JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
48, 2, pp. 505-516, Warsaw 2010

FINITE ELEMENT ANALYSIS ON THE FLEXURAL BEHAVIOUR OF CONCRETE FILLED STEEL TUBE BEAMS

Soundararajan Arivalagan

Dr M.G.R.Educational and Research Institute, Department of Civil Engineering, and Dr M.G.R.University, Chennai, TamilNadu, India
e-mail: arivu357@yahoo.co.in

Shanmugasundaram Kandasamy

Dean, Anna University-Trichirappali, Ariyallur Campus, TamilNadu, India

Concrete-filled steel tube (CFST) beams are studied and verified by the Finite Element program ANSYS against experimental data. In the numerical analysis, the cross sections of the CFST are square steel sections, and sections strengthened by being filled with normal mix concrete and quarry waste concrete. Numerical analyses have shown that for square CFST a good confining effect can be provided. This effect is enhanced especially by the filling.

Key words: finite element analysis, concrete filled steel tubes, normal mix concrete, quarry waste concrete

1. Intoduction

Steel-concrete composite beams have been extensively used in building and bridge structures. Concrete-filled-steel-tube (CFST) structures have the advantages of high strength and ductility due to steel tubes and high loading capacity due to concrete. Experimental studies on the ultimate strength of steel-concrete composite beams in combined bending and shear have been of interest to researchers. Chen and Li (2001) presented analytical investigation of behaviour of connections between a steel beam and concrete-filled circular steel tube column. Finite element analyses were conducted to investigate the force transfer mechanism of various configurations of connection details. Good agreement between experimental and analytical results was obtained. The connection of a beam directly welded to the steel tube cannot develop the required flexural strength due to distortion of the tube wall. Both external diaphragm and side plate reinforced connections possess sufficient flexural strength that can be transferred and resisted by the concrete core inside the steel tube.

Lakshmi and Shanmugam (2002) presented a semianalytical method to predict the behavior of in-filled columns. Moment-curvature-thrust relationships were generated for column cross sections by an iterative process. Nonlinear equilibrium equations resulting from geometric and material nonlinearities were solved by an incremental-iterative numerical scheme based on the generalized displacement control method. Square, rectangular, and circular cross sections of compact steel tubes filled with concrete were considered in the analysis. The columns were pin-ended and subjected to uniaxial or biaxial loading. The accuracy of the proposed analytical method was established by comparing the results with the corresponding experimental values. Hu *et al.* (2003) conducted a study for proper material constitutive models for concrete-filled tube (CFT) columns. The investigation was verified by the nonlinear finite element program ABAQUS against experimental data. The cross sections of the CFST columns in the numerical analysis are categorized into three groups, i.e., circular, square, and square hollow section stiffened by reinforcing ties. Via the numerical analyses, it is shown that for circular CFST columns, the tubes can provide a good confining effect to the concrete especially when the width-to-thickness ratio D/t is small (say $D/t < 40$). For the square CFST columns, the tubes do not provide a large confining effect to the concrete especially when the width-to-thickness ratio B/t is large (say $B/t > 30$). The confining effect of the square CFST columns with reinforcing ties is enhanced by the use of reinforcing ties especially when the tie spacing is small and the tie number (or tie diameter) is large. Szlendak (2004) studied the composite connection, made with RHS chord or column filled by concrete and branches with RHS steel profile. The aim of his research was to derive a simple theoretical formula for calculating the strength and stiffness of such joints. Test results of twelve connections in natural scale were described. Geometry and material properties of the tested joints were given. Theoretical solution of the joint strength and stiffness wre proposed and the comparisons between theoretical and experimental results were presented.

Liang *et al.* (2005), used the finite element method to investigate the flexural and shear strengths of simply supported composite beams under combined bending and shear. A three-dimensional finite element model was developed to account for geometric and material nonlinear behaviour of composite beams, and verified by experimental results. The verified finite element model was then employed to quantify the contributions of the concrete slab and composite action to the moment and shear capacities of composite beams. The effect of the degree of shear connection on the vertical shear strength of deep composite beams loaded in shear was studied. Design models for vertical shear strength including contributions from the concrete slab and composite action and for the ultimate moment-shear interaction were proposed for the design of simply supported composite beams under combined bending and shear. The proposed design models provide a consistent and economical design procedure for simply supported composite beams.

Han *et al.* (2007) studied a nonlinear finite-element analysis (FEA) model. In that study based on the elastoplastic finite-element theory he analysed the load versus deformation of steel beam to concrete-filled steel tubular column connections. Six tests on steel beam to concrete-filled steel tubular (CFST) column connections using external ring after exposure to the ISO-834 standard fire were used to verify the theoretical model. The test parameters included the column cross-sectional type, the fire duration time, the level of axial load in the column, and the beam-column strength ratio. Each test specimen consisted of a CFST column and two steel beam segments in cruciform arrangement to represent the interior joint in a building. Three of the six composite connection specimens had circular cross sections and three had square cross sections. Five of the test specimens were simultaneously exposed to the standard ISO-834 fire condition. After they had cooled down to room temperature, each was tested under a constant axial load and a cyclically increasing flexural load. The analyis presented experimental results to validate the FEA model and to evaluate the influences of different testing parameters on various characteristics of the beam-column connection performance. Comparisons between the predicted results and the experimental results indicated that the FEA model can predict the P-relations of steel beam to CFST column connections and the column lateral load resistance after fire with reasonable accuracy. Finally, the FEA model was used to make a parametric study of the influence of various factors on the postfire behaviour of the steel beam to CFST column connections.

Liang *et al.* (2007) investigated the critical local and post-local buckling behaviour of steel plates in concrete-filled thin-walled steel tubular beam-columns by using the finite element analysis method. High strength steels and concrete lead to the use of thin steel plates in concrete-filled steel tubular beam-columns. However, the use of thin steel plates in composite beam-columns gives a rise to local buckling that would appreciably reduce the strength and ductility performance of the members. Geometric and material nonlinear analyses were performed to investigate the critical local and post-local buckling strengths of steel plates under compression and in-plane bending. Based on the results obtained from the nonlinear finite element analyses, a set of design formulas were proposed for determining the critical local buckling and ultimate strengths of steel plates in concrete-filled steel tubular beam-columns. In addition, effective width formulas were developed for the ultimate strength design of clamped steel plates under non-uniform compression.

In this research, the results of experiments are compared with numerical analyses. Moreover, the specimens of square CFST beams are studied and analysed by the finite element program ANSYS, and the proposed FE models are verified against the experimental data obtained by the authors (2008).

2. Experimental reference model

Nine beam specimens were included in the investigation program. Square hollow section of 72 mm size and 3.2 mm thickness were used. Among them, three were hollow steel sections, three were filled with normal mix concrete and the remaining three were filled with quarry waste concrete. A simply supported beam set-up with two-point loading was used. The length of the beam was 1.20 m and the span between the supports was 1.0 m. Loading point deflections and mid-span vertical deflections were measured by a deflectoemeter placed at the beam bottom loading point and beam mid-span. Also strain values on the top and bottom flanges were measured with the help of strain indicator to identify ductility of the beam.

3. Finite element method

The FE method has been extensively used to study the structural behaviour of steel-concrete composite section. However, to model the contact interaction between the outer surface of the concrete core and the inner surface of the steel tube, surface-to-surface contact technique method was used. The validity of such FE model was justified by comparing the numerical results with the experimental results. The modelling technique was then used to study other types of CFST beams. The pre- and post-processing work was performed by ANASYS which is a graphical user interface module that allows the user to execute a FE analysis process from start to finish. The FE model can be viewed and checked interactively and the results (stress, strain, displacements, etc.) can be visualized graphically.

3.1. Finite element material models

3.1.1. Steel tube

The average stress-strain curves obtained from the material tests were used to model the steel tubes, assuming isotropy of the material. The behaviour of the steel tube is simulated by an elastic-perfectly plastic model. When the steel is subjected to multiple stresses, von Misses yield criterion is employed to define the elastic limit.

3.1.2. Concrete core

The Poisson's ratio ν_c of concrete under flexural stress ranges from 0.15 to 0.22, with a representative value of 0.19 or 0.20. In this study, Poisson's ratio of concrete is assumed to be $\nu_c = 0.20$. The properties of the material used in the FE model are given in Table 1.

Table 1. Material properties used in FE model

Specimen/properties	Elastic modulus of steel/concrete E_s and E_c [MPa]	Poisson ratio	Compressive strength [MPa]
Hollow steel tubes (SHS)	$2.1 \cdot 10^5$	0.3	–
Normal mix concrete (NMC)	$2.842 \cdot 10^4$	0.2	32.3
Quarry waste concrete (QWC)	$2.624 \cdot 10^4$	0.2	27.55

3.1.3. Boundary condition

The boundary conditions have to be applied correctly for the nodes lying on the planes of symmetry to reflect the actual behaviour. The nodal displacements perpendicular to the plane of symmetry are restrained while the two remaining transitional degrees of freedom and free; the nodal rotation perpendicular to the plane of symmetry is free while the two remaining rotational degrees of freedom are restrained. Furthermore, at the support, the nodal displacement in the Y-direction is restrained while the two remaining transitional degrees of freedom are free (support located at 100 mm from the end).

3.1.4. Finite element model

The interaction between the steel tube and its core concrete is the key issue to understand the behaviour of CFST members. In order to analyse the interaction of CFST under flexural conveniently, the ANSYS software has been selected for calculation. For the purposes of reasonable analysis, the material proportion for steel and the combined, element-type, its size and boundary condition, steel-concrete moment are assumed rationally.

In the modelling of CFST beams, a properly graded mesh is essential. In particular, the same sizes of the elements are considered for full length of the beam. Moreover, while creating a model of the specimen, the whole 1.0 m long beam is to be modelled. No imperfection of boundary conditions or loading are taken into consideration.

In the FE model, the concrete and steel were modelled using the first order reduced integration 8-noded brick-element with 45 degrees of freedom per node. A finer mesh reflecting the model sensitivity to the number of elements was used. Based on literature review (Al-Rodan and Al-Tarawnah, 2003) the difference in the peak stress was very small when using a coarse mesh to save computational time. Figure 1 shows the beam finite element model. It can be seen that the same mesh size is adopted for full length of the model. The model included the steel hollow tube and concrete core. The steel tube part was divided into 2000 elements and 2040 nodes. The concrete model included 7140 elements and 10251 nodes.

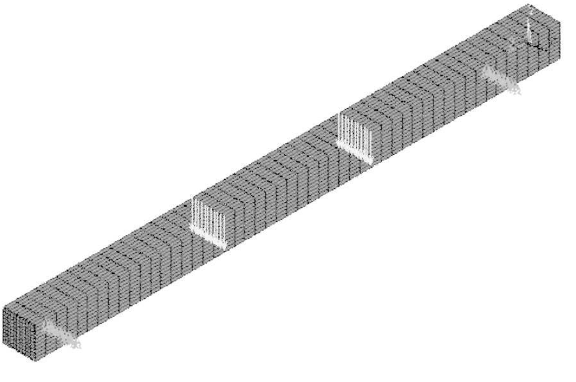

Fig. 1. FE model of concrete-filled SHS beam

3.1.5. Contact between steel and concrete

Surface-to-surface contact technique was used to model the interaction between the outer surface of the core concrete and the inner surface of the hollow steel tube. Figures 2 and 3 show the strain contour diagram of the hollow and filled specimens.

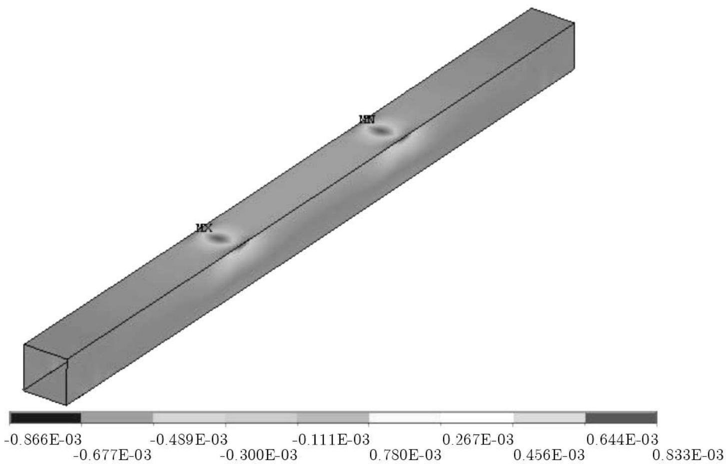

Fig. 2. Strain values of SHS beam

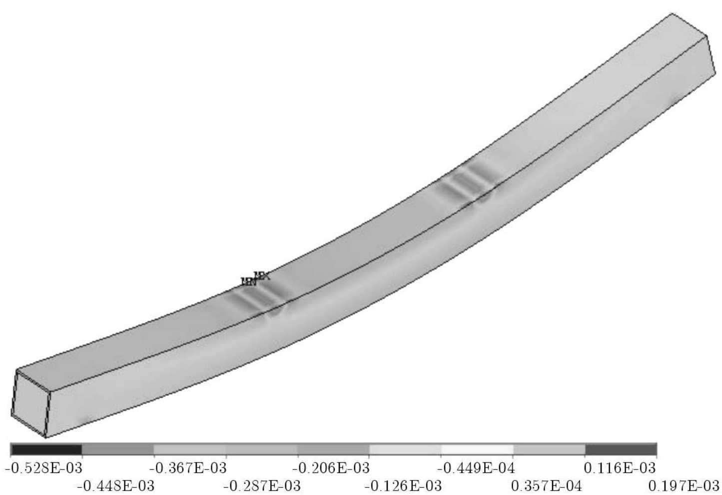

Fig. 3. Strain values of concrete-filled SHS beam

4. Results and discussion

The proposed finite element model is used to calculate strains, deflection and ultimate loads of CFSTs when applied as a beam.

The load-deflection behaviour of the square hollow section is shown in Fig. 4a. The results from the test and FEA are impressed in this figure. Up to a load of 20 kN the agreement between both the results is pretty close. About 20 kN there is an insignificant deviation between the results. The behaviour of the filled tubular member with normal mix concrete is shown in Fig. 4b. The results of test and FEA are in fairly good agreement. After a load of 10 kN this behaviour is non-linear. The results from both tests and FEA are shown in Fig. 4c for the square hollow section filled with quarry waste concrete. Up to 20 kN, both results shown a linear trend. Above 25 kN, the FEA solution shows an increase in deflection with respect to the test programme. In this region both results exhibit non-linear behaviour.

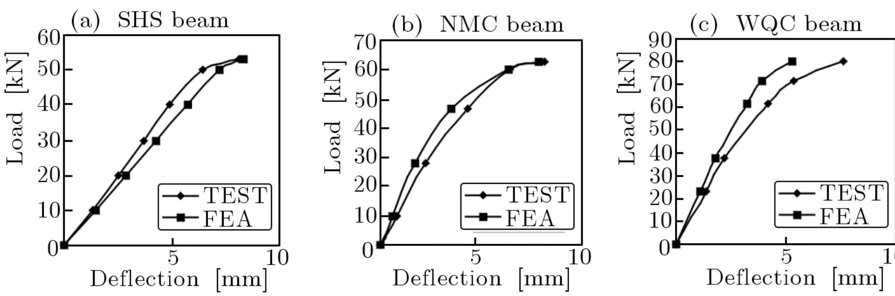

Fig. 4. Load vs. mid-span deflection of the beam

The measured and obtained by FEA is shown in Figs. 5a-c. The strain measured was higher in the test programme with the section filled with normal mix concrete and quarry waste concrete. In the experiments, non-linear behaviour starts above 30 kN. Above 50 kN there appears hardening of the specimen. From the above results, it can be observed that increased strain values, lower deflection, better ductility and greater stiffness are typical for the filled section than the hollow section specimen due to strength of the filling material.

The tensile strain of the square section is shown in Figs. 6b and 6c. Both the test and FEA results up to 50 kN are in close agreement. From 50 kN to 60 kN there is a slight deviation due to non-linear behaviour. As far as the load vs. tensile strain of the square hollow section looks like shown in Fig. 6a,

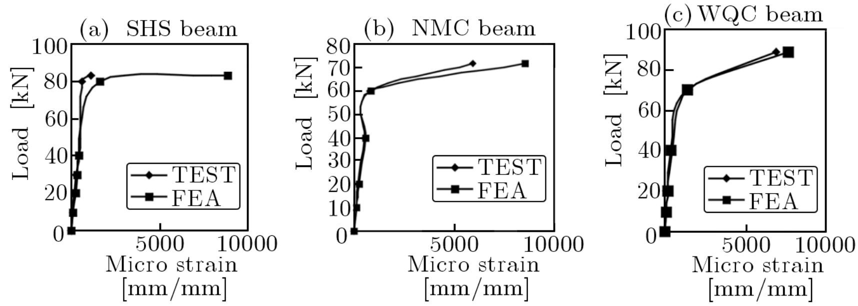

Fig. 5. Compressive strain of hollow and filled beams

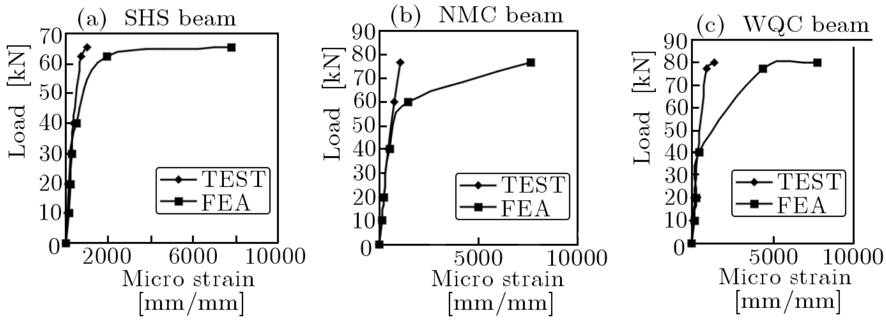

Fig. 6. Tensile strain of hollow and filled beams

the both results are in very good agreement. Table 2 shows the experimental ultimate load, FEA analysis load and EC_4 load and a comparison between these results for the hollow section without filling. The table indicates that the ratio of the test load to the FE predicted value varies between 6% to 11%. The lower test results are probably due to local buckling of the specimen. The ultimate load of EC_4 is shown in Table 2, but it is not being discussed here. For beams SHS-1 to SHS-3, which are hollow sections, Table 2 shows that the ratio of the experimental ultimate load to the EC_4 perditions are between 13% to 19%.

On the other hand, beams NMC-1 to NMC-3 are filled with normal mix concrete. The results show a slight decrease in the FE predictions, which are about 18% to 19% lower than the experimental results. The experimental results show for QWC (quarry waste concrete) increased values when compared to the FE result. The variation is from 5% to 8% only. In EC_4 prediction, the increased value is 9% to 15% for quarry waste concrete. Both the FEA and EC_4 codal values are safer side values. They are lower than the experimental values. From the above discussion, it can be concluded that the hollow steel tube

Table 2. Ultimate load of tested specimens

Beam No.	Ultimate load [kN]			Pu/FEA	Pu/EC_4
	Experimental load [Pu]	FEA load	EC_4		
SHS-1	54	51.15	47.85	1.06	1.13
SHS-2	55			1.08	1.15
SHS-3	57			1.11	1.19
NMC-1	61	72.00	65.25	0.85	0.93
NMC-2	58			0.81	0.89
NMC-3	63			0.88	0.97
QWC-1	60	66.40	63.51	0.93	0.94
QWC-2	61			0.92	0.96
QWC-3	63			0.95	0.99

improves the ductility of concrete as it provides confinement to the concrete core. Brittle behaviour of concrete, as shown in figures, is not observed when confined by steel sections, indicating significant improvement of ductility. As expected, the maximum deflection occurs at the middle of the beam, and defection reduces gradually to zero at the support (100 mm from the end).

5. Conclusion

From the presented work it can be concluded that:

- Finite element analysis was shown to be a promising method to obtain data for the development of design aid for CFST beams.
- FE model can accurately reproduce conditions of the test.
- FE load-deflection curves for different mix concrete filled beams show satisfactory agreement with those of tests.
- Deflections and strains predicted by the FE models compare favourably with the tests.
- Results of FE analysis and EC_4 standard code show that the experimental investigation yields conservative prediction for the behaviour of CFST beams.

References

1. Al-Rodan A., Al-Tarawnah, 2003, FE analysis of the flexural behaviour of rectangular tubular sections filled with high strength concrete, *Emirates Journal for Engineering Research*, **8**, 1, 71-77

2. Arivalagan S., Kandasamy S., 2008, Flexural behaviour of concrete-filled SHS beams, *Journal of Civil Engineering and Managemet*, **14**, 2, 107-114

3. BS5400, 1979, (Part 5), Concrete and Composite Bridges; Code of Practice for Design of Composite Bridges, British Standards Institution, London

4. Chen C.C., Li H.L., 2001, Finite element analyses of steel beam to concrete-filled circular steel tube column connections, *Proceedings of the Eighth International Conference on the Application of Artificial Intelligence to Civil and Structural Engineering Computing*, Stirling, Scotland, 171-172

5. EUROCODE 4, 1999, (Part 1.1), Design of composite steel and concrete structures, general rules and rules for buildings, British Standards Institution, London

6. Han L.-H., Huo J.-S., Wang Y.-C., 2007, Behavior of steel beam to concrete-filled steel tubular column connections after exposure to fire, *Journal of Structural Engineering*, **133**, 6, 800-814

7. Hu H.T., Huang C.S., Wu M.H., Wu T.M., 2003, Nonlinear analysis of axially loaded concrete-filled tube columns with confinement effect, *Journal of Structural Engineering, ASCE*, **129**, 10, 1322-1329

8. Lakshmi B., Shanmugam N.E., 2002, Nonlinear analysis of in-filled steel-concrete composite columns, *Journal of Structural Engineering, ASCE*, **128**, 7, 922-933

9. Liang Q.Q., Uy B., Bradford M.A., Ronagh R.H., 2005, Strength analysis of steel-concrete composite beams in combined bending and shear, *Journal of Structural Engineering, ASCE*, **131**, 10, 1593-1600

10. Liang Q.Q., Uy B., Liew J.Y.R., 2007, Local buckling of steel plates in concrete-filled thin-walled steel tubular beam-columns, *Journal of Constructional Steel Research*, **63**, 26, 750-760

11. Szlendak J.K., 2004, Strength and stiffness of RHS beam to RHS concrete filled column joints, *Proceedings of the Fifth International Conference on Connections in Steel Structures*, Bialystok Technical University, Poland, 1024-1036

Metoda elementów skończonych w badaniu właściwości stalowych kolumn wypełnionych betonem

Streszczenie

W pracy przedstawiono analizę porównawczą wyników eksperymentalnych i otrzymanych z metody elementów skończonych (ANSYS) w odniesieniu do kolumn zbudowanych ze stalowych rur wypełnionych betonem (CFTS). Analizę numeryczną przeprowadzono dla kolumn o przekroju kwadratowym wzmacnianym normalną mieszanką betonową oraz betonem zawierającym odpady z kamieniołomu. Rezultaty symulacji numerycznych pokazały, że dla kolumn CFTS o przekroju kwadratowym uzyskuje się dobry efekt wzmocnienia wynikający z wypełnienia.

Manuscript received March 23, 2009; accepted for print September 25, 2009