthened RC Beam Tested by Gao *et al.* (2004)

A CFRP strengthened RC beam (2000 mm × 150mm ×200 mm) tested by Gao *et al.* (2004) is modelled using the developed FE model. The details of steel reinforcement and dimension of the beam is illustrated in Figure 2. The tension side of the RC beam is externally bonded with 1200mm long, 75 mm wide, and 0.22 mm thick CFRP. The material properties of concrete, steel reinforcement, CFRP and epoxy adhesive are given in Table 1.



(a) Longitudinal section the CFRP strengthened RC beam.



(b) Cross-section of the CFRP strengthened RC beam.

Figure 2. A CFRP-strengthened RC beam tested by Gao *et al.* (2004) (Dimensions: mm).

Table 1. Material properties of the materials of the CFRP RC beam.

Material	**Young Modulus (GPa)**	**Compressive strength (MPa)**	**Tensile strength (MPa)**	**Yield Strength (MPa)**	**Poisson's ratio**
Concrete	25	35.7	4.182		0.2
Steel	200			531	0.3
CFRP	235		4200		0.35
Epoxy	1.0				0.35

Due to symmetry, a quarter of the beam is analyzed. A convergence study is carried out in the control RC beam without FRP strengthening using the developed model. The computed maximum central deflection of the control RC beam with varying mesh size of 25 mm (1122 elements), 15 mm (6733 elements) and 12.5 mm (8031 elements) is presented in Figure 3. It can be seen that the computed central deflection converges when the size of the element is 15 mm (6733 elements) to the experimental result of 4.26 mm. Thus the finite element model with the mesh size of 15 mm is used for the analysis of the FRP-strengthened RC beam.

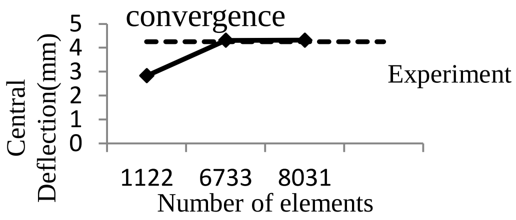


Figure 3. Convergence test for the control beam.

The load-central deflection curves obtained from the finite element analysis and experiment for both the control beam and the FRP-retrofitted RC beam are presented in Figure 4. Very good agreement between the computed results and the experimental results are obtained for the control beam and FRP strengthened beam. This demonstrates the effectiveness and accuracy of the model in the nonlinear finite element analysis of the FRP-RC beams.

Comparing the load-deflection relationship of the RC beam and the FRP strengthened RC beam, it is obvious that the FRP strengthening reduces the deformation of the RC beam. At 50 KN, the central deflection of the control beam is 4.308 mm while for FRP strengthened RC beam, it is 3.836 mm (a reduction of 12%). The control beam fails much earlier (failed around 48 kN) than the beam strengthened with FRP (failed around 65 kN).

5 SUMMARY

A simple finite element model is developed in this paper for nonlinear finite element analysis of FRP-strengthened RC beams. In this finite element model, all the constituents of the RC beams i.e. concrete, steel reinforcement, FRP and epoxy are appropriately represented. Concrete, steel rebar, FRP and adhesive are modelled using Solid 65, Link 180, Shell 181 and Solid 45 elements respectively. Concrete is modelled using Nitereka and Neal's model for compression, isotropic and linear elastic model before cracking with strength gradually reducing to zero after cracking for tension. For steel reinforcement, the elastic perfectly plastic material model is used. FRPs are assumed to be linearly elastic until rupture, and epoxy is assumed to be linearly elastic. The finite element model is used to model the load-displacement relationship of a control RC beam without FRP and a CFRP strengthened RC beam. The computed results agree very well with those obtained from experimental results, and this demonstrates the efficiency and accuracy of the developed finite element model. It should be noted that in this model, perfect bond between FRP/concrete interfaces is assumed. A finite element model with the bond-slip behavior between the FRP and concrete interface will be developed in the future research.

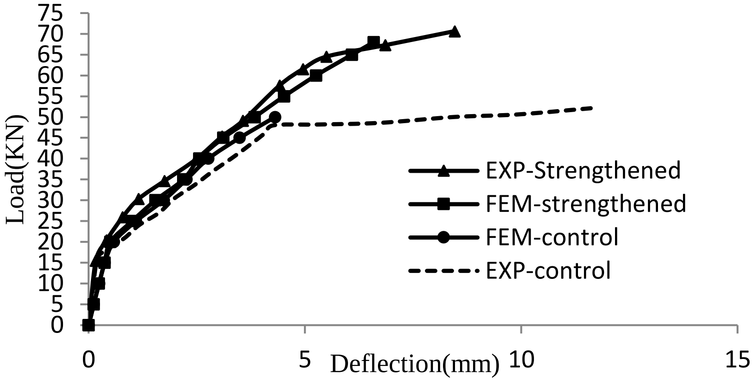


Figure 4. Load-central deflection of the control beam and FRP strengthened RC beam.

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