Steel and Composite Structures, Vol. 5, No. 1 (2005) 35-47
DOI: http://dx.doi.org/10.12989/scs.2005.5.1.035

Behaviour of cold-formed steel hollow and concrete-filled members

H. Jane Helena† and G. M. Samuel Knight‡

College of Engineering, Guindy, Anna University, Chennai 600 025, Tamil Nadu, India

(Received August 26, 2004, Accepted January 14, 2005)

Abstract. This paper presents the results of a series of tests carried out on hollow and concrete-filled cold-formed steel sections subjected to axial and bending forces. The effects of eccentricity ratio and strength of in-fill on the behaviour of these sections were studied. A total of forty-eight medium sized columns and six beams were tested to failure. Extensive measurements of material properties, strains, axial shortening and lateral deflection were carried out. Interaction of local and overall buckling was observed in the tests. Failure mode observations were local buckling coupled with overall buckling. A description of the specially fabricated end fixtures for applying eccentric loading to the columns and to simulate pinned end condition is also presented. The experimental results of hollow columns are compared with the existing Indian, British and American codes of practice and the results of concrete-filled columns are compared with EC4 recommendations. It is seen that in the case of hollow columns predictions based on British and American codes of practice and in the case of concrete-filled columns predictions based on EC4 recommendations agree reasonably well with the experimental results. From the experiments it is seen that the provision of in-fill substantially increases the ultimate load carrying capacity of the order of one and a half to two times and the increase in strength of the in-filled concrete from a low grade concrete of compressive strength 24.94 MPa to a high grade concrete of compressive strength 33.26 MPa increases the ultimate load carrying capacity by one and a half times irrespective of the eccentricity of loading.

Key words: column; cold-formed; concrete-filled; buckling; composite.

1. Introduction

Since Euler's pioneering work on elastic buckling of columns was presented in 1759, extensive studies concerning the behaviour of columns have been conducted worldwide. The current trend is to reduce costs, improve productivity, quality and take full advantage of information technology and benefits from the new economy. As a result, enhanced research effort has focused attention on developing techniques for combining steel and concrete effectively. Research on square and rectangular concrete-filled steel hollow sections has been conducted worldwide extensively during the last couple of decades (Shakir-Khalil and Zeghiche 1989, Shakir-Khalil 1990, Hunaiti 1996, Uy 1998, Wang 1999, Han 2002, Mursi and Uy 2003, Hossain 2003, Campione and Scibilia 2003). Yet the behaviour of such columns under combined axial and biaxial moments is not fully comprehended. In this paper an attempt has been made to study

†Research Scholar
‡Professor of Civil Engineering, Corresponding author, E-mail: gmsk@annauniv.edu

the effectiveness of combining cold-formed thin-walled steel and normal concrete to resist pure axial force, pure moment and a combination of axial force and bending moment. In order to achieve this forty-eight pin-ended columns under axial, uniaxial and biaxial loading and six beams subjected to two point loading have been tested.

The tests were performed on both hollow and concrete-filled sections with a view to determine the gain which could be made by the provision of concrete and also by changing only the strength of the filled concrete under various eccentricity ratios. The experimental results are compared with the existing Indian, British and American codes of practice for hollow sections and with EC4 recommendations for concrete-filled sections.

2. Experimental investigation

Experiments were carried out on commercially available cold-formed steel sections of size 100×50×2 mm. The sections chosen are slender. For concrete-filled sections, two grades of concrete are used, one with a compressive strength of 24.94 MPa (low grade) and the other with a compressive strength of 33.26 MPa (high grade). The relative slenderness according to Eurocode for a hollow section is 1.22 and in the case of concrete-filled sections it is 1.47 and 1.54 for low and high grades respectively. The failure loads were found for several eccentricity ratios and different planes of bending. Three eccentricity ratios $\bar{e}_x = e_x/B$, for uniaxial bending about the minor axis and three eccentricity ratios $\bar{e}_y = e_y/D$, for uniaxial bending about the major axis, and nine combinations of eccentricity ratios $\bar{e}_x$, $\bar{e}_y$ for biaxial bending were studied (where B and D are the breadth (50 mm) and depth (100 mm) of the section). The details of experiments carried out are shown in Fig. 1. The same set of experiments was repeated for concrete-filled sections.

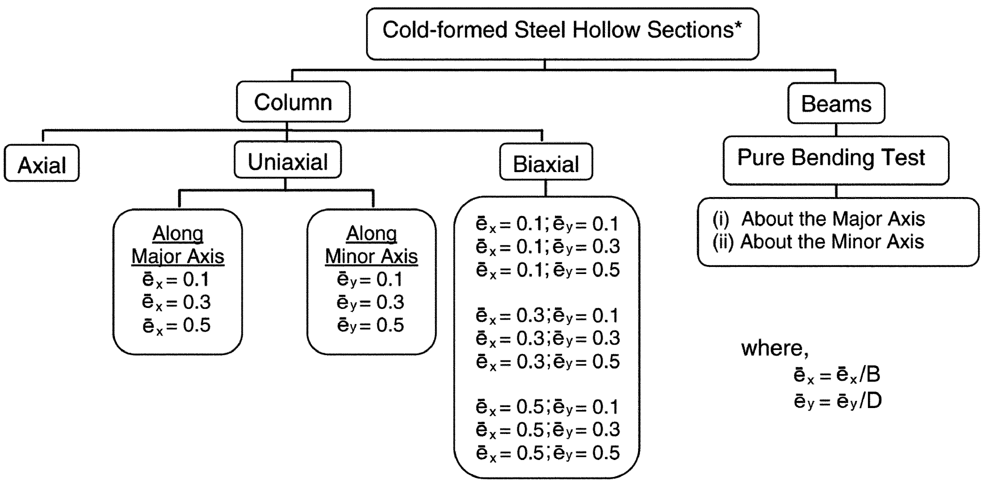


Fig. 1 Details of experiments (* similar experiments were carried out for concrete-filled sections)
(Total no. of experiments: Columns: 3×16=48 and Beams: 3×2=6)

2.1. Fabrication and casting of specimens

The ends of the steel hollow sections which were available in 6 m lengths were cut and machined to 1.8 m length. Each length was cut into several pieces for the preparation of tension coupons, bond specimens and the test sections. The inner surfaces of the hollow sections were wire brushed to remove any rust, and grease or oil if any, were thoroughly cleaned. The specimens were cast in the vertical position and concreting was done in layers. To measure the compressive strength of concrete 150 mm cubes were also cast along with the test specimens. All the specimens were naturally cured in the indoor climate of the laboratory. A rich mix of cement mortar was used to fill the small gap, which occurred due to longitudinal shrinkage at the top, and the concrete was made flush with the steel hollow section in order to facilitate loading of both steel and concrete simultaneously.

2.2. Preliminary tests

2.2.1. Material properties

To ascertain the stress-strain behaviour of steel a series of tensile coupons were cut and machined as per ASTM E646. Three coupons were taken from each face of the steel hollow section and tension test was conducted. From these tension tests it was found that the average yield strength is 360 N/mm^2, the ultimate stress is 425 N/mm^2, percentage elongation is 14 and the Modulus of Elasticity is 2×10^5 N/mm^2.

2.2.2. Push-out test

The bond between concrete and steel is a major factor in concrete-filled members and hence four tests in each grade of concrete were carried out to ascertain the bond strength. From the tests carried out the load slip behaviour of all the specimens were found to follow a similar pattern and the average bond strength of the specimens filled with low grade concrete was found to be 0.432 N/mm^2 and that of specimens filled with high grade concrete was found to be 0.597 N/mm^2.

2.2.3. Test on columns

In order to apply eccentric loading to the test specimens, 16 mm thick plates were directly welded to the ends of the specimen such that the specimen is at the required eccentricity with respect to the centre of the plate. To simulate simply supported end condition two plates 30 mm thick and size 300×300 mm with a spherical groove at the centre to accommodate a ball of 40 mm diameter was bolted to the end plates at either end by four 16 mm diameter bolts such that their centers coincide. The grooved plate and the ball were fabricated from EN8 material and hardened. The end fixture details are shown in Fig. 2.

Each column was mounted on the loading frame by bolting the column end plate to the plate with the central groove. Theodolite was used to check the verticality of the column. The hydraulic loading was transferred from the machine to the specimen by means of a proving ring. Four 10 mm electrical strain gauges were used to measure the strains at mid-height. As the columns were subjected to equal end eccentricities, lateral deflections were measured on all four sides only at mid-height and one-fourth heights. Axial shortening was also measured. The deflection and strain readings were noted for each increment of the load. To study the softening response of the columns, the loads were applied at closer intervals near the ultimate load. The post buckling strength of the specimens were also studied.

(a) Top fixture (b) Bottom fixture

Fig. 2 End fixture details

2.2.4. Test on beams

Hollow and concrete-filled beams were tested in the Buckton's UTM of 1000 kN capacity. The ends of the beam were welded to 10 mm thick square mild steel plates of size 100 mm and the edge of the plates were rounded off to simulate simply supported end condition. Two beams in each series were tested to failure one with the longer side vertical and the other with the shorter side vertical. The aim is to obtain the ultimate moment of the section along the strong and weak axis.

A loading arrangement was fabricated so that two point loads were applied at one-third span in order to simulate pure bending condition. Above this arrangement a proving ring was placed to apply the load from the machine to the specimen. 10 mm electrical strain gauges were fixed at six different locations on the top and bottom fibres of the beam. Three deflectometers were placed at the bottom and one at the side to measure the vertical and lateral deflections. The beam test set-up is shown in Fig. 3.

Fig. 3 Beam test set-up

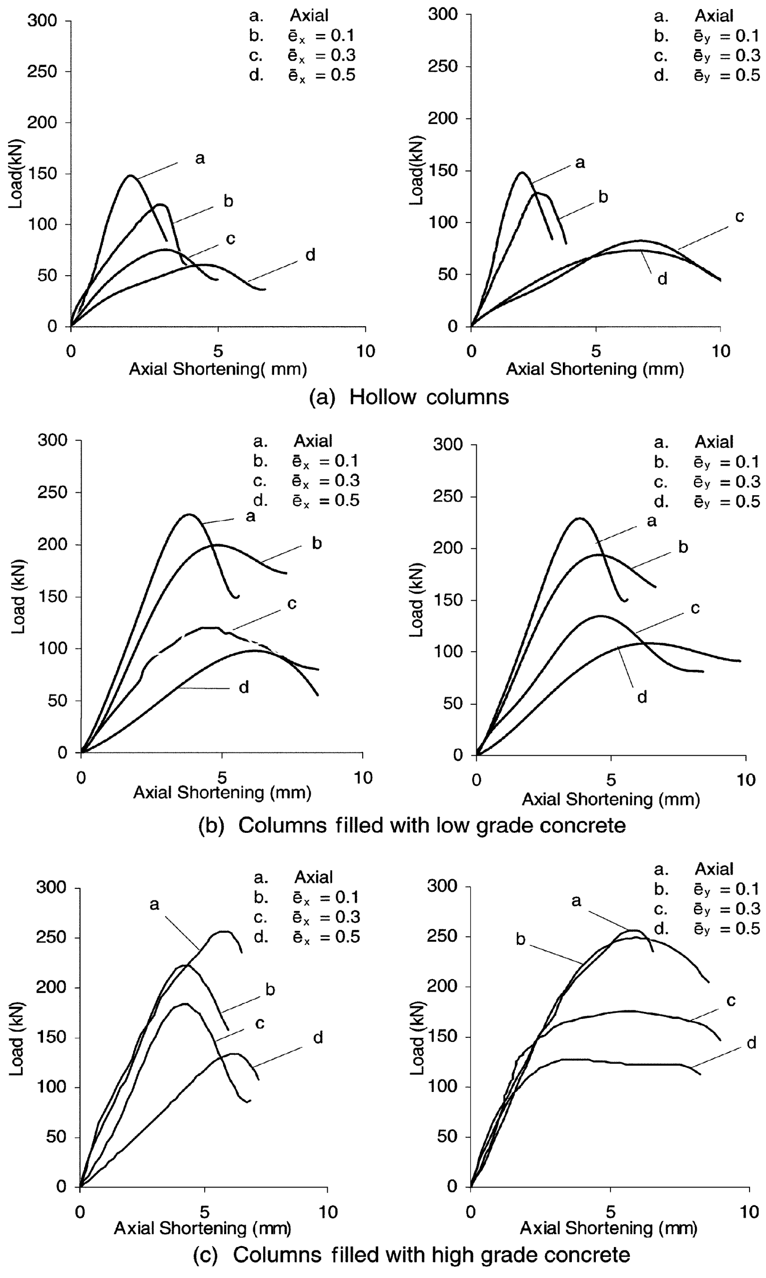


Fig. 4 Load versus axial shortening behaviour

3. Results and discussion

The behaviour of columns under various stages of loading is characterized by the study of load versus axial shortening, load versus strain and load versus lateral deflection behaviour at mid-height as well as at one-fourth height.

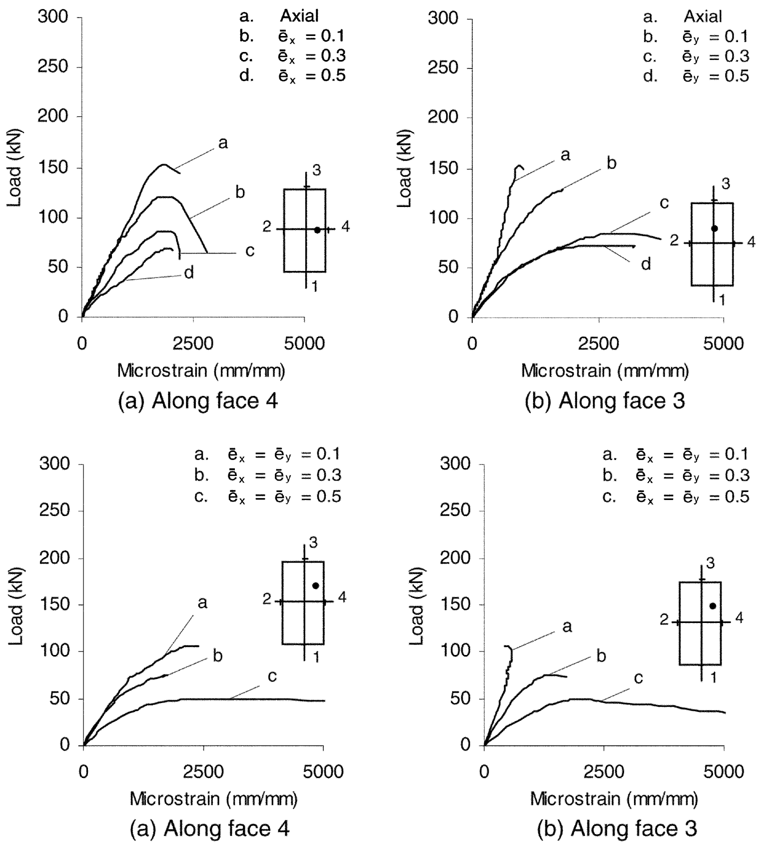


Fig. 5 Load versus strain behaviour of hollow columns

From Fig. 4 it can be seen that stiffness degradation is rapid with increase in eccentricity ratio in the case of hollow columns compared to concrete-filled columns. The reduction in load carrying capacity with increase in eccentricity ratio is 30 to 40% and is the same for all the uniaxial cases. In both the cases of bending, the columns exhibit a gradual failure mode when the eccentricities are large and there is a sudden drop in load when the eccentricities are small. Columns filled with low grade concrete exhibit similar load versus axial shortening behaviour irrespective of the axis of bending. In the case of columns filled with high grade concrete the initial stiffness remains the same irrespective of the eccentricity ratio. Hollow columns and columns filled with low grade concrete subjected to large eccentricities exhibit non-linearity in behaviour right from the onset of loading whereas all other columns exhibit non-linearity in behaviour close to the ultimate load.

Fig. 5 shows the load versus compressive strain behaviour of hollow columns along faces 3 and 4 of the cross-section. Except columns loaded uniaxially about the minor axis, all the other columns exhibit gradual strain behaviour. Biaxially loaded columns subjected to large eccentricity ratio exhibit large plastic strains along both the faces.

Fig. 6 shows the load versus compressive strain behaviour for columns filled with low grade concrete along faces 3 and 4 of the cross-section. It can be seen that in the case of axially loaded columns, there is a changeover from compression to tension along the longer side indicating the initiation and occurrence of local buckling along that side. In all the columns the behaviour tends to become gradual with

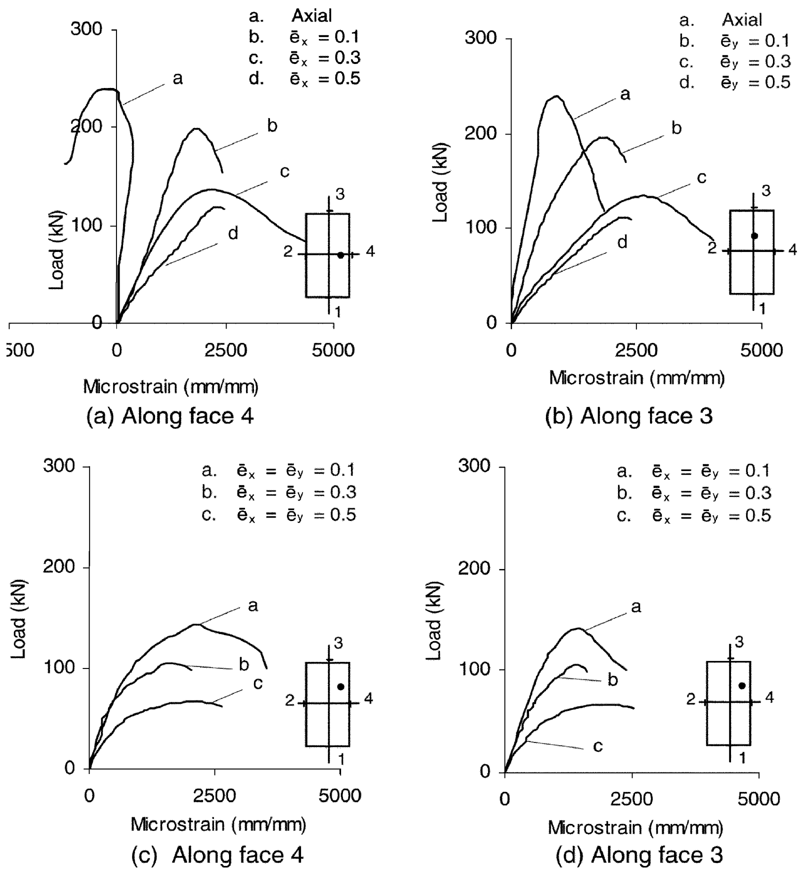


Fig. 6 Load versus strain behaviour of columns filled with low grade concrete

increase in eccentricity. Axially loaded columns and uniaxially loaded columns with low eccentricity ratios exhibited very small plastic strains. Whereas, biaxially loaded columns exhibited relatively large strains along the longer face.

Fig. 7 shows the load versus compressive strain behaviour of columns filled with high grade concrete. Axially loaded column tends to changeover from compressive strain to tensile strain beyond ultimate load indicating local buckling. This initiation first starts along the longer face. Uniaxially loaded columns exhibit sudden drop in load along the longer face and the behaviour is gradual along the shorter face. Biaxially loaded columns with the same eccentricity ratio along both the axis exhibit similar compressive strain pattern along both the faces.

Fig. 8 shows the overall and local buckling pattern of a hollow and concrete-filled column. Hollow columns exhibited inward local buckling along the longer face and outward local buckling along the shorter face. In the case of columns filled with concrete, as expected the concrete prevented the inward local buckling and only outward local buckling occurred in such columns.

Fig. 9 shows the comparison of theoretical and experimental load capacity of hollow columns. It was found that the IS 801-1975 is unconservative for larger biaxial eccentricities and for the larger values of uniaxial eccentricity along the major axis. The BS and the AISI-LRFD give conservative predictions within a margin of 20% for almost all the cases of eccentricity.

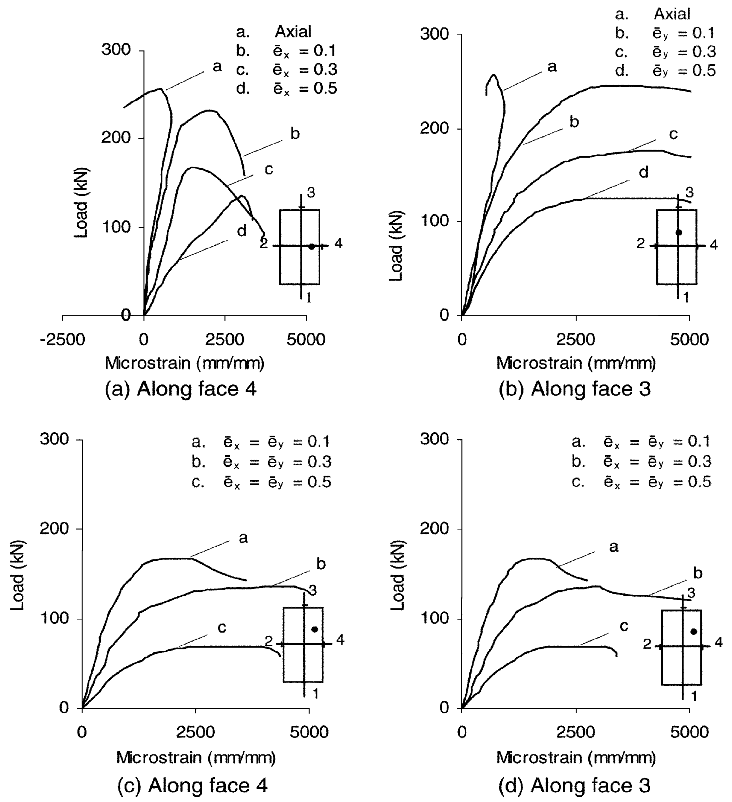


Fig. 7 Load versus strain behaviour of columns filled with high grade concrete

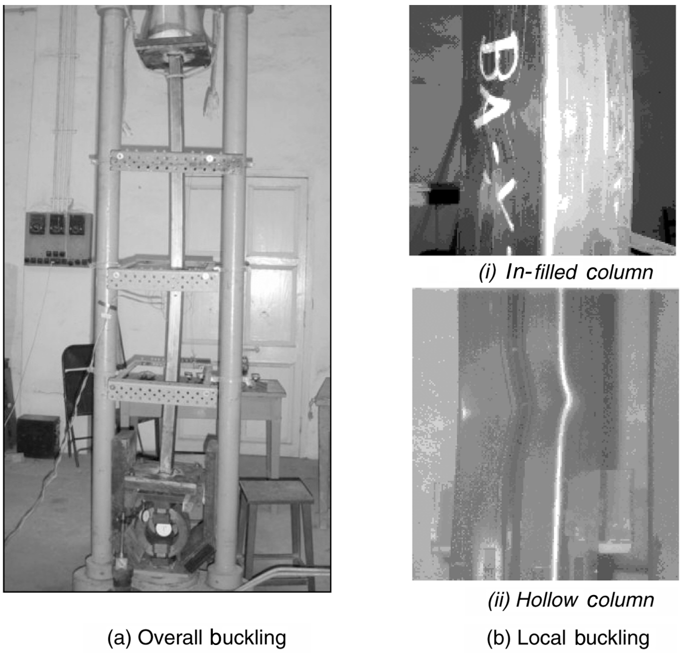


Fig. 8 Failure pattern of columns

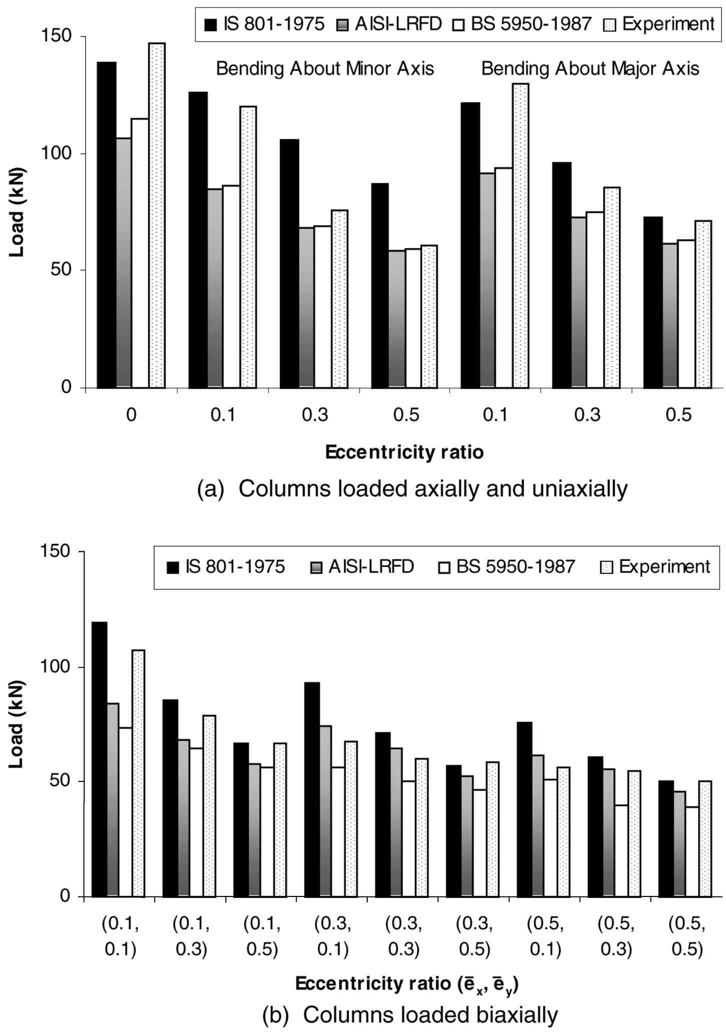


Fig. 9 Comparison of experimental and theoretical load capacity for hollow columns

Fig. 10 shows the Interaction curves for uniaxially loaded concrete-filled columns. It can be seen that EC4 closely predicts the ultimate capacity within a margin of 10%. The comparison of experimental and theoretical ultimate load capacity of biaxially loaded concrete-filled columns are given in Table 1. To calculate the biaxial failure load simplified interaction formulae based on separate calculations under uniaxial design moments for each principal axis is carried out.

Fig. 11 shows the Moment versus Strain behaviour of hollow and concrete-filled beams subjected to pure bending about the minor axis. As expected the behaviour of moment versus strain is symmetrical except in the case of hollow sections where there is a change-over from compressive strain to tensile strain at nearly 95% of the ultimate load due to local buckling. The nonlinearity in strain starts at 75% and 95% of the ultimate load in case of compressive and tensile strain respectively. The local buckling of the beam under the concentrated load was observed at 90% of the ultimate load. All concrete-filled beams exhibited a similar pattern and did not show any changeover in the strain pattern. The lateral

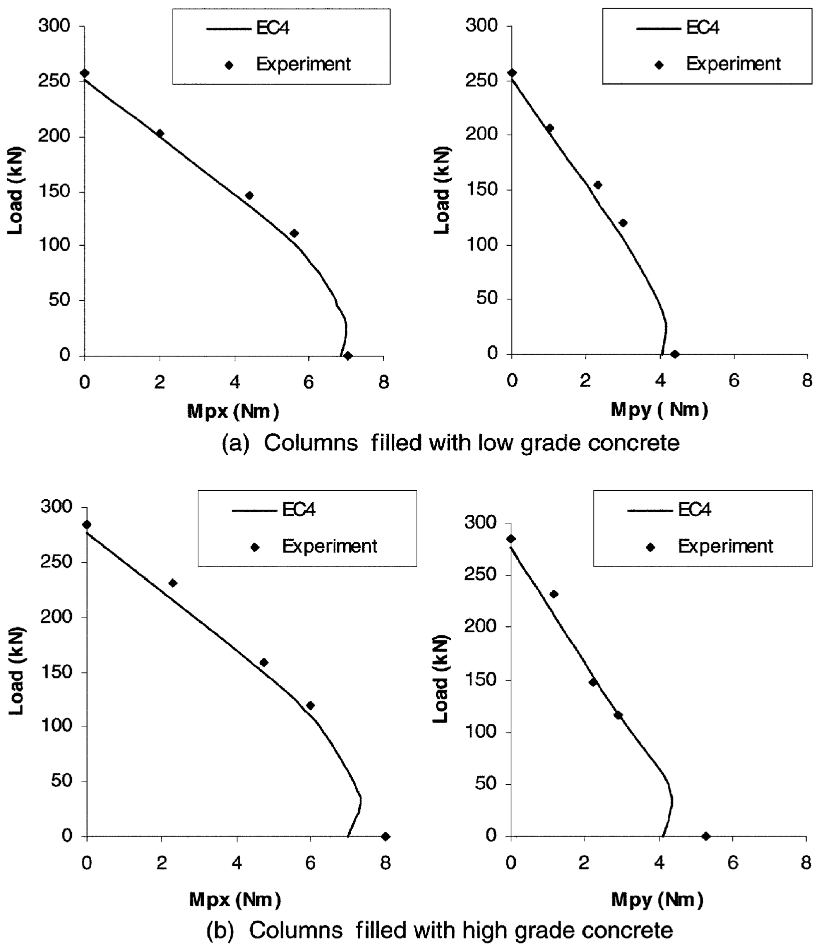
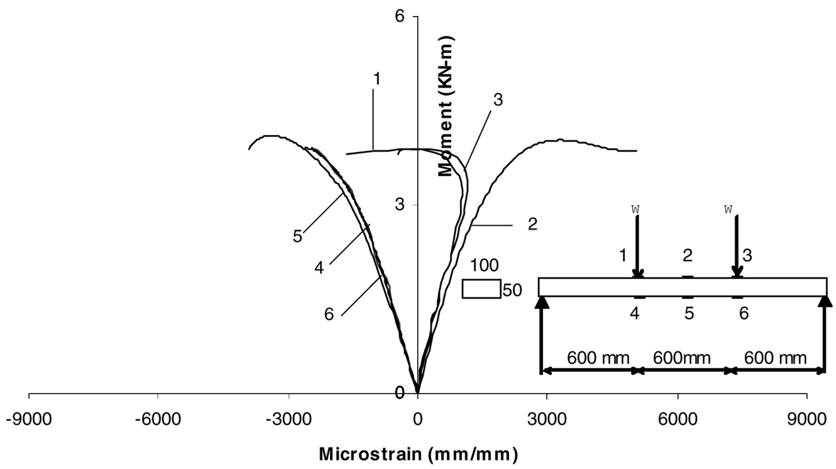


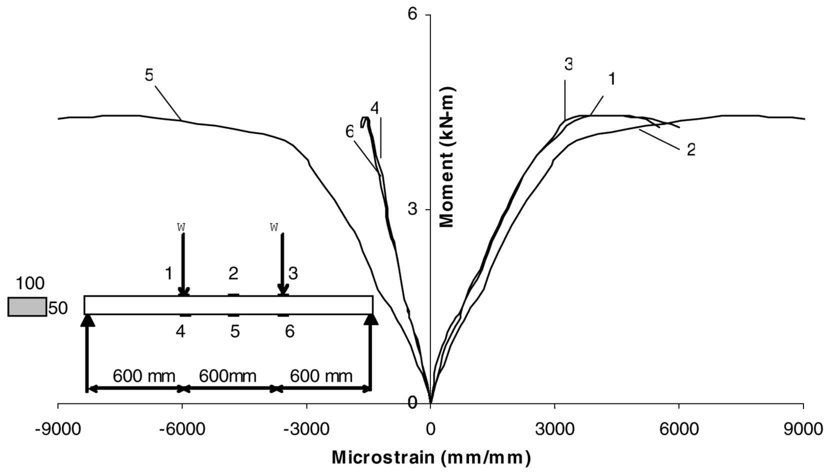
Fig. 10 Interaction curves for uniaxially loaded concrete-filled columns

Table 1 Comparison of experimental and theoretical ultimate loads for biaxially loaded concrete-filled columns

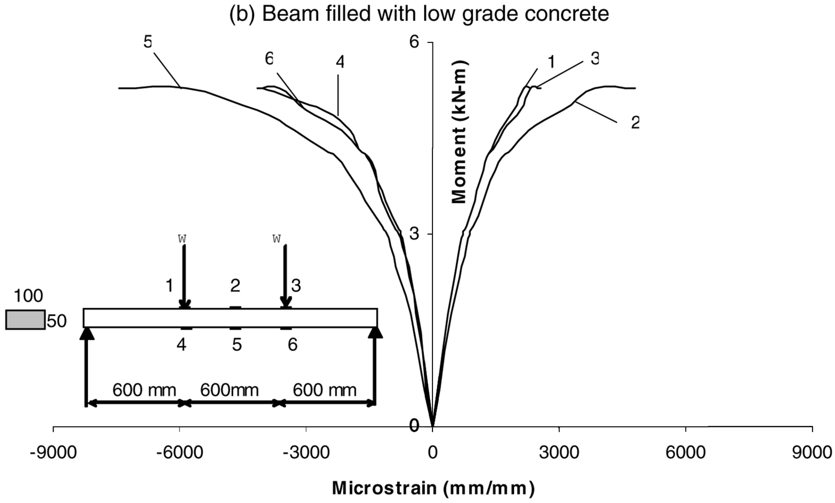
S. No	$\bar{e}_x$	$\bar{e}_y$	Experimental ultimate load (kN)		Predicted ultimate load by EC4 (kN)		P_{exp}/P_{th}	
			In-fill grade		In-fill grade		In-fill grade	
			Low	High	Low	High	Low	High
1	0.1	0.1	171.68	181.49	190.12	205.78	0.90	0.88
2	0.1	0.3	112.82	139.02	114.80	148.75	0.98	0.93
3	0.1	0.5	103.00	115.76	103.18	107.95	1.00	1.07
4	0.3	0.1	114.76	135.38	100.27	155.75	1.14	0.87
5	0.3	0.3	104.97	115.27	91.51	125.55	1.15	0.92
6	0.3	0.5	80.44	111.83	70.81	93.97	1.14	1.19
7	0.5	0.1	94.18	117.72	82.68	128.75	1.14	0.91
8	0.5	0.3	84.37	90.25	73.98	77.85	1.14	1.16
9	0.5	0.5	65.73	73.58	57.71	62.14	1.14	1.18



(a) Hollow beam



(b) Beam filled with low grade concrete



(c) Beam filled with high grade concrete

Fig. 11 Moment versus strain behaviour of beams subjected to pure moment deflection was insignificant in all the beams tested. The failure of the beam was indicated by the overall bending of the beam followed by the localised buckling of the beam under the concentrated load in the case of hollow beams and by overall bending in the case of concrete-filled beams.

4. Conclusions

From the experiments carried out, the following conclusions are drawn

- All the columns except axially loaded columns filled with high grade concrete failed by overall buckling followed by local buckling. Column filled with high grade concrete and loaded axially failed by local buckling followed by overall buckling. The resistance to flexural buckling increases with increase in the strength of the filled concrete.
- In the case of eccentrically loaded columns, compressive strains were found to be always more at a particular load as compared to tensile strains with a gradual drop in both tensile and compressive strains.
- Non-linearity in behaviour starts right at the onset of loading for all columns loaded eccentrically with an eccentricity ratio of 0.3 and 0.5 irrespective of the axes.
- Provision of in-fill increases the load carrying capacity of the order of one and a half to two times and increase in the strength of in-fill from low to high increases the load carrying capacity by one and a half times.
- For hollow columns prediction by IS 801-1975 is unconservative for columns loaded with larger biaxial eccentricities and for larger values of uniaxial eccentricity along the major axis. Prediction by BS 5950-1987 and the AISI-LRFD method give conservative results.
- For concrete-filled columns predictions based on EC4 recommendations agree well within a margin of 10% on the conservative side with the experimental results for axially and uniaxially loaded columns. For columns loaded biaxially the predictions differ by 5% with the experimental results for lower eccentricities whereas when the eccentricities are larger the difference is 15%.
- The failure of the beam was indicated by the overall bending of the beam followed by the localised buckling of the beam under the concentrated load in the case of hollow beams and by overall bending in the case of concrete-filled beams.
- All concrete-filled beams exhibited a similar pattern and did not show any changeover in the strain pattern.

References

AISI (1996), "Cold-formed steel design manual".

BS 5950: Part 5, (1987), "British standard structural use of steelwork in building code of practice for design of cold-formed sections".

Campione, G. and Scibilia, N. (2003), "Beam-column behaviour of concrete filled steel tubes", *Steel and Composite Structures*, **2**(4), 259-276.

Eurocode 4 (1992), "Design of composite steel and concrete structures, Part 1.1 General rules and rules for buildings", ENV 1994-1-1, Brussels, Belgium.

Han, L.H. (2002), "Tests on stub columns of concrete-filled RHS sections", *J. Construct. Steel Res.*, **58**, 353-372.

Hossain, K.M.A (2003), "Axial load behaviour of thin-walled composite columns", *Composites: Part B*, **34**, 715-725.

IS 801 (1975), "Indian standard code of practice for use of cold-formed light gauge steel structural members in

general building construction".
Mursi, M. and Uy, B. (2003), "Strength of concrete-filled steel box columns incorporating interaction buckling", *J. Struct. Eng.*, ASCE, **129**(5), 626-639.
Shakir-Khalil, H. and Zeghiche, J. (1989), "Experimental behaviour of concrete-filled rolled rectangular hollow-section columns", *The Structural Engineer*, **67**(19), 346-353.
Shakir-Khalil, H. and Mouli, M. (1990), "Further tests on concrete-filled rectangular hollow section columns", *The Structural Engineer,* **68**(20), 405-413.
Uy, B. (1998), "Local and post-local buckling of concrete-filled steel welded box columns", *J. Construct. Steel Res.*, **47**, 47-72.
Wang, Y.C. (1999), "Tests on slender composite columns", *J. Construct. Steel Res.*, **49**, 25-41.
Yasser, M. Hunaiti (1996), "Composite action of foamed and lightweight aggregate concrete", *J. Materials in Civil Engineering*, **8**(3), 111-113.

CC