Nonlinear Analysis of Shear Dominant Prestressed Concrete Beams using ANSYS

Job Thomas
Indian Institute of Science, Bangalore, India
Ananth Ramaswamy
Indian Institute of Science, Bangalore, India

Abstract

This study reports the details of the finite element analysis of eleven shear critical partially prestressed concrete T-beams having steel fibers over partial or full depth. Prestressed T-beams having a shear span to depth ratio of 2.65 and 1.59 that failed in shear have been analyzed using the 'ANSYS' program. The 'ANSYS' model accounts for the nonlinearity, such as, bond-slip of longitudinal reinforcement, post-cracking tensile stiffness of the concrete, stress transfer across the cracked blocks of the concrete and load sustenance through the bridging action of steel fibers at crack interface. The concrete is modeled using 'SOLID65'- eight-node brick element, which is capable of simulating the cracking and crushing behavior of brittle materials. The reinforcement such as deformed bars, prestressing wires and steel fibers have been modeled discretely using 'LINK8' – 3D spar element. The slip between the reinforcement (rebars, fibers) and the concrete has been modeled using a 'COMBIN39'- nonlinear spring element connecting the nodes of the 'LINK8' element representing the reinforcement and nodes of the 'SOLID65' elements representing the concrete. The 'ANSYS' model correctly predicted the diagonal tension failure and shear compression failure of prestressed concrete beams observed in the experiment. The capability of the model to capture the critical crack regions, loads and deflections for various types of shear failures in prestressed concrete beam has been illustrated.

Introduction

The shear failures in reinforced concrete (RC) structures are highly brittle when compared with the flexural failures. The addition of chopped steel fibers in the concrete matrix is effective in mitigating the brittle failures of RC structures. The addition of fibers in the matrix improves the strength and post cracking tensile stiffness of the concrete. The chopped fibers induce confinement effect in concrete matrix, which contributes to the increase in the strength characteristics of concrete. The toughening mechanisms, such as, fiber pullout, fiber bridging or fiber fracture at crack interface improves the post cracking tensile stiffness of the matrix. Thus, the presence of fibers increases the strength and results in a relatively ductile type of failure of RC beams. In the literature, the modeling of various effects due to the addition of fibers in RC structures has not been attempted extensively (Padmarajaiah and Ramaswamy, Reference 1). The present study addresses this lacunae and reports the details of the finite element analysis of eleven shear critical partially prestressed concrete T-beams having steel fibers over partial or full depth. The finite element (FE) analysis of the T-beams has been carried out in the 'ANSYS' program. The predicted results, namely, loads, deflections and cracking behavior using the 'ANSYS' model have been compared with the corresponding test data.

Details of Prestressed Concrete T-beams

Eleven T-beams of 3.85 m long having varying concrete strength (f′cu = 35 MPa, 65 MPa and 85 MPa) and presence or absence of fibers (V_f = 1.5 Percent) in the flange, web or entire section were considered in the study. The reinforcement details of the beams are given in **Error! Reference source not found.**. The designation of test beams is given in **Error! Reference source not found.**. Two beams (S65FFCWFC-A, S85FFCWFC-A) were tested over a shear span to depth ratio (a/d) of 1.59 and remaining nine beams (S35FOCWOC, S65FOCWOC, S85FOCWOC, S35FFCWFC, S65FFCWFC, S85FFCWFC, S35FOCWFC, S65FOCWFC, S85FOCWFC) were tested over a shear span to depth ratio (a/d) of 2.65.

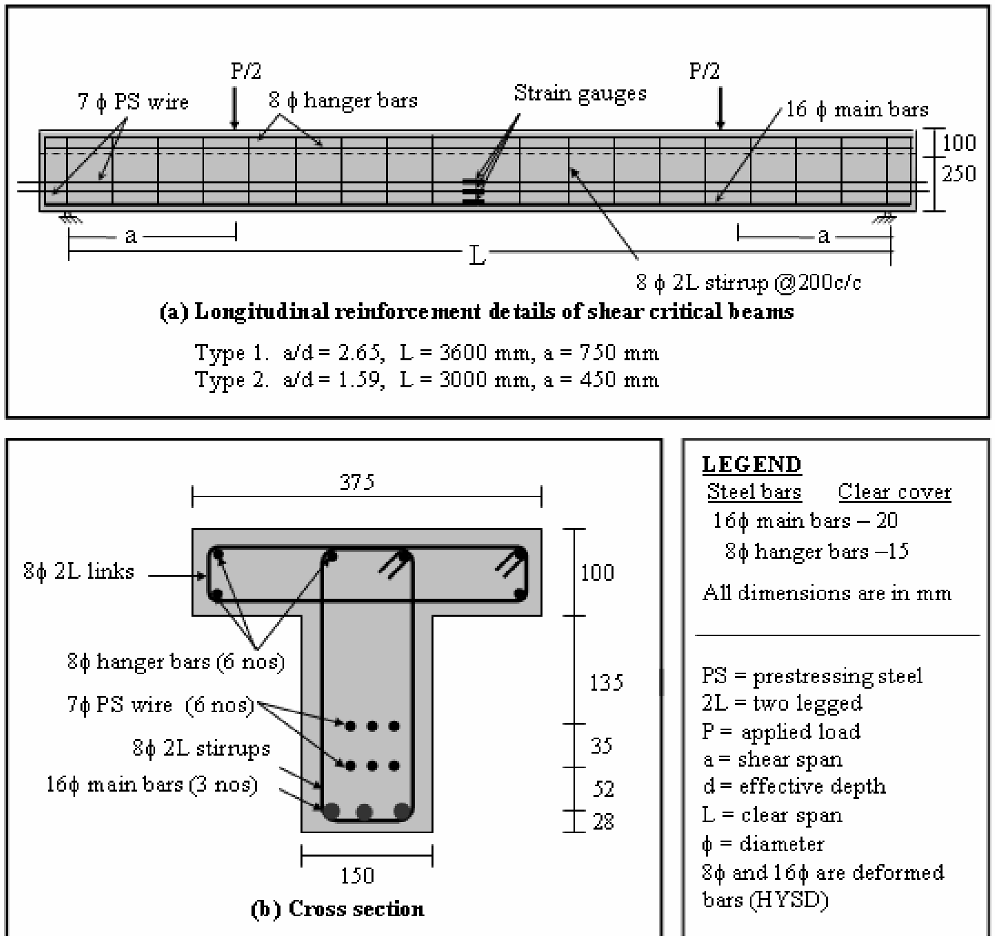

Figure 1. Reinforcement details of the prestressed concrete T-beam

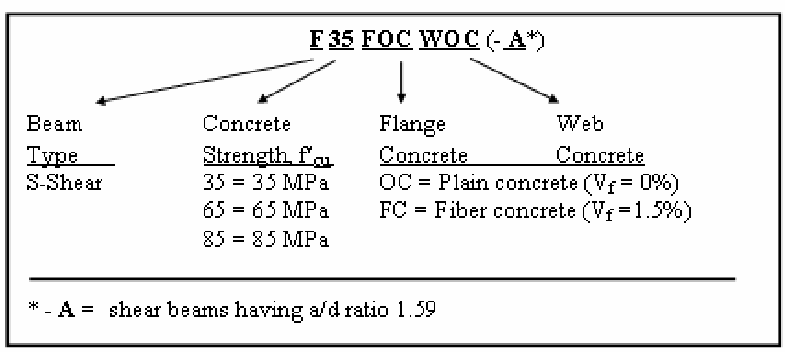

Figure 2. Designation of prestressed concrete T-beam

FE Analysis of the T-beams using the 'ANSYS'

The partially prestressed concrete T-beams have been analyzed using the ANSYS. The 'ANSYS' model accounts for the nonlinearity, such as, bond-slip of longitudinal reinforcement, post-cracking tensile stiffness of the concrete, stress transfer across the cracked blocks of the concrete, load sustenance through the bridging action of steel fibers at crack interface and yielding of reinforcement. The analysis was carried out in stages using Newton-Raphson technique.

Modeling of Concrete and Steel Fibers

The concrete has been modeled using 'SOLID65' 8 node brick element capable of simulating the cracking and crushing of brittle materials. The test data of the cylinder compressive strength and split tensile strength based on the companion specimens cast and tested along with the T-beams have been used for defining the concrete ('CONCR') properties in the 'ANSYS'. For plain concrete of all grades, the shear transfer coefficients in opening (β_t) or closing (β_c) have been assumed to take a value of 0.25 (β_t) and 0.70 (β_c). In fiber reinforced concrete, the shear transfer at the cracks depends on the matrix strength fiber interaction in the fiber pullout mechanism. To account for this fact that the β_t has been assumed to take a value of 0.35, 0.40 and 0.65 and β_c as 0.75, 0.80, and 0.90 for fiber reinforced concrete (V_f = 1.5 percent) of normal strength (35 MPa), moderately high strength (65 MPa) and high strength (85 MPa) concrete, respectively. In the 'ANSYS' model, the failure surface of the concrete is computed based on the Willam and Warnke model (Reference 2). In the present analysis, the mesh size was fixed based on the guidelines in the earlier literatures that discuss issues of non-objectivity of the mesh with refinement vis-vis the aggregate size and considering the computational efforts involved. The size of the mesh along the longitudinal axis of the beam was fixed to 100 mm in the shear span and 50 mm in the constant moment zone. The details of the mesh used for the FE analysis of partially prestressed T-beams have been presented in **Error! Reference source not found.**. In the ANSYS model, smeared representation of crack is used in 'SOLID65'. Before cracking or crushing the concrete is assumed to be an isotropic elastic material. After crushing, the concrete is assumed to have lost its stiffness in all directions. After cracking, the concrete is assumed to be orthotropic having stiffness based on a bilinear softening stress-strain response in the crack normal direction.

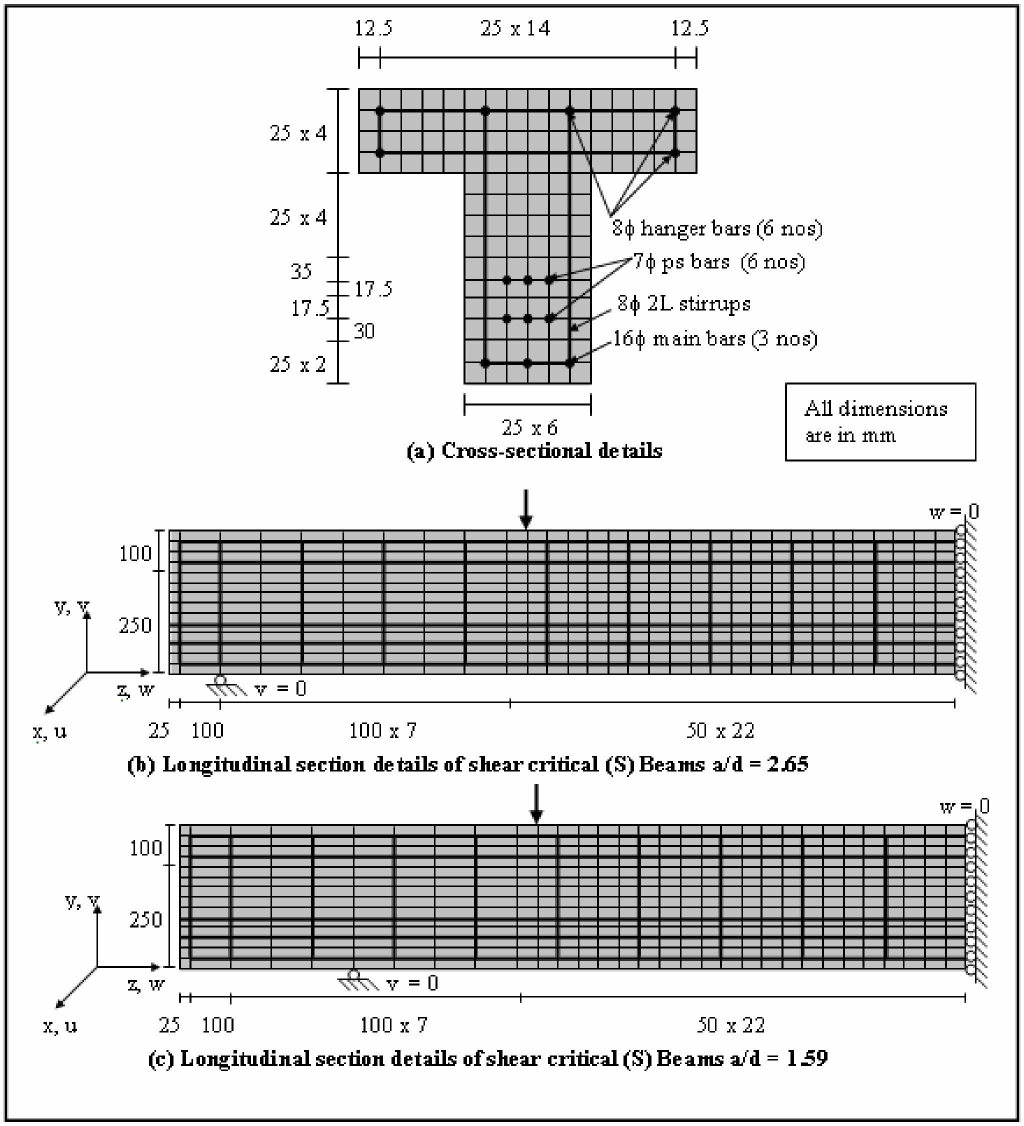

Figure 3. Details of FE mesh used for the analysis of prestressed concrete T-beam

As the compressive strength and tensile strength ascertained based on the test data of respective concrete specimens (plain or fiber reinforced concrete) is used in the analysis, the increase in the strength properties due to the addition of fibers has been accounted for in the FE analysis. To account for the effect of addition of steel fibers on the post cracking tensile stiffness of the concrete, the fibers have been modeled discretely. As the load sustenance against crack growth is mainly derived through the bridging action of fibers orienting along the longitudinal axis of the beam, only this fraction of the fibers has been modeled as discrete reinforcement in the FE analysis. The fibers have been modeled using ‘LINK8’ elements. Area of the ‘LINK8’ element representing the fiber has been computed based on the tributary area concept used by Padmarajaiah and Ramaswamy (Reference 1). The area of discrete reinforcement representing the fiber (A_F) is computed by:

$$A_F = \alpha' V_f A_{ct}$$

The orientation factor ‘α' ’ is assumed to take a value of 0.64, which is the average of the values proposed by Souroushian and Lee (Reference 3) for 2D and 3D orientation of fibers in a beam. ‘V_f’ is the volume fraction of the fiber. ‘A_{ct}’ is the tributary area of the concrete over which the fibers present is represented by a discrete reinforcement. The tributary area concept is illustrated in **Error! Reference source not found.**. The tributary area for the discrete reinforcement representing the fiber connecting to an edge node, a corner node and interior node has been shown as hatched area in **Error! Reference source not found.**(b). Rate independent multilinear isotropic hardening option (MISO) with von-Mises yield criterion has been used to define the material property of steel fibers. An elasto-plastic stress-strain response as shown in **Error! Reference source not found.**(a) has been used for steel fibers. The Young's modulus of steel fibers is taken as 200 GPa and Poisson's ratio as 0.3.

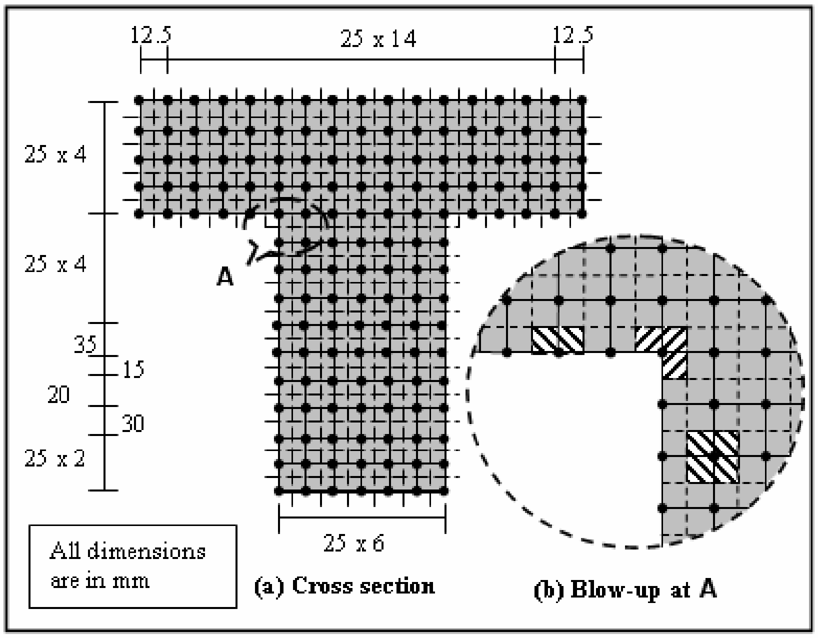

Figure 4. Tributary area employed for computing the area of the discrete reinforcement representing the fiber

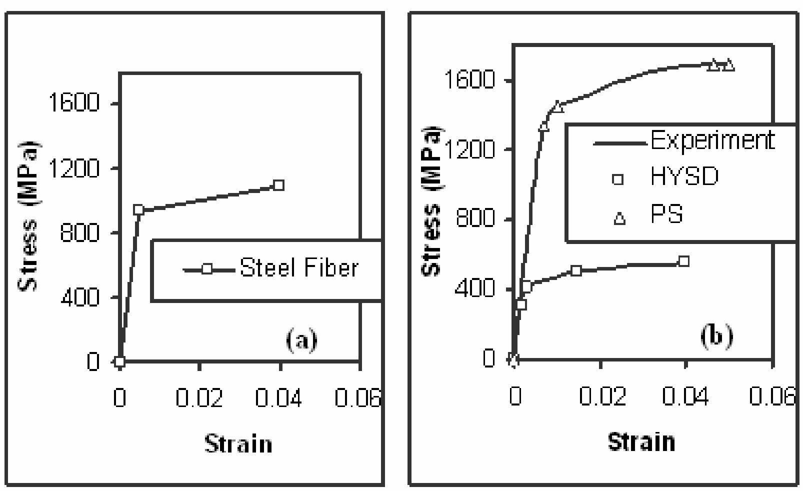

Figure 5. Stress-strain response of steel reinforcement

Modeling of Rebar

The longitudinal and transverse reinforcement, namely, High Yield Strength Deformed (HYSD) bars and Prestressing Steel (PS) wires have been modeled as discrete reinforcement using 'LINK8' elements. Rate independent multilinear isotropic hardening option (MISO) with von-Mises yield criterion has been used to define the material property of steel rebar. The tensile stress-strain response of steel based on the test data (**Error! Reference source not found.**b) has been used in the present analysis. An initial strain (corresponding to the effective prestress) has been defined for the discrete 'LINK8' element representing the prestressing steel wires in order to simulate the prestressing effect.

Modeling of Bond-slip of Reinforcement

The bond-slip between the reinforcement (fibers, deformed bars and prestressing steel wires) has been modeled using 'COMBIN39' nonlinear spring element. The'COMBIN39' having very small dimension connecting the nodes of 'LINK8' elements and 'SOLID65' elements has been used to model bond-slip of the reinforcement in the present analysis. The slip test data reported in the literature has been used for the load-deformation characteristics of the 'COMBIN39' element. The slip test data of Mirza and Houde (Reference 4) has been used for HYSD bars (**Error! Reference source not found.**a). For smooth PS wires, the test data for mild steel having smooth finish by Edward and Yannopoulos (Reference 5) has been used (**Error! Reference source not found.**a). A linear variation with out tension cutoff as used by Padmarajaiah and Ramaswamy based on the test data of Nammur and Naaman (Reference 6) has been used for steel fibers (**Error! Reference source not found.**b). The transverse reinforcement (stirrups) are assumed to be perfectly bonded to the surrounding concrete in the present analysis. The 'COMBIN39' having very small dimension connecting the nodes of 'LINK8' elements and 'SOLID65' elements has been used to model bond-slip of the reinforcement in the present analysis (**Error! Reference source not found.**).

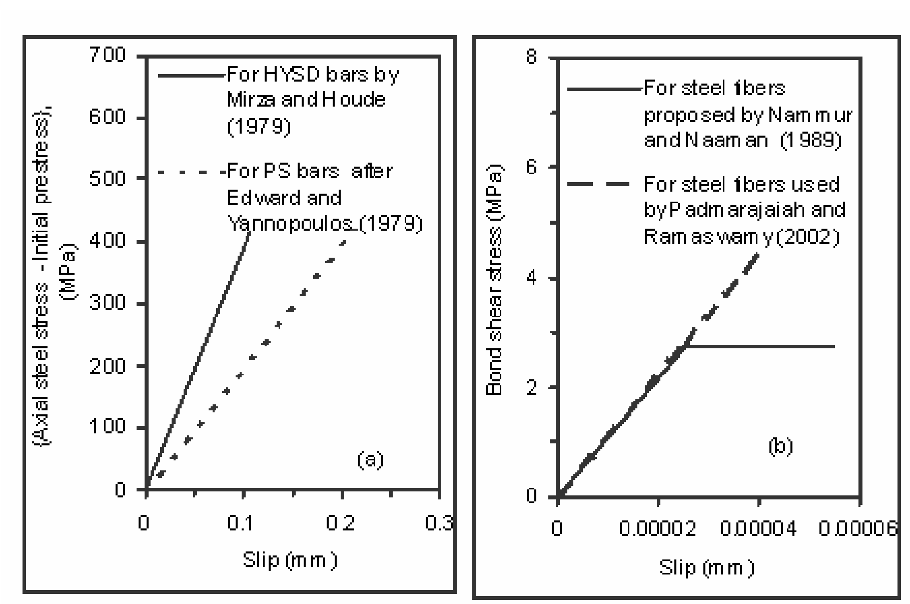

Figure 6. Slip response of steel reinforcement

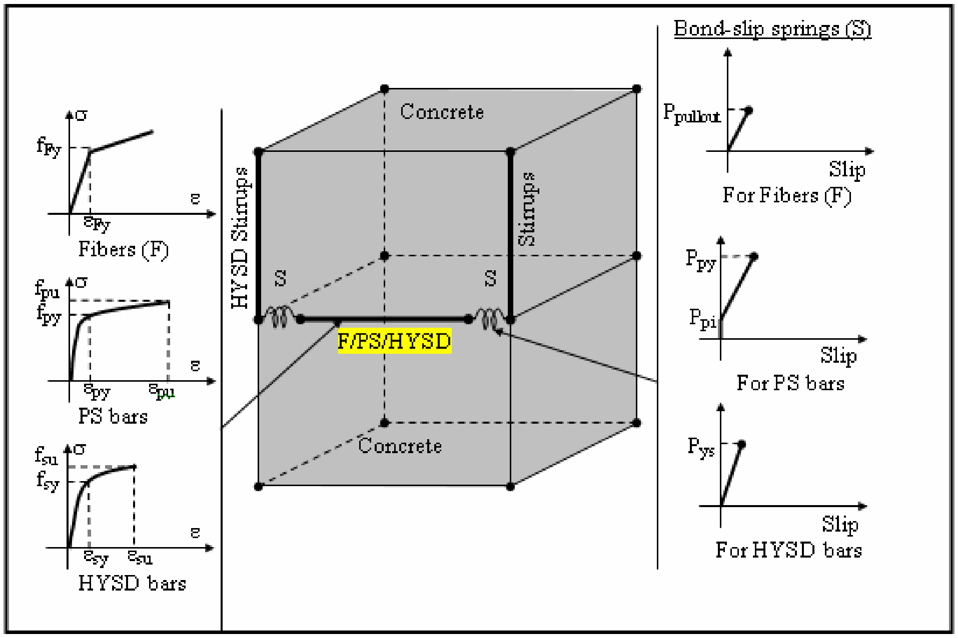

Figure 7. Details of the FE model

Comparison between Predicted and Experimental Results

The predicted load in T-beams at first crack and at ultimate stage has been compared with the corresponding test data (**Error! Reference source not found.**). The average value of the ratio of the predicted load at first crack to the corresponding load observed in the experiment was found be 0.90 with a standard deviation of 4 percent. The average value of the ratio of the predicted load at ultimate to the corresponding load observed in the experiment was found be 0.98 with a standard deviation of 4 percent. **Error! Reference source not found.** indicates that, the 'ANSYS' model predicted the load at various stages, namely, at cracking and at ultimate quite accurately.

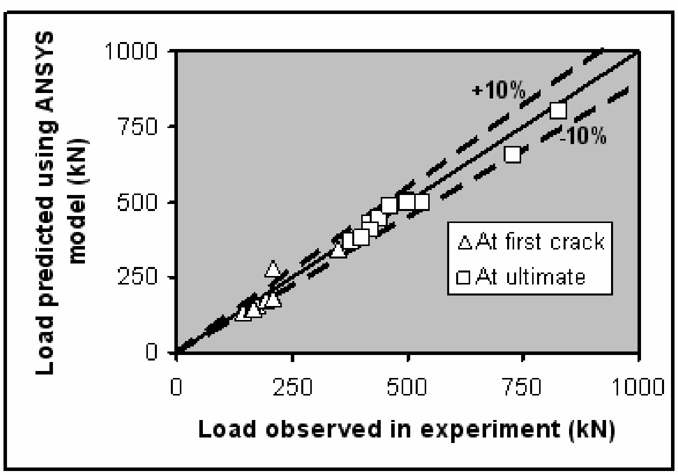

Figure 8. Comparison of predicted load in T-beams with the corresponding experimental data

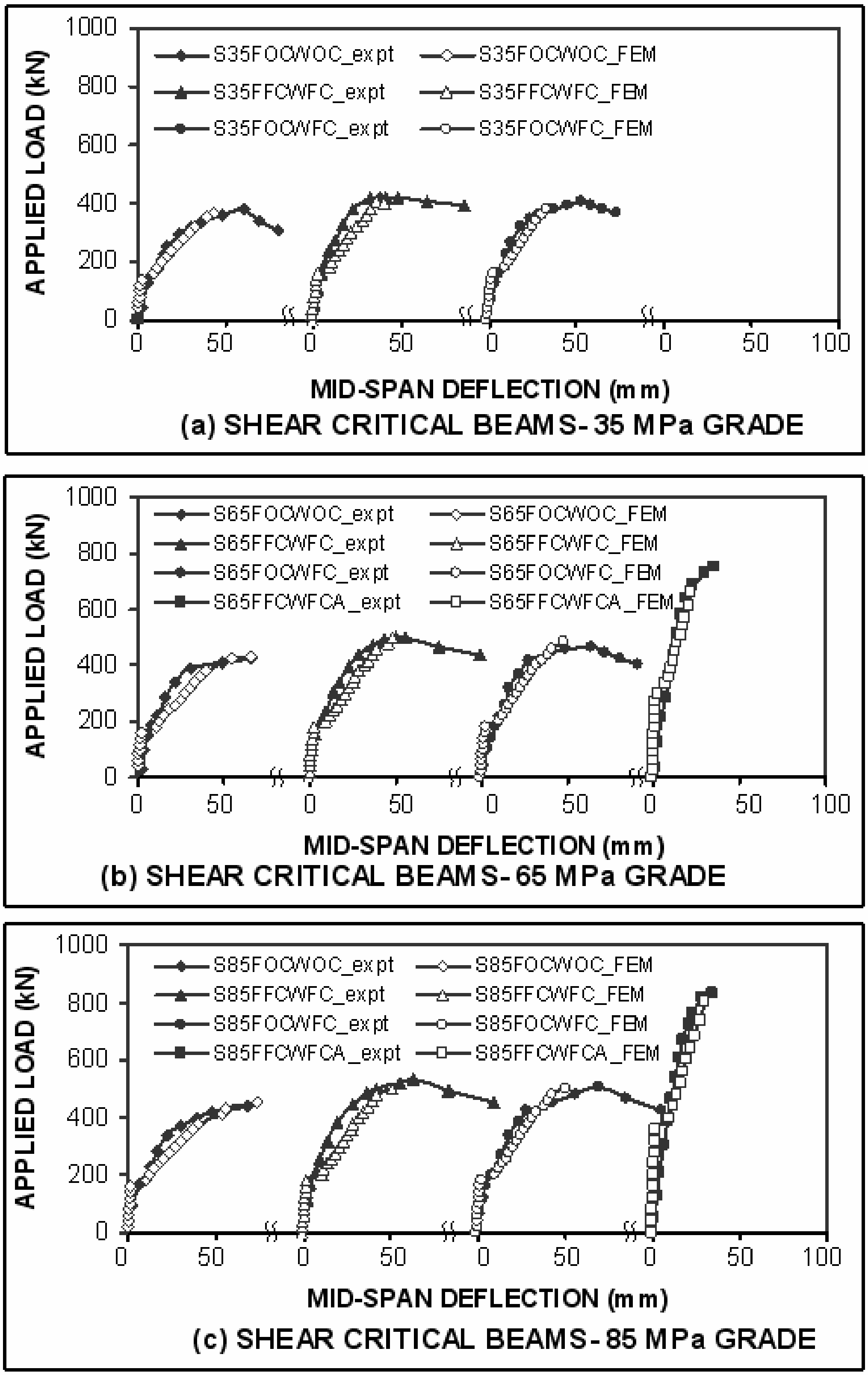

Figure 9. Comparison of predicted load-deflection response of T-beams with the corresponding experimental data

The load-deflection response of T-beams predicted using the ‘ANSYS’ model has been compared with the corresponding experimental results (**Error! Reference source not found.**). The initial stage of loading, the predicted load-deflection response of various beams corroborates with the corresponding test data. However, the ‘ANSYS’ model predicted slightly softer deflection results in the post-cracking regime when compared with the corresponding test data. This variation in the predicted results may be attributed to the difference in the bond-slip model of reinforcement used in the analysis when compared with that present in the test. It is expected that the use of an improved bond-slip model, the ANSYS model would predict the post-cracking regime of the load-deflection response of T-beams more accurately. The post peak region of the load deflection response showing a softening behavior has not been captured. This may be attributed partly to the manner in which crushing of concrete is handled in the ANSYS model, namely, complete softening of material behavior in all directions. Moreover, in this load deformation regime, fibers tend to pullout of the matrix leading to further softening. To capture this, the load steps need to be applied very gradually.

As observed in the experiment, the ANSYS model predicted the first crack in the constant moment zone. In the later stages, the ANSYS model predicted propagation of existing cracks, more cracks in the constant moment zone and new cracks in the shear span. The predicted orientation of the crack in the T-beam was vertical in the constant moment zone and inclined in the shear span (**Error! Reference source not found.**). The cracks predicted using the ‘ANSYS’ model was found to be in good agreement with the experimental observation. At ultimate, one of the inclined cracks in the shear span widened and concrete near the tip of the crack close to the loading point crushed. The ‘ANSYS’ model predicted crushing of concrete at the ultimate, which was indicated by large deformation at the node. Four T-beams, namely, S65FOCWOC, S85FOCWOC, S65FFCWFC-A and S85FFCWFC-A, failed in diagonal tension forming a through crack (**Error! Reference source not found.**c). The comparison of the crack/crush pattern predicted to that observed in the experiment indicated that the ‘ANSYS’ model predicts the zones of critical cracks quite accurately.

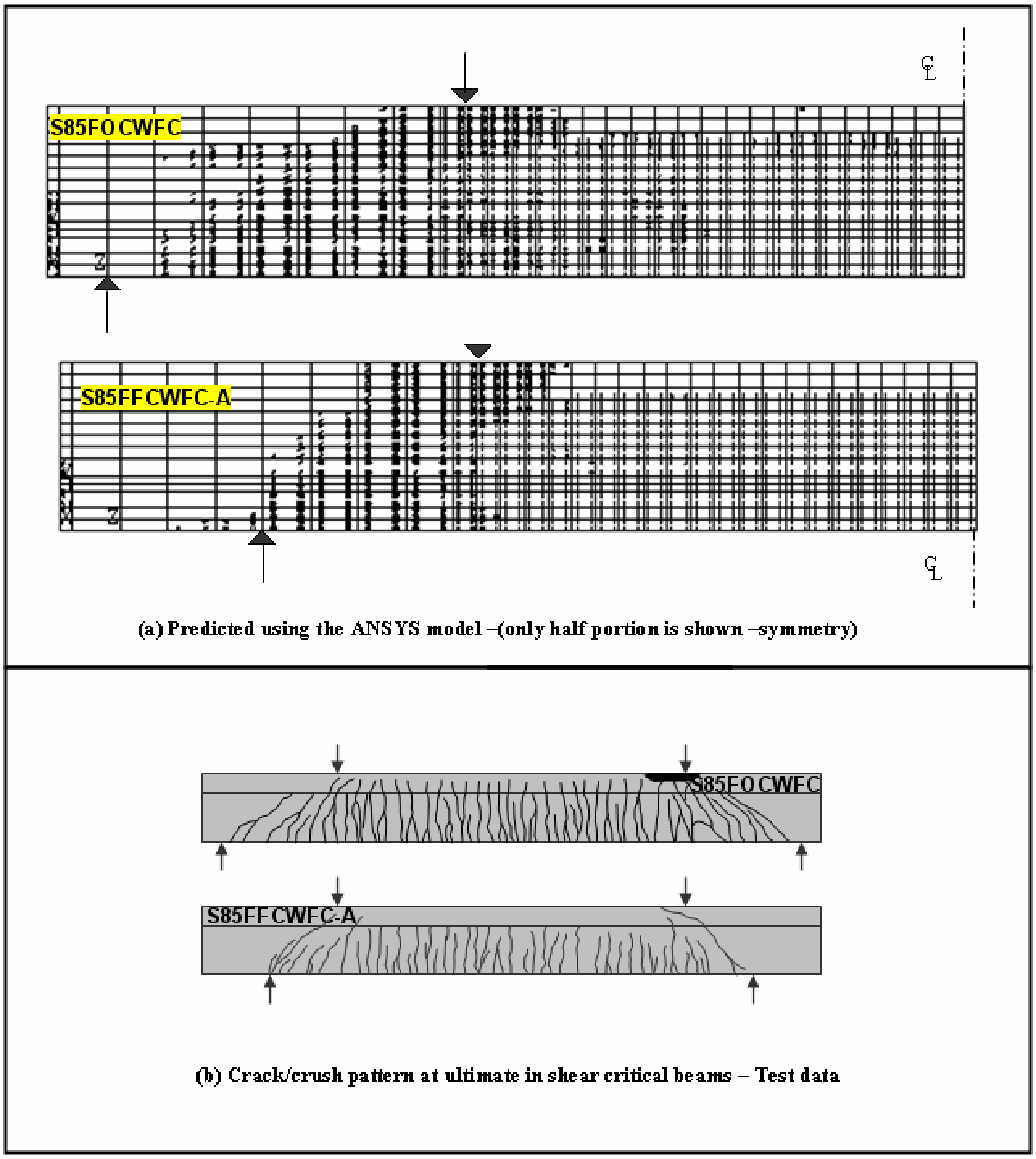

Figure 10. Comparison of predicted crack/crush pattern with the corresponding test data

Conclusion

Based on the comparison of the predicted results of partially prestressed beams having steel fibers over partial or full depth with the corresponding experimental data, following conclusions were drawn.

- The predicted load in of T-beams at various stages was found to be in good agreement with the test data.
- The proposed model predicted slightly softer results in post-cracking regime of the load-deflection response of T-beams. This variation is due to the difference in the bond-slip model of reinforcement used in the analysis when compared with that present in the test.
- The 'ANSYS' model correctly predicted the diagonal tension failure and shear compression failure of prestressed concrete beams observed in the experiment.

It is expected that the modeling strategy for the finite element analysis proposed in this study will be used for designing/ analyzing SFRC members

References

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