Steel and Composite Structures, Vol. 6, No. 1 (2006) 71-85

DOI: http://dx.doi.org/10.12989/scs.2006.6.1.071

Behaviour of cold-formed steel concrete infilled RHS connections and frames

R. Angeline Prabhavathy† and G. M. Samuel Knight‡

College of Engineering, Guindy, Anna University, Chennai-600 025, India

(Received September 15, 2004, Accepted June 7, 2005)

Abstract. This paper presents the results of a series of tests carried out on cold-formed steel rectangular hollow and concrete infilled beam to column connections and frames. A stub column was chosen such that overall buckling does not influence the connection behaviour. The beam chosen was a short-span cantilever with a concentrated load applied at the free end. The beam was connected to the columns along the strong and weak axes of columns and these connections were tested to failure. Twelve experiments were conducted on cold-formed steel direct welded tubular beam to column connections and twelve experiments on connections with concrete infilled column subjected to monotonic loading. In all the experiments conducted, the stiffness of the connection, the ductility characteristics and the moment rotation behaviour were studied. The dominant mode of failure in hollow section connections was chord face yielding and not weld failure. Provision of concrete infill increases the stiffness and the ultimate moment carrying capacity substantially, irrespective of the axis of loading of the column. Weld failure and bearing failure due to transverse compression occurred in connections with concrete infilled columns. Six single-bay two storied frames both with and without concrete infill, and columns loaded along the major and minor axes were tested to failure. Concentrated load was applied at the midspan of first floor beam. The change in behaviour of the frame due to provision of infill in the column and in the entire frame was compared with hollow frames. Failure of the weld at the junction of the beam occurred for frames with infilled columns. Design expressions are suggested for the yielding of the column face in hollow sections and bearing failure in infilled columns which closely predicted the experimental failure loads.

Key words: hollow steel column; infilled column; cold-formed; hollow frames; infilled frames.

1. Introduction

The use of cold-formed square and rectangular hollow sections has increased worldwide. Square and rectangular hollow sections with slender geometries minimise the amount of material, and are superior to conventional structural elements because of lesser susceptibility to corrosion, ease of fabrication, maintenance and aesthetics. Connections play a key role in determining whether or not a structure will reach its computed ultimate load because plastic hinges are usually formed at the intersection of two or more members. Full utilization of the cold-formed steel members as load bearing elements is possible only by proper design of connections and this becomes complex because of its thinness. Concrete infilled tubular sections are widely used in many countries, because the properties of steel and concrete are

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

effectively used to their maximum advantage. Concrete infilling of rectangular hollow sections enhances considerably their performance due to confinement provided by hollow sections (Packer and Fear 1991). Extensive studies have been conducted on hollow section connections in the last two decades (Zhao and Hancock 1991, Packer and Cassidy 1995, Nayak and Bhattacharyya 1998, Cao *et al.* 1998, Zhao *et al.* 1999, Wilkinson and Hancock 2000, Zhao 2000, Beutel *et al.* 2001, 2002, Kosteski *et al.* 2003). Monotonic and cyclic behaviour of composite column to beam connections in hot rolled sections are also studied in detail by Beutel *et al.* (2001, 2002). It has been concluded that the reinforcing bars welded to the top and bottom flanges and embedded into the concrete are very effective in transferring both tensile and compressive loads thereby increasing the capacity of the connection. In this paper, an attempt has been made to study the behaviour of cold-formed steel rectangular hollow and concrete infilled beam to column connections and frames.

Experiments were conducted on cold-formed steel connections with rectangular hollow beams connected to hollow columns and rectangular hollow beams connected to concrete infilled columns to study the effect of infill and their behaviour. The study included single bay two storied frames with rectangular hollow and infilled sections as beam and column.

2. Experimental investigation

2.1. Test specimen details

Rectangular and square hollow sections were used as columns. Rectangular hollow sections were used as beams. The beams were directly welded to the major and the minor axes of the column. The columns and beams chosen for infilled section connections were of the same sizes as that of hollow section connections. The columns were filled with concrete of grade M20 and the beams were kept hollow. The beams were directly welded to the column sides for loading the column along the major and the minor axes. A typical front elevation of the hollow beam to hollow column connections showing the flange-web radii is shown in Fig. 1.

Single bay two storied frames of rectangular hollow sections with columns of size 100×50×2 mm and beams of size 80×40×2 mm sections were chosen. Six different types of frames were fabricated such that

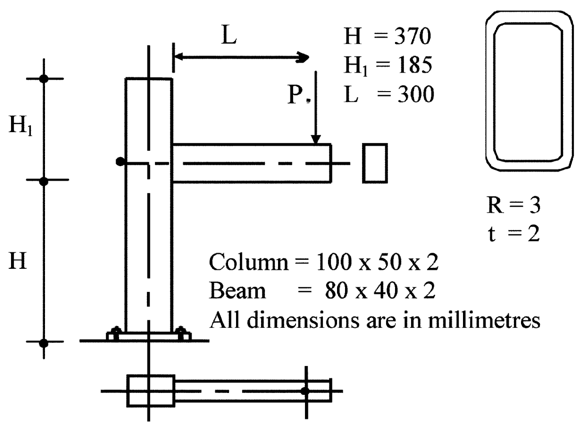


Fig. 1 Typical test joint

Table 1 Tension test results

Description	Dimensions (mm)	E (N/mm^2)	Fy (N/mm^2)	Fu (N/mm^2)
Rectangular section column	100×50×2	2.04×10^5	334	389
Square section column	60×60×2	2.05×10^5	339	378
Rectangular section beam	80×40×2	2.08×10^5	378	428

the beams were directly welded to the short sides and to the long sides of the columns with both beams and columns hollow, column alone with concrete infill and both column and beam with concrete infill.

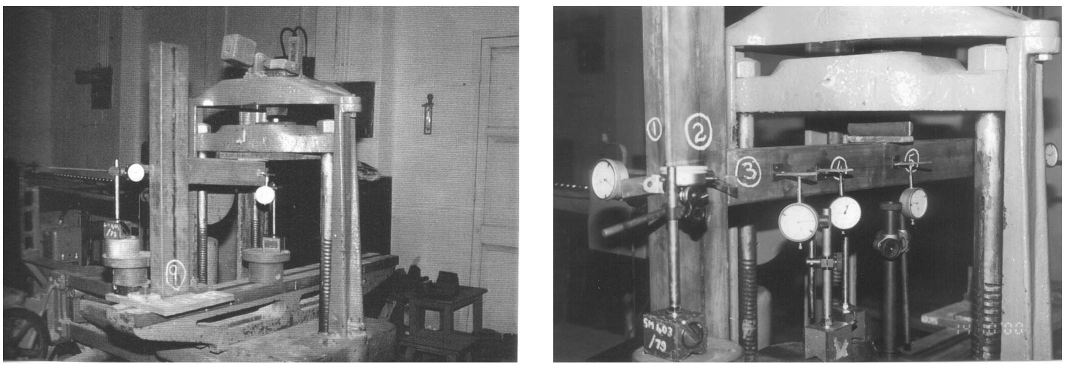
In order to study the material properties of the rectangular hollow sections used for fabrication of the test specimens, tension tests are conducted on standard flat coupons, which are cut from the rectangular hollow sections. These tension test coupons are dimensioned according to the guidelines provided by ASTM standard A370 for sheet type metals. Results of the tension tests are given in Table 1.

2.2. Test set-up

All the experiments were conducted in the Olsen's Universal Testing Machine of capacity 222.5 kN. The beam deflection was measured below the concentrated load at the free end and the lateral deflection of the column was measured at the intersection of the beam and column centre lines. The test set-up for hollow section connection and single bay two storied hollow frame are shown in Fig. 2. Deflections were measured at seven different locations in frames.

2.3. Tests on connections with hollow sections and concrete infilled columns

Twelve experiments were conducted in direct welded connections with cold formed steel rectangular hollow beams connected to rectangular and square hollow columns and the behaviour was studied. Twelve experiments were conducted in connections with hollow rectangular beam connected to rectangular and square concrete-infilled columns. Fig. 3 shows the details of the hollow and infilled section connections tested.



(a) Hollow beam to column connection (b) Single bay two storied hollow frame

Fig. 2 Test setup

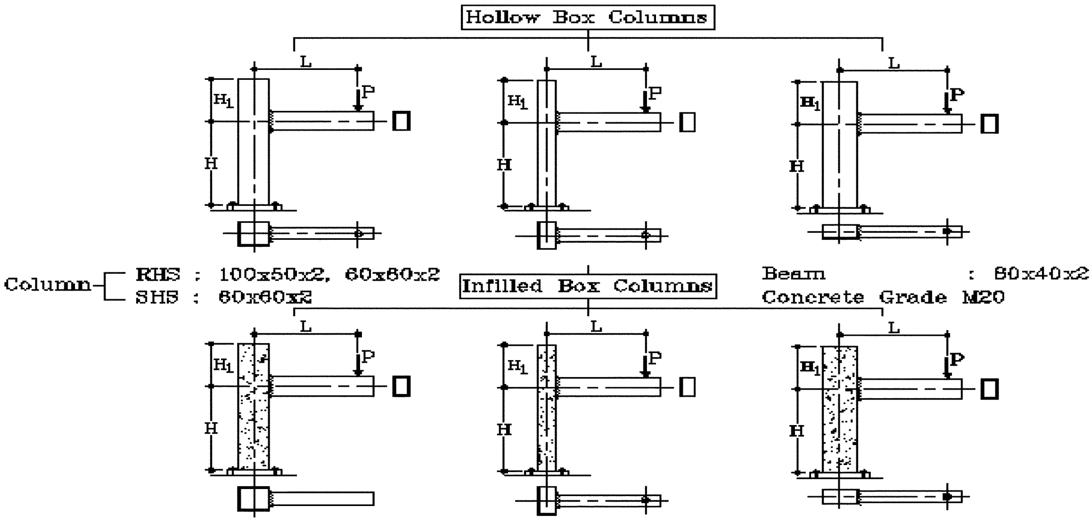


Fig. 3 Details of the hollow and infilled section connections

2.3.1. Moment versus rotation behaviour

The moment versus rotation behaviour of the connections with rectangular hollow beam welded to hollow and concrete infilled column loaded through minor and major axes is shown in Fig. 4. Three distinctly different behaviours are noticed in the case of hollow section connections. For connections with columns loaded along the major axis, the initial stiffness is steep with a horizontal plateau and a

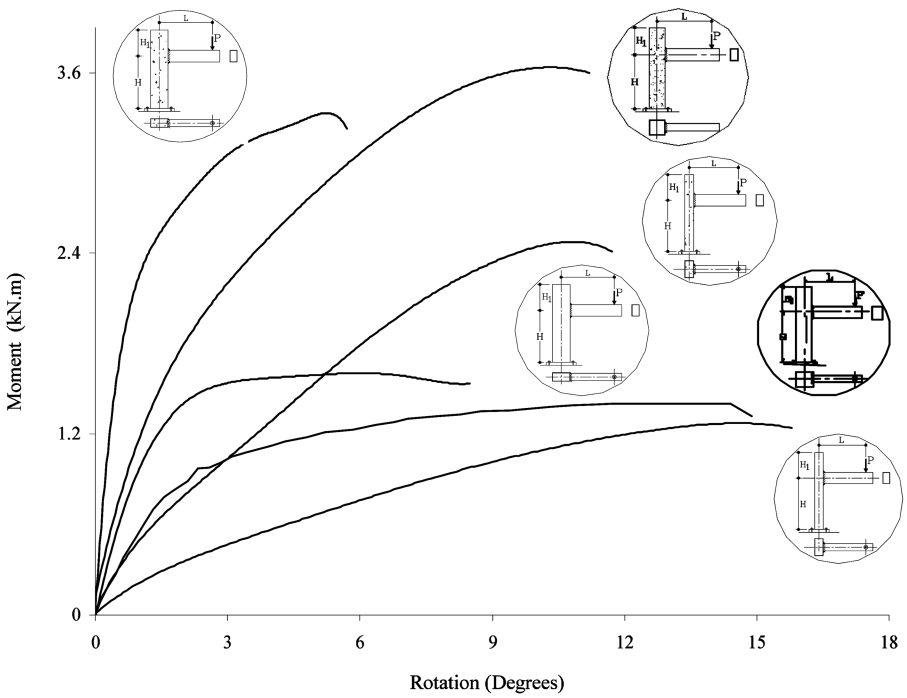


Fig. 4. Moment vs rotation behaviour of connections with hollow and infilled section column

reasonable ductility is observed. The moment carrying capacity is also relatively high as compared to other connections. There is a gradual drop in the moment at failure. The flat width to thickness ratio of the component plates of the column along the shorter side is less than that of the limiting value according to the Indian Standard Code of practice for use of cold-formed light gauge steel structural members in general building construction, IS 801. This postpones the local buckling of column plates and hence the initial moment versus rotation behaviour is steep, enabling the connection to take a higher moment. This connection takes 40% of the plastic moment of the beam. For connections with hollow section, when the columns are loaded along the minor axis, a different behaviour is observed with gradual decrease in stiffness, right from the onset of loading. The flat width to thickness ratio of the component plates of the column along the longer side is greater than that of the limiting value with the result, there is pronounced local buckling, bulging and out of plane deformations. The connection behaves as a flexible connection with less initial stiffness and large ductility. This connection takes 36% of the plastic moment of the beam. An intermediate behaviour is noticed in the case of connections with square hollow columns. The flat width to thickness ratio chosen for the column is less than that of the limiting value. The ultimate moment carrying capacity is almost the same as that of the connection with column loaded along the major axis.

When a column is filled with concrete, the moment capacity of the member increases. The performance of sections with laterally confined concrete with respect to strength and stiffness is better than that of sections with unconfined concrete. The steel casing in a concrete filled tubular section confines the core triaxially and the infilled concrete prevents local buckling of the shell. As in hollow section connections, the behaviour is distinctly different with connections when the columns are infilled with concrete. They exhibit a steep initial stiffness, high moment carrying capacity and a short horizontal plateau. In the case of connections loaded along the minor axis of the column, the non-linearity in the behaviour starts early. There is a sudden drop in the moment after the ultimate load. The beneficial confinement effect of the concrete core is provided by the steel plates.

Irrespective of the axis of loading of the column and irrespective of the cross section of the column whether square or rectangular, provision of infill increases the initial stiffness, and the moment carrying capacity. In connections with square sections as column and connections with rectangular columns loaded along the major axis, the ductility improves marginally but when the columns are loaded along the minor axis, the ductility reduces. This is due to the large width to thickness ratio of the component plates of the column that plays a key role in considering the confinement effect provided by the concrete core. The effect of confinement is minimal since the width to thickness ratio exceeds the limiting value.

For connections with hollow rectangular beams with hollow rectangular columns, if the axis of loading is changed from minor to major, there is substantial increase in the initial stiffness and ductility ratio but marginal increase in the ultimate moment. The initial stiffness, the ultimate moment and the ductility ratio of hollow square column connections are less than that of connections with rectangular columns loaded along the strong axis. In case of loading the column through minor axis, the beam is connected to the larger face of the column and the flat width to thickness ratio of component plates of the column is greater than that of the limiting value, there is non-linear behaviour from the onset of loading. For the connections with infilled rectangular columns, if the axis of loading is changed from minor to major, as in hollow section connections, there is substantial increase in the initial stiffness and ductility ratio but marginal increase in the ultimate moment. Hollow rectangular columns loaded along major axis have the maximum ductility ratio and infilled rectangular columns loaded along major axis have the maximum ultimate moment and initial stiffness.

2.3.2. Failure modes for hollow section and infilled section connections

Different failure modes can exist depending on the type of joint, loading conditions and various geometric parameters. The design guide for hollow structural section connections describes the possible failure modes for square and rectangular hollow section connections subjected to in-plane bending moments as chord face yielding, cracking in chord, cracking in branch member, crippling of the chord side wall and chord shear failure. The strength is characterized by the ultimate bearing capacity. Chord face yielding is the dominant mode of failure of the hollow section connections and it occurred for low to medium branch width to chord width ratios in connections with relatively thin web member. The dominant modes of failure for infilled section connections are weld failure and bearing failure due to transverse compression. Weld crack occurred at the level of the tension flange of the beam.

2.3.3. Proposed formula for hollow section connections

A moment yield line mechanism of rectangular hollow section column has been used for estimating the strength of the hollow section connections due to the development of yield line mechanism of the connecting face of the main member. The beam welded to the column cause yielding of the column face due to stress concentration. The yield zones in the beam allow the column flange to deform plastically out of its plane, which results in the formation of yield lines. Fig. 5 shows the yield mechanism in the column face when yield load is attained in the hollow beam to hollow column connection.

The tension flange of the beam tend to pull the column plate away from the column whereas the compression flange of the beam tend to push the column plate inwardly. It is assumed that this outward pull is equal to the inward thrust. This closely predicts the experimental yield strengths of rectangular hollow section connections with branch width to chord width ratio ranging from 0.4 to 0.8. The estimated yield strength for each specimen by yield line mechanism to the experimental yield strength range from 0.91 to 1.04. The ratio of beam flange width to column flange width, plays a dominant role in the application of this theory.

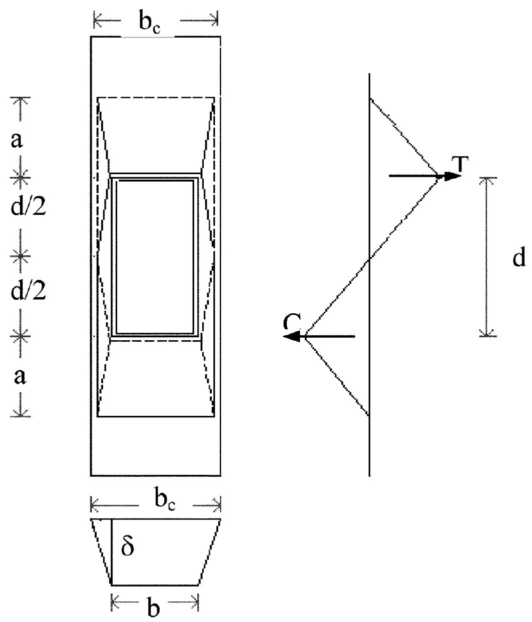


Fig. 5 Yield line pattern of hollow section

In the yield line analysis for moment connections, the stiffness of the joint is calculated in terms of three parameters, width to thickness ratio of the column, depth to width ratio of the beam, and beam width to column width ratio. As the ratio of width of beam to the width of column decreases, strength and stiffness decrease considerably in the case of the rectangular hollow section connection since the connecting column face is relatively flexible. The effects of membrane action and strain hardening are ignored in the simplified yield line models.

Failure load corresponding to the yield line pattern is the product of the moment per unit length of the yield line (a function of yield stress and the column flange thickness) and the total length of the yield lines. Yielding of the column face occurred at the tension flange level of the beam in all the connections. In the case of connections with square and rectangular hollow sections as columns, the plastic moment capacity of the beam could not be reached due to local yielding of the column face due to tension or local buckling due to compression.

For hollow section direct welded connections, the following expression is derived from the yield line pattern shown above. The details of the derivation are shown in Appendix.

$$T = \frac{f_{yc}t_{fc}^2}{\beta}\left[2\sqrt{\frac{b_c}{(b_c-b)}} + \left(\frac{(b_c-b)}{2d}\right) + \left(\frac{d}{b_c-b}\right)\right] \tag{1}$$

The experimental and theoretical failure loads using the proposed formula for direct welded connections in hollow sections are given in Table 2.

Fig. 6 shows the failure mode of the connections with rectangular hollow beam to rectangular hollow section connections. It can be seen that the theoretical predictions are less than the experimental

Table 2 Failure loads of hollow section connections

Type of connection		Failure loads (kN)		$\frac{P_{Prop}}{P_{Exp.}}$
		Experimental	Proposed	
Rectangular hollow section beam connected to rectangular hollow section column	Major axis	20.50	21.28	1.04
	Minor axis	16.28	14.74	0.91
Rectangular hollow section beam connected to square hollow section column		17.31	16.54	0.96

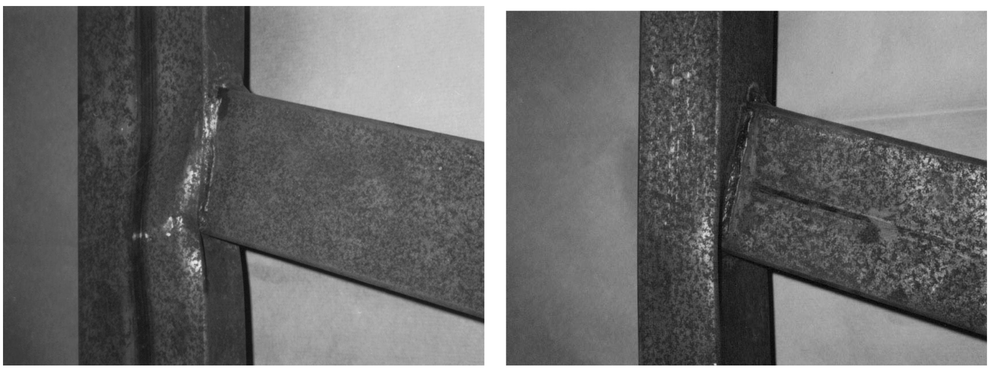


Fig. 6 Web buckling and yielding of column face of the hollow section connection

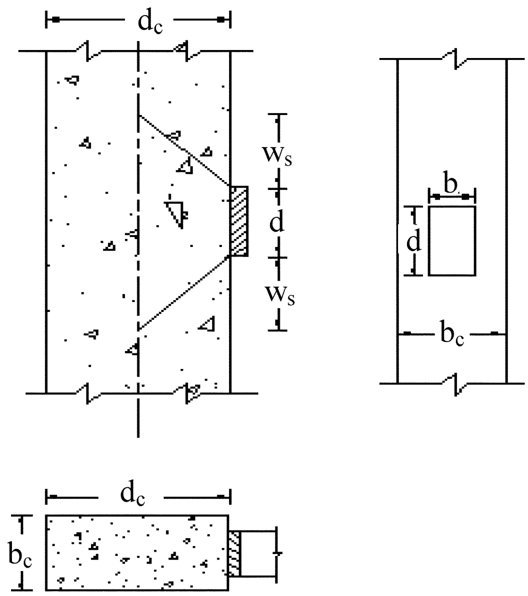


Fig. 7. Concrete infilled rectangular hollow section under transverse compression

predictions for connections with square hollow sections and for connections with rectangular hollow sections loaded along the minor axis.

2.3.4. Proposed formula for infilled column connections

The Design guide for hollow structural sections by Canadian Institute of Steel Construction suggests the following expression for connections with concrete infilled column subjected to transverse compression as shown in Fig. 7. The factored resistance of a concrete-filled rectangular hollow section connection is taken as

$$N_1 = \phi_c f_c^1 \left[\frac{A_1}{\sin\theta_1} \sqrt{\frac{A_2}{A_1}} \right] \quad (2)$$

The slope of the dispersed bearing area is 2:1 taken longitudinally along the column. For cold-formed steel connections with concrete infilled section columns, the following expression is proposed based on the experiments conducted.

$$P_i = k f_{ck} \sqrt{A_1 A_2} \quad (3)$$

Table 3 Failure loads of infilled concrete section connections

Type of connection		Weld failure (kN)	Bearing capacity (kN)	Lowest failure load (kN)	Experimental failure load (kN)	$\frac{P(\text{theo.})}{P(\text{Exp.})}$
RHS beam connected to RHS infilled column	Major axis	43.24	44.72	43.24	42.92	1.01
	Minor axis	43.24	35.86	35.86	34.71	1.03
RHS beam connected to SHS infilled column		43.24	38.81	38.81	46.13	0.84

(a) Yielding of the column flange

(b) Weld failure

Fig. 8 Failure modes of connections with rectangular hollow beam and concrete infilled column

The comparison of experimental and theoretical failure loads using the proposed formula for direct welded connections in infilled concrete sections are given in Table 3.

The theoretical failure loads overestimate the experimental loads in the case of connections with rectangular column sections and underestimates the failure loads for connections with square hollow sections. The failure modes of connections with rectangular hollow beam and concrete infilled columns are shown in Fig. 8.

In the case of connections with rectangular hollow section beam connected to rectangular infilled section column loaded along the major axis, weld starts cracking at 93 % of the ultimate load. This is due to the degradation in the steel section and the sudden release of concrete confinement.

All these connections tested are analysed using ANSYS and a 2D beam model. Higher ductility and lower ultimate moments characterize hollow column sections when compared to infilled sections. Hence relative flexibility of beam and column as well as the flexibility of joints are considered and a methodology is developed by Prabhavathy *et al*. (2003). Both detailed FE model and the 2D beam model

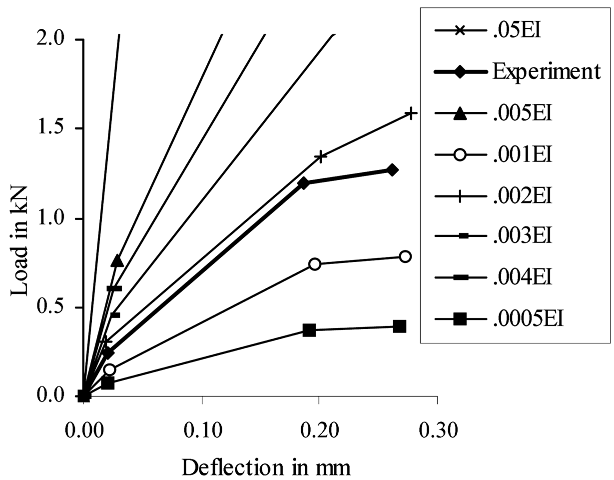


Fig. 9 Load-deflection response for a ratio of beam inertia/column inertia of 2 (different flexibility)

fit with test results if one accounts for flexibility of joints suitably. The response shows the flexibility of joints influences the behaviour in three different modes. The 2D beam model based on test results can be applied to other combinations also. The bilinear or trilinear curves of load-deflection response for a particular ratio of beam inertia/column inertia for different flexibility level of joints are shown in Fig. 9 where EI is the flexural rigidity of beam.

2.4. Single-bay two storied frames

If the beam to column joint is a part of a frame, the change in behaviour of the connection is studied. In order to achieve this, six single-bay two storied frames with and without concrete infill, and columns loaded along the major and minor axes were tested to failure. The details of the frames tested are shown in Fig. 10. The frames were tested for gravity loads with concentrated load acting at the midspan of first floor beam. The change in behaviour of the frame due to provision of infill in the column and in the entire frame was also studied.

2.4.1. Load versus deflection behaviour

Fig. 11 shows the load versus deflection behaviour of hollow, column infilled and infilled frames. For hollow frames and column infilled frames, change in axis of loading from minor to major increases the initial stiffness by 60%, and increases the ultimate load marginally, but the ductility ratio decreases by 20% and 45% respectively.

For infilled frames, there is an increase in initial stiffness, ultimate moment and ductility ratio by 80%, 12% and 45% respectively. It can be seen that for connections with column loaded along the major axis, there is a steep increase in initial stiffness and drastic increase in deflection after yield load in the form of a horizontal plateau. Irrespective of whether the frame is hollow or infilled with concrete there is a distinct

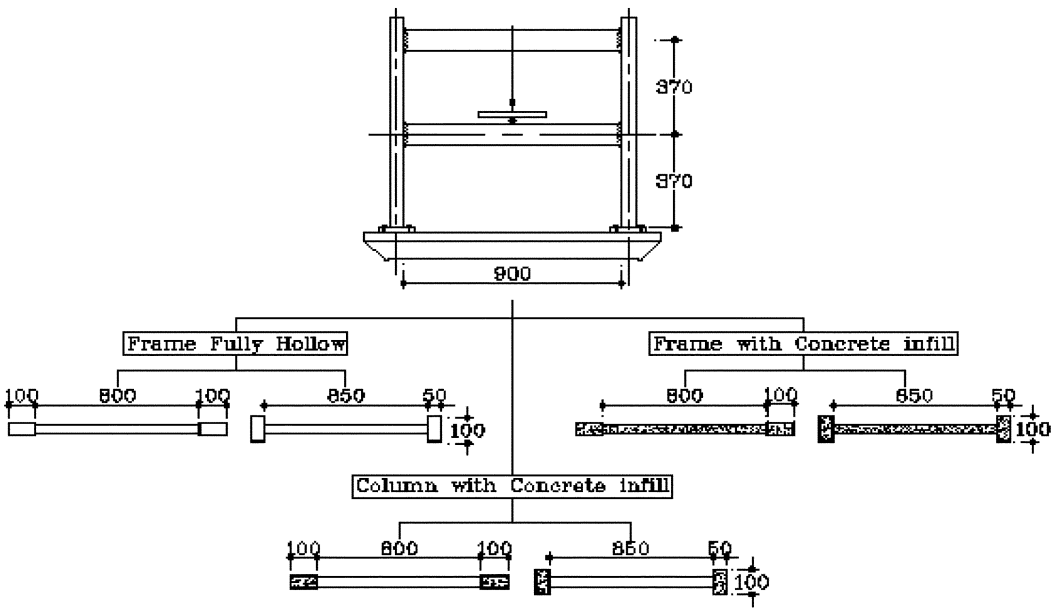


Fig. 10 Details of the hollow and infilled section frames

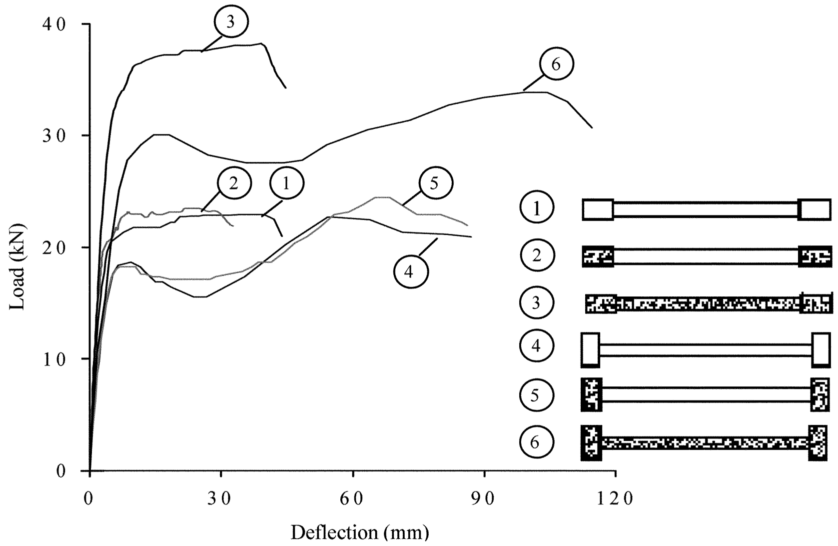


Fig. 11 Load vs deflection behaviour of connections with hollow and infilled section frames

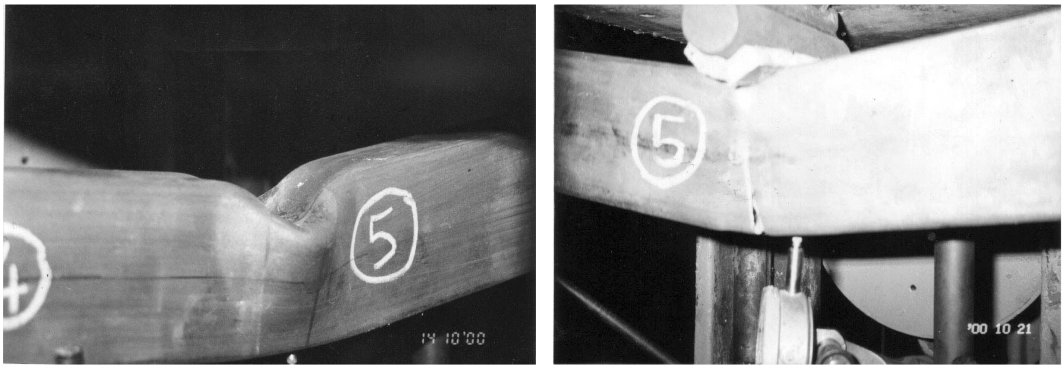
horizontal plateau showing sufficient ductility. In the case of connections with column loaded along the minor axis, there is a sudden drop in the load after the yield load and then there is a gradual increase in the load up to the ultimate load. This type of behaviour may be due to the beam butting against the column flange when the deflection of the beam takes place. In the elastic range, the behaviour of the frame with respect to both axes is similar. In the case of infilled frames, when loaded along the major and minor axes, the load deflection behaviour is the same as that of hollow frames and column infilled frames. But there is a drastic increase in load carrying capacity as compared to the other two frames. Bulging of the compression flange takes place at 80% of the ultimate load and the increase in load takes place because the beam butts against the column web when the deflection. The depression in the behaviour is substantial in the case of infilled concrete column frame for minor axis loading.

2.4.2. Failure modes of the frames

In the case of connections in hollow and infilled concrete frames, failure occurred in the following modes.

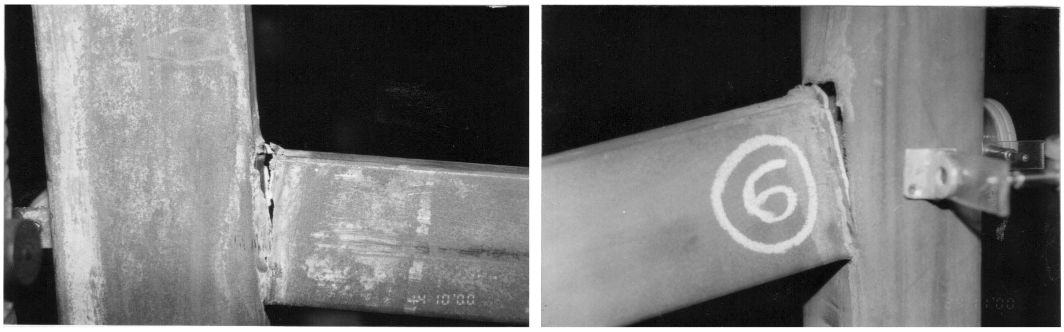
- Bearing failure of the hollow beam
- Tearing of the tension flange of beam if the beam is filled with concrete
- Failure of the weld at the junction of the beam and column
- Tearing of the component plates of the column at the compression flange level of the beam

When the load is increased at the centre of first floor beam, there is local buckling (bearing failure) in the compression flange of the hollow beam below the concentrated load. Plastic hinges are formed in the beam below the concentrated load. Local buckling effect depend on the slenderness of the component plates of the beam. The beam bulges laterally in the compression zone below the concentrated load. If the beams are hollow, these type of failure occur at 80% of the ultimate load. Tearing failure of the tension flange of the beam normally occurs at 95% of the ultimate load. Failure modes of hollow and infilled beams in frames are shown in Fig. 12.



(a) Bearing failure of the hollow beam (b) Tearing of the tension flange of the infilled beam

Fig. 12 Failure modes of hollow and infilled beams in frames



(a) Weld failure at the connection (b) Tearing of the column face

Fig. 13. Failure modes of connections in hollow and infilled frames

In the case of hollow frames, column infilled frames and infilled frames loaded along the major axis, failure due to tension always occurred at the junction of the weld with columns at the top flange level of the beam as shown in Fig. 13(a). Yielding of the tension flange is not the dominant mode of failure due to the reason that the width to thickness ratio of the flange of the column chosen is far less than that of the limiting value for all connections in frames. For connections in hollow frames and column infilled frames, when the column is loaded along the minor axis, yielding of the column web started at 80% of the ultimate load because the flat width to thickness ratio of the web of the column, is much greater than that of the limiting value. In the case of infilled frame with the column loaded along the minor axis, yielding of the column web started at 90% of the ultimate load. Concrete infill in the beam gives additional stiffness to the frame that delays the yielding of the infilled column and failure occurred due to tearing of the column web along the weld contour as shown in Fig. 13(b).

Hollow frames exhibit higher ductility. For connections with hollow beam and infilled column loaded along the major axis, provision of infill in the column decreases the ductility ratio substantially but there is no significant change in the initial stiffness and ultimate load carrying capacity. When the infilled column is loaded along the minor axis, provision of infill in the column increases the ultimate load marginally and there is also no significant change in the initial stiffness and ductility ratio. For connections in infilled frames, provision of concrete infill in the whole frame increases the initial stiffness and the ultimate load substantially when compared to connections in hollow frames and column infilled frames loaded along the major axis.

The ductility ratio increases by 15% as compared to column infilled frame and decreases by 25% when compared to hollow frame. Earlier research conducted by Zhao and Hancock (1999) concludes that the concrete infill in the case of rectangular hollow section beams increase the ductility ratio. However, the ductility ratio of the concrete infilled frame is less than that of the hollow frame due to the combined effect of the column infill that decreases the ductility ratio and the beam infill that increases the same.

3. Conclusions

- For hollow section connections, change in axis of loading of the column from minor to major, increases the initial stiffness and ductility ratio substantially but there is marginal increase in the ultimate moment
- The failure mode in the case of hollow section connections is the yielding of the column flange or web. The yield line analysis closely predicted the experimental yield strengths of rectangular hollow section connections with flange width to chord width ratio ranging from 0.4 to 0.8. For hollow section connections, the following expression is proposed for failure load.

$$T = \frac{f_{yc}t_{fc}^2}{\beta}\left[2\sqrt{\frac{b_c}{(b_c-b)}} + \left(\frac{(b_c-b)}{2d}\right) + \left(\frac{d}{b_c-b}\right)\right]$$

- Connections with hollow sections as column loaded along the major axis, take 40% of the plastic moment of the beam whereas infilled section connections take 75% of the plastic moment of the beam.
- For the connections with infilled rectangular columns, if the axis of loading is changed from minor to major, as in hollow section connections, there is substantial increase in the initial stiffness and ductility ratio but marginal increase in the ultimate moment. In infilled connections, theoretical bearing capacity due to transverse compression governed the failure. For connections with infilled sections, the following expression is proposed for failure load.

$$P_i = kf_{ck}\sqrt{A_1A_2}$$

- For connections with hollow beam and infilled columns with square and rectangular sections loaded along the major axis, provision of infill increases the initial stiffness, the moment carrying capacity and the ductility ratio marginally but when the columns are loaded along the minor axis, the ductility reduces.
- In the case of infilled frames, when loaded along the major and minor axes, the load deflection behaviour is the same as that of hollow frames and column infilled frames. But there is a drastic increase in load carrying capacity as compared to the other two frames.

References

Angeline Prabhavathy, R., Samuel Knight, G.M. and Rajaraman, A. (2003), "Flexibility of beam to column connections in hollow construction", *Proc. of the Int. Conf. on ADVANCES IN STRUCTURES (ASSCCA'03)*, Sydney, Australia, JUNE, 961-965.

Beutel, J.G. Thambiratnam, D.P. and Perera, N.J. (2001), "Monotonic behaviour of composite beam-column

connections", *J. Eng. Struct.,* **23**(9),1152-1161.
Beutel, J.G. Thambiratnam, D.P. and Perera, N.J. (2002), "Cyclic behaviour of composite beam column connections", *J. Eng. Struct.*, **24**(1), 29-38.
Cao, J.J., Packer, J.A. and Yang, C.J. (1998), "Yield line analysis of RHS connections with axial loads", *J. Constr. Steel Res.*, **48**, 1-25.
Kosteski, N., Packer, J.A. and Puthli, R.S. (2003), "A finite element method based yield load determination procedure for hollow structural steel connections", *J. Constr. Steel Res.*, **59**, 453-471.
Nayak, A.N. and Bhattacharyya, S.K. (1998), "Welded T-joints with hollow sections: An experimental study," *Int. J. Struct.*, **18**(1), 29-50.
Packer, J.A. and Cassidy, C.E. (1995), "Effective weld length for HSS T,Y and X connections", *J. Struct. Eng.*, ASCE, **121**(10), 1402-1408.
Packer, J.A. and Fear, C.E. (1991), "Concrete-filled rectangular hollow section X and T connections", *Proc. the 4th Int. Symp. on Tubular Structures*, Delft, The Netherlands, 382-391.
Packer, J.A. and Henderson, J.E. (1992), *Design Guide for Hollow Structural Section Connections*, Canadian Institute of Steel Construction, Canada.
Wilkinson, T. and Hancock, G.J. (2000), "Tests to examine plastic behaviour of knee joints in cold-formed RHS", *J. Struct. Eng.*, ASCE, **126**(3), 297-305.
Zhao, X.L. and Hancock, G.J. (1991), "T-joints in rectangular hollow sections subject to combined actions", *J. Struct. Eng.*, ASCE, **117**(8), 2258-2277.
Zhao, X.L. (2000), "Deformation limit and ultimate strength of welded T joints in cold-formed rectangular hollow section", *J. Constr. Steel Res.*, **53**, 149-165.
Zhao, X.L. and Grzebieta, R. (1999), "Void-filled SHS beams subjected to large deformation cyclic bending", *J. Struct. Eng.*, ASCE, **125**(9), 1020-1027.
Zhao, X.L., Riadh, Al-Mahaidi and Kiew, K.P. (1999), "Longitudinal fillet welds in thin-walled C450 RHS members", *J. Struct. Eng.*, ASCE, **125**(8), 821-828.

Notation

A_1 : bearing area over which the transverse load is applied ($A_1 = d.b$)
A_2 : dispersed bearing area in mm^2 at a slope of 2:1 longitudinally along the column $b(d + 2\,w_s)/2$
N_1 : factored resistance of infilled section subjected to transverse compression
T : theoretical failure load of hollow section connection in N
P_i : failure load of infilled section connections in N
B : width of the beam in mm
b : external width of the beam in mm
b_c : external width of the column in mm
d : depth of the beam in mm
d_c : external depth of the column in mm
f_{yc} : yield stress of the column N/mm^2
f_{c1} : 28 day crushing strength of concrete by cylinder tests
f_{ck} : characteristic strength of concrete in N/mm^2
k : proposed resistance factor based on experimental investigation (0.55)
t_{fc} : thickness of the hollow column in mm
β : ratio of beam width to column width of hollow section connection
ϕ_c : resistance factor for concrete in bearing = 0.6
θ_1 : angle between the chord and branch member

Appendix

Yield line analysis for RHS section
Horizontal yield lines (*AB* & *EF*)

$$AB = mb\left(\frac{\delta}{a}\right)$$

$$EF = mb_c\left(\frac{\delta}{a}\right)$$

Vertical yield lines (*EJ* & *FK*) and vertical component of inclined yield lines)

$$= 2\,m\,\left(a + \frac{d}{2}\right)\left(\frac{\delta}{\left(\frac{b_c - b}{2}\right)}\right)$$

Horizontal component of inclined yield lines

$$= 2\,m\,\left(\frac{b_c - b}{2}\right)\left(\frac{\delta}{a}\right) + 2m\left(\frac{b_c - b}{2}\right)\left(\frac{\delta}{d/2}\right)$$

Taking moment about the compressive force *C*, and equating it to the sum of the moments of the yield lines

$$Td = mb\left(\frac{\delta}{a}\right) + mb_c\left(\frac{\delta}{a}\right) + 4\,m(a + d/2)\left(\frac{\delta}{\frac{b_c - b}{2}}\right) + 2\,m\left(\frac{b_c - b}{2}\right)\left(\frac{\delta}{a}\right) + 2\,m\left(\frac{b_c - b}{2}\right)\left(\frac{\delta}{d/2}\right)$$

Taking $m = \frac{f_{yc}t_{fc}^2}{2}$, simplifying and then dividing with β (beam width to column width ratio)

$$T = \frac{f_{yc}t_{fc}^2}{\beta}\left[2\sqrt{\frac{b_c}{(b_c - b)}} + \left(\frac{(b_c - b)}{2d}\right) + \left(\frac{d}{b_c - b}\right)\right]$$

CC