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An experimental study of connections between I-beams and concrete filled steel tubular columns

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Abstract. Frame composed of concrete-filled steel tubular columns and I-shaped steel beam has been researched in order to development reasonable connection details. The present paper describes the results of an experimental program in four different connection details. The connection details considered include through-bolt between I-shaped steel beams and concrete-filled steel tubular columns and two details of welded connections. One of the welded connection details is stiffened by angles welded in the interior of the profile wall at the beam flange level. The specimens were tested in a cruciform loading arrangement with variable monotonic loading on the beams and constant compressive load on the column. For through-bolt details, the contribution of friction and bearing were investigated by embedding some of the bolts in the concrete. The results of the tests show that through-bolt connection details are very ductility and the bearing is not important to the behavior of these moment connections. The angles welded in the interior of the profile wall increase the strength and stiffness of the welded connection detail. In addition, the behavior curves of these connections are compared and some interesting conclusions are drawn. The results are summarized for the strength and stiffness of each connection.

Key words: concrete filled steel tubular columns; connections; bolted connections; welded connections; through-bolt connections; beam-column connection behavior; extended endplate.

1. Introduction

The increasing use of concrete filled steel tubular columns in building structures is a justifiable tendency due to its high economical and structural performance.

The main characteristics of these elements are high strength and stiffness, capacity to absorb energy, absence of formwork and reinforcement, reduced construction and material costs and labor saving in construction. However, one of the main concerns about these elements is related to their connection with other structural elements of buildings. Therefore, from a structural point of view, their superior performance as axially loaded members is well known, and the major drawback is the complexity and cost of connections.

The concrete filled steel tubular columns are very popular in regions subject to earthquakes due to their high ductility and stiffness when resisting significant vertical forces. The use of these elements in association with compact steel beams produces a very economical structural system, although they are very susceptible to deformations. The beam-column connection requires attention, mainly in areas

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subject to seismic loads. In this case, the connection detail must have full moment connection. Besides, the connection detail must be easy to assemble, and have good structural behavior. The costs of connection are also another very important factor to be considered.

The major obstacle to the effective use of concrete-filled steel tubular columns is the lack of effective connection details, especially when the concrete core is relied upon to carry a substantial proportion of the axial load. Therefore, the development of new beam-column connection details is of major importance in order to guarantee a crescent use of the concrete filled steel tubular columns.

Researchers in many countries have studied several connection details which can be placed into three broad categories. The ones that connect to the steel profile only (external connections), those that attempt to distribute some or all of the flange forces directly into the concrete core via embedded elements (internal connections) and those whose reinforcing bars of the concrete slab or composite slab are used to resist a some of the flange forces (composite connection detail).

The external connections make the transference of the beam forces only to the steel profile (Vandegans and Janss 1995, Oh *et al*. 1995, France *et al*. 1999). Welding the steel beam or connecting elements directly to the steel profile of composite columns should be avoided as the transfer of tensile forces to the steel profile can result in a separation of the profile from the concrete core, thereby overstressing the steel profile. Welding of the thin steel profile could result in large residual stresses, too. On the other hand, the external connection offers no internal flow restrictions to the pump filling of the steel profile. In general, it seems that when correctly designed and detailed, such an external connection would perform adequately. However, the amount of material and fabrication required in such connections could make them uneconomical.

The internal connections are an alternative in which the forces are transmitted to the core concrete via anchor bolts or steel elements embedded in the concrete core. Therefore, in the internal connections, steel elements are anchored in the column, transferring part of the flange forces directly to the concrete core (Azizinamini and Prakash 1993, Ricles *et al.* 1995). However, such connections introduce concrete flow restrictions into the steel profile and could result in the formation of voids in the concrete.

Another alternative is the composite connection, in which the slab makes the transference part of the flexural moment (Bernuzzi *et al.* 1995, Malaska *et al.* 2001). In the composite connection, the tension force resulting from the beam end moment is primarily resisted by the longitudinal reinforcement of the composite beam, composite slab or composite floor beam. Additional information about each one of these connection details is presented in some paper (De Nardin and El Debs 2002, De Nardin 2003).

The study of beam-column connection details has been developed over the last two decades. Expectations of technical and economic flexibility and cost-effectiveness that alternative feasible solutions may offer have motivated research and development in this field.

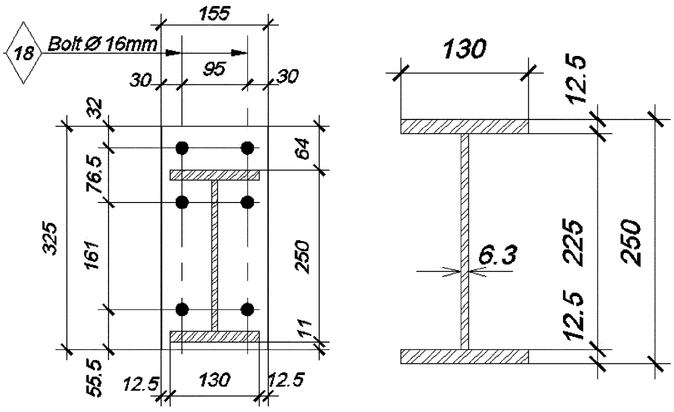
The present study focuses on the behavior of beam-column connections. The experimental results of four cruciform beam-column connection details are presented and discussed.

2. Experimental study

2.1. Test specimens and material properties

The experimental study comprises a concrete filled tubular column with nominal dimension of 200×200×6.3 mm and length of 1950 mm connected on both sides to identical steel beams of 1650 mm length.

The main parameters investigated are: type of connection detail, bearing between through-bolts and



(a) Endplote (22.4 mm thick)   (b) Beam section

Fig. 1 Geometry of endplates and beams

concrete core and internal stiffeners contribution.

Four connection details were tested in order to determine the joint behavior. The C1 connection detail has extended endplates and six through bolts. The C2 connection detail is similar to C1 detail but without bearing on bolt-concrete contact. The C3 specimen is a welded connection detail and C4 detail is similar to C3 but stiffened by four internal angles. For convenience, the connection details will be referred as a "C1 detail", "C2 detail", "C3 detail" and "C4 detail".

Through-bolt connections for concrete-filled hollow structural steel sections were investigated by other researchers (Prion and Mclellan 1994).

The beams and the endplates are made of A-36 steel. The endplates were bolted to the column with six bolts of 16 mm diameter and 280 mm of length with thread on all their lengths. The bolts are made of ASTM-A325 steel. The geometry of endplates and beams are shown in Fig. 1.

Table 1 gives the strength characteristics for the steel material. In order to characterize the steel material, three coupons were taken from each steel component: web and flanges of beams, endplates and steel profile. These coupons were tested according to E 8M – 00: Standard test methods for tension testing of metallic materials.

Three bolts were instrumented with strain gauges and tested for tension tests. The results of yield strength and ultimate strength are given in Table 1.

The composite columns investigated in this paper were completely filled with concrete. The steel profiles were filled with a concrete that had a measured compressive strength of 60 MPa.

Table 1 Steel strength of the connection specimens

Specimen	Column		Flange beam		Web beam		Endplate		Bolts		Angle	
MPa	fy	fu	fy	fu	fy	fu	fy	fu	fy	fu	fy	fu
C1/C2 details	303	430	343	473	328	469	269	458	702	768	-	-
C3 detail	269	416	287	439	356	484	-	-	-	-	-	-
C4 detail	383	464	287	439	356	484	-	-	-	-	264	384

Note
fy: yield strength; fu: ultimate strength

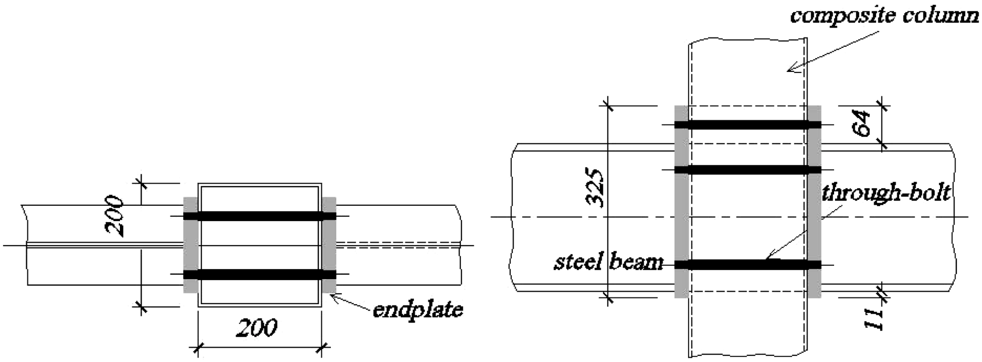


Fig. 2 C1 and C2 endplate details – general layout

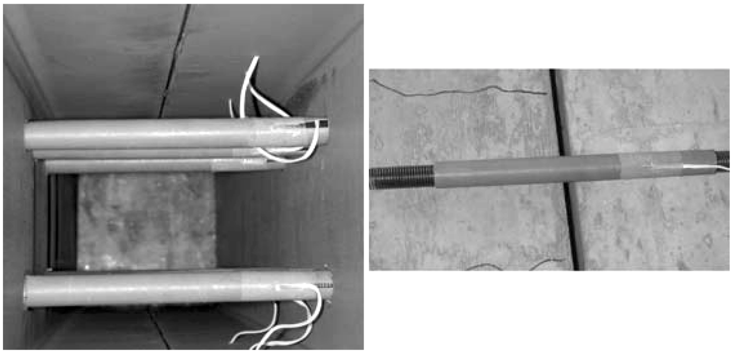


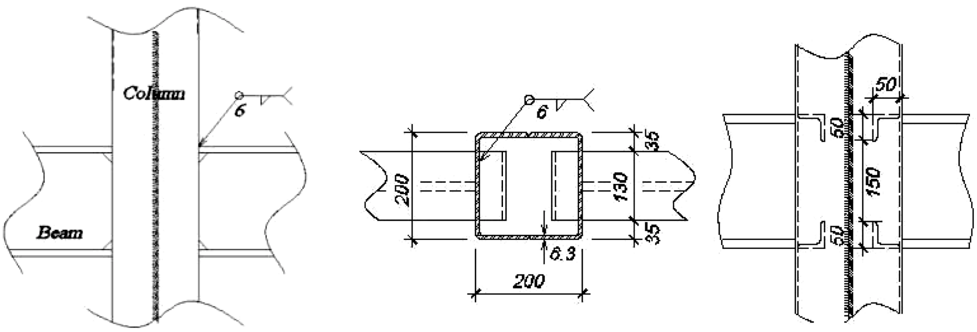
Fig. 3 Bolts inside the plastic tubes – C2 detail

2.2. C1 and C2 through-bolt specimens

In Fig. 2, C1 and C2 extended endplate connection details are showed. They are composed of I 250×37 kg/m beams, stiffened by plates 8.0 mm thick on the region where vertical forces are introduced. Six bolts of high strength steel (threaded on all lengths) go through the column. To avoid slip between the through-bolts and the concrete, in the C2 detail the bolts were placed inside the plastic tubes, permitting relative movement between the concrete and the bolts. The bolts and the plastic profiles are showed in Fig. 3.

2.3. C3 and C4 welded specimens

The C3 detail represented the simplest connection detail in which the beam was welded directly to the face of the steel profile. C4 detail was identical to C3 detail, however, four angles L50×50×130, 6.3 mm thick were welded by fillet weld on the internal surface of the steel profile. The angles were embedded in the concrete core and the angles were placed at the same level as the upper and bottom flanges of the steel beams. Fig. 4 presents the layout of the C3 and C4 details. In these details the columns and beams with identical dimensions to the C1 and C2 details were used.



(a) C3 detail (b) C4 detail

Fig. 4 Geometry of C3 and C4 details specimens

2.4. Test set up and measurements

In all the tests, concrete filled steel columns and beams were loaded. The vertical forces on the beams were introduced by two computer controlled hydraulic actuator. The speed of load application was 0.005 mm/second in the C1, C2 and C4 details and 0.01 mm/second in the C3 detail. The vertical forces were applied at 1500 mm from the column face. All the tests were performed in a 500 kN capacity hydraulic actuator.

Vertical compression load of 450 kN were applied in the composite column, corresponding approximately to 20% of its squash load (compressive strength of the concrete core plus compressive strength of the steel profile). This compression load was applied using hydraulic jack. A typical set up is shown in Fig. 5.

In order to obtain as much information as possible from each test, many parameters were recorded during the tests e.g., connection rotation, beam strain, bolt strain, endplate strain and displacements.

A general arrangement of the displacement transducers for all specimens is shown in Fig. 6. Displacements were measured at several points of the endplates and deflections were also measured along the beams at several points.

In order to measure strains, strain gauges were placed in some positions. Web and flanges of the beams, steel profile, extended endplates and through-bolts were instrumented (Fig. 7).

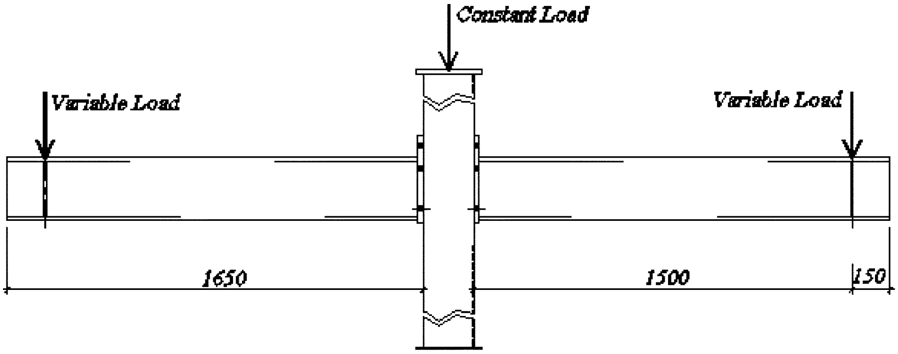
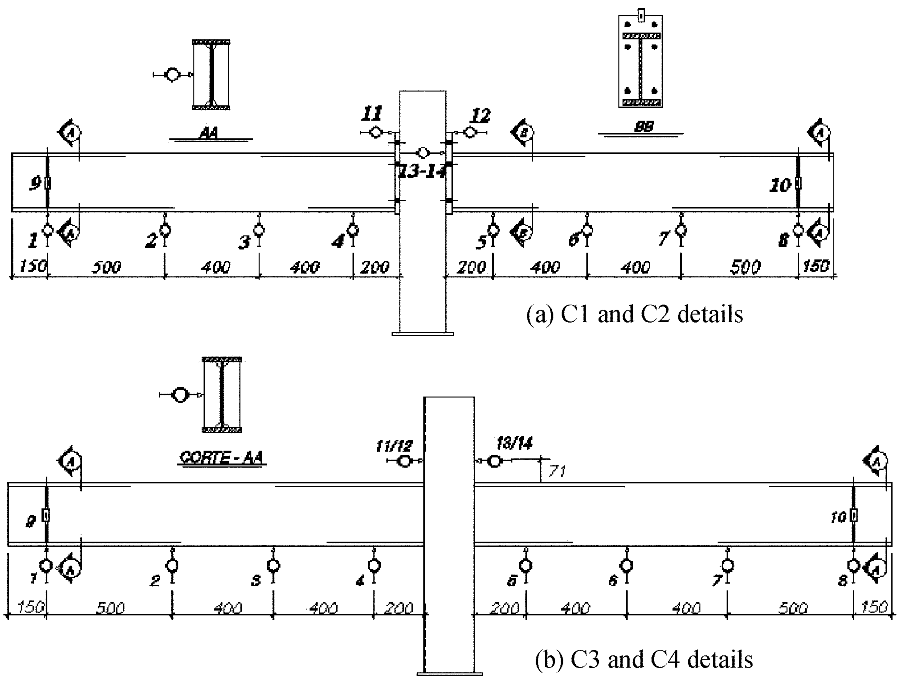


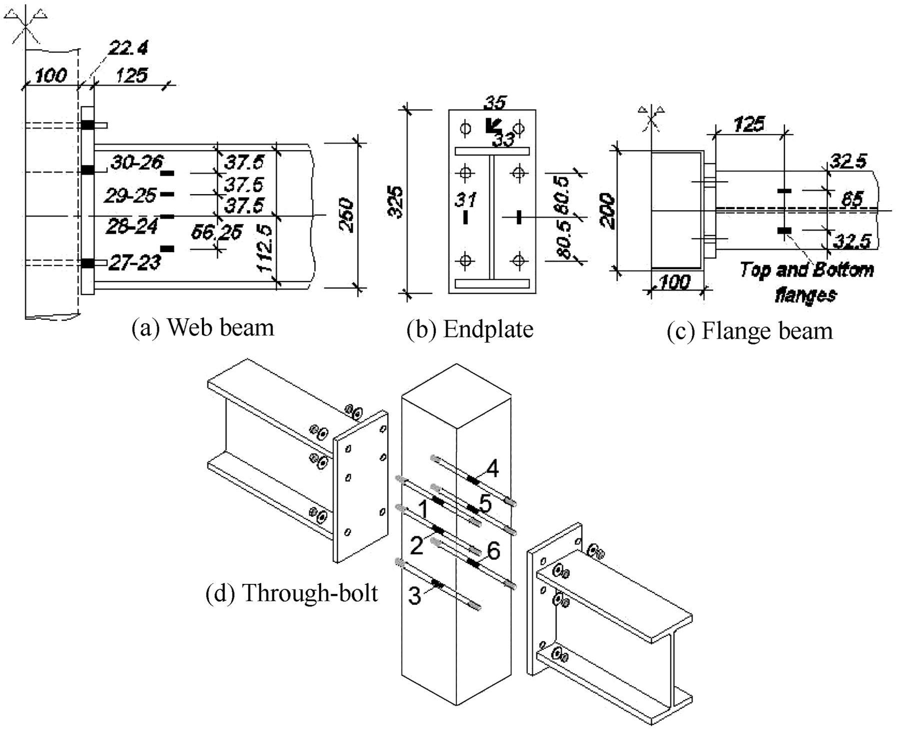
Fig. 5 Loading arrangement of tests



(a) C1 and C2 details

(b) C3 and C4 details

Fig. 6 Displacement transducers arrangement



(a) Web beam

(b) Endplate

(c) Flange beam

(d) Through-bolt

Fig. 7 Strain gauges arrangement

3. Test results and discussion

The main results are presented here in the form of plots of the connection moment against the post-processed data calculated directly from the recorded data. The detailed test results for each of the individual parameters are also presented.

The connection moments were taken as the product of the applied load and the length of the lever arm assumed to be the distance from the centre of the applied load to the outside surface of the composite column.

3.1. Connection moment capacity and moment-rotation curves

Experimental values of ultimate force, moment capacity and corresponding displacements of the beams are given in Table 2.

In C1 and C2 details there are no significant differences for the obtained ultimate forces and moments connection capacity. Therefore, bolt-concrete bearing does not have a great influence on the moment connection capacity and displacement values.

C3 detail presents large vertical displacements while C4 detail presents lower values. The ultimate displacement value of the C4 detail was the result of the stiffening caused by the internal angles. The internal angles increase the stiffness of the C4 connection detail.

Connection rotations are obtained by taking the displacement of the beams 200 mm from the face of the composite column.

The moment-rotation relation for each connection will be used as the basis to evaluate and compare the performance of each detail. In Fig. 8 the moment-rotation behavior for tested connections is shown.

For C1 and C2 details, the moment-rotation behavior is similar but C2 detail presents lower connection moment capacity. However, a similar behavior does not occur between C3 and C4 details, where C4 detail presents an initial stiffness much higher than the C3 detail. The angles work as stiffeners and cause a great increase in the stiffness related to the C3 welded detail.

Through-bolt connections present more expressive moment connection capacity and rotation capacity than welded connections. Therefore, through-bolt connections had more stiffness than welded connections.

Table 2 Connections test average results

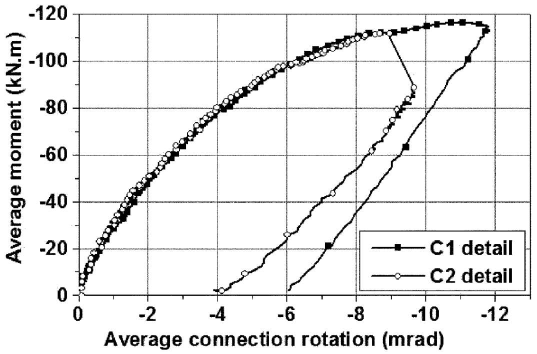
Specimen	Ultimate load (kN)	Ultimate moment (kN.m)	Displacement ultimate (mm)
Connection 1	77.6	116.4	21.8
Connection 2	74.6	111.9	17.5
Connection 3	29.0	43.5	40.2
Connection 4	32.8	49.2	25.3

3.2. Behavior of strains

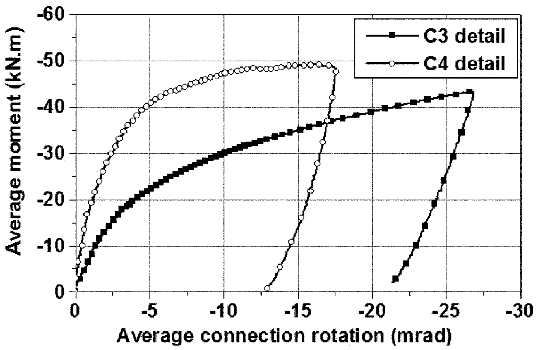
3.2.1 Steel beam strains

The steel beam flange strains are plotted against average connection moments in Fig. 9. Strains on top and bottom flanges of steel beams are plotted.

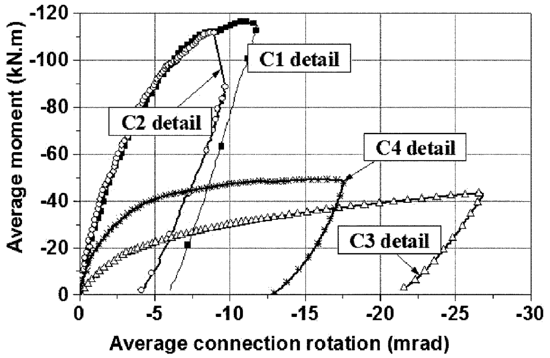
The bottom flange strains were high for through-bolt connections as shown in Fig. 9(b), indicating



(a) C1 and C2 through-bolt connections



(b) C3 and C4 welded connections



(c) Moment rotation curves

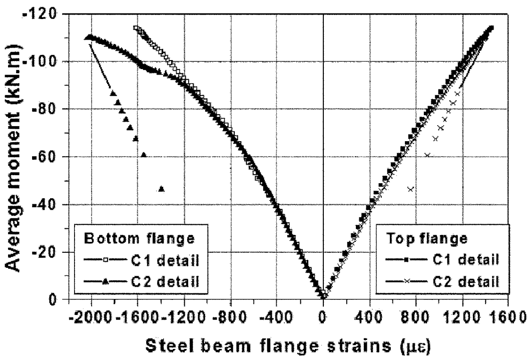
Fig. 8 Moment versus rotation connection curves

that the behavior of the strains on the top flange (tensioned) is identical in both C1 and C2 details (Fig. 9a). Therefore, the concrete-bolt bearing does not modify the strain distribution on the top flanges of the steel beams.

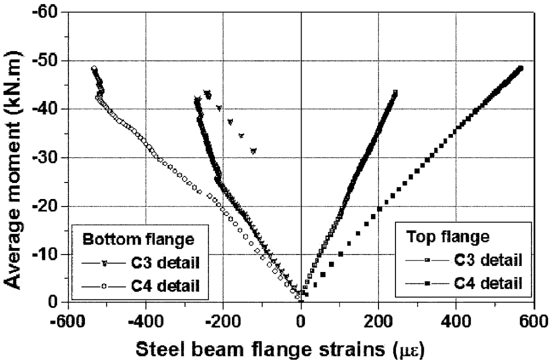
The behavior of the strains is similar on the bottom flanges of the steel beams during the initial stage of loading. After the moment connection has exceeded about 85% of its capacity, a change in the behavior of the bottom flanges in C2 detail can be observed. On this bottom flange (C2 detail) there is a sudden increasing of the strains caused by the sliding of the nut-bolt.

The C3 and C4 details are welded connections but C4 detail is stiffened by internal angles. For C3 and C4 details, the behavior of the top flanges of the beams is more uniform than on the bottom flanges. In addition, the strain on flanges for C3 detail is less significant than for C4 detail beam flanges, indicating that the internal angles increase the connection stiffness. Therefore, for the same value of connection moment, more significant strains are observed for C4 detail beam flanges (Fig. 9b).

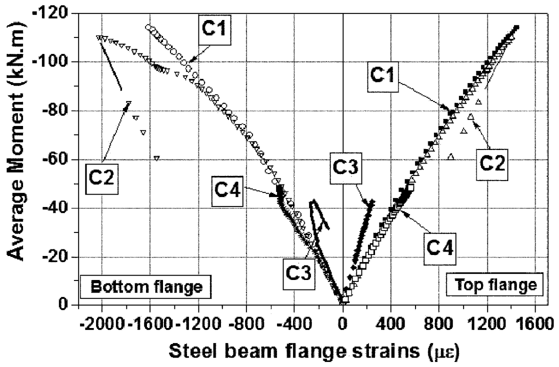
Fig. 10 shows the average horizontal strain behavior of the beam webs, which is similar for tensioned line (26-30) and compressed line (23-27). However, the neutral axis position is different between C3 and C4 details, due to the fact that the C4 detail was stiffened by the internal angles welded in the tensioned region (top).



(a) C1 and C2 through-bolt connections

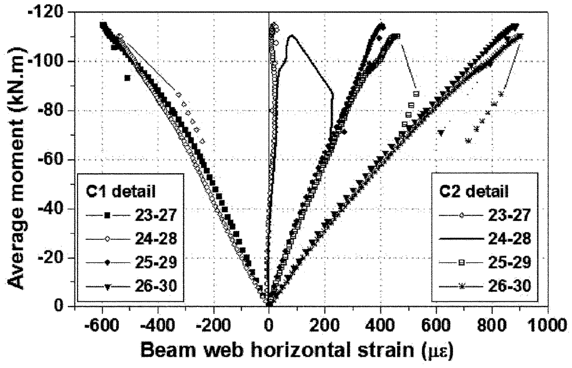


(b) C3 and C4 welded connections

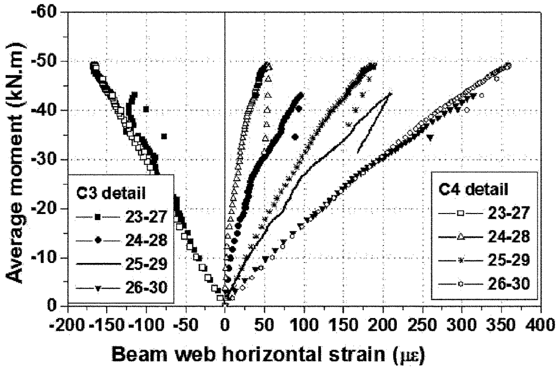


(c) C1 to C4 details

Fig. 9 Steel flange beam strains versus connection moment



(a) C1 and C2 details



(b) C3 and C4 details

Fig. 10 Steel web beam strains versus connection moment

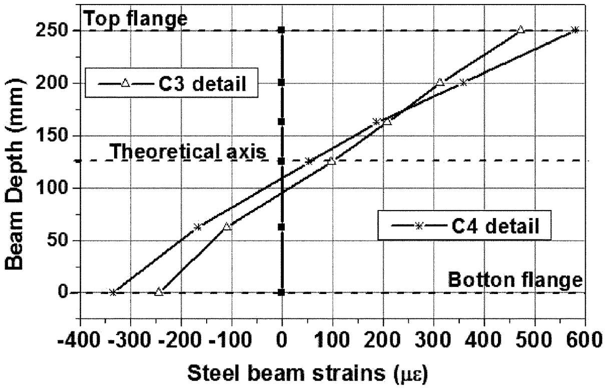


Fig. 11 Neutral axis – C3 and C4 details

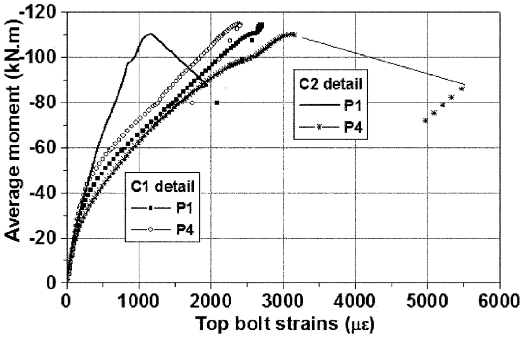
The neutral axis position for C3 and C4 details is shown in Fig. 11, where the influence of the angles is clear. For the C4 detail, the neutral axis is nearer the centerline of the steel beam web than for the C3 detail as the angles increase the local stiffness. The neutral axis is below the centerline of the steel beam web and the tensioned area is larger than the compressed one. The beam web horizontal strains remained below the yield strength, as shown in the figure.

Besides, the stiffening of tensioned region balances part of the composite column stiffness of the compressed area. No influence of angles was verified on compressed region.

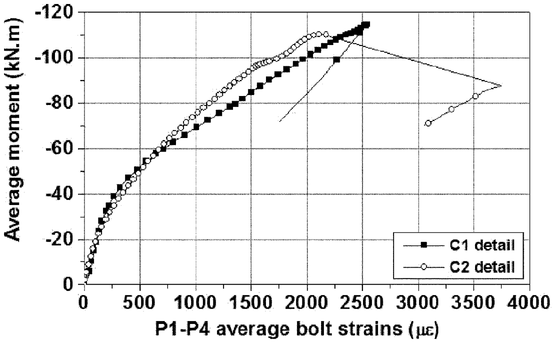
3.2.2. Top bolt strains

Strain gauges on bolts were used to indicate the behavior for embedded bolts. The bolt strains behavior are showed in Fig. 12. The strain gauge readings on the bolts showed that the strains behavior on the top row bolts is very different for C1 and C2 details. For these details, it can be seen that the top row bolts were tensioned during all loading stages.

P1 and P4 bolts are placed in the same row. For the C1 detail, these bolts present a similar behavior but with little difference between strain values. The same occurs for the C2 detail, although in this case the behavior between P1 and P4 bolts is quite different. The longitudinal strains on P1 and P4 bolts are inferior to failure strain. The bolt-nut pair failed due to the sliding of the nut in relation to the bolt. The nut-bolt sliding is occurred in P5 bolt.



(a) Average bolt strains - C1 and C2 details



(b) P1 and P4 strains behavior

Fig. 12 Top bolt strains versus connection moment

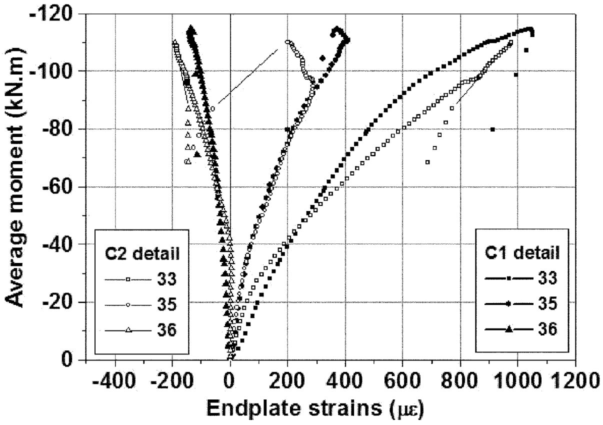


Fig. 13 Endplate strains versus connection moment

3.2.3. Endplate strains

The variation of endplate strains against connection moment is shown in Fig. 13. It can be seen that these strains do not exceed the yield strength for C1 and C2 details. Bolt-concrete bearing has no significant influence on the endplate strains behavior and these strains are similar for all the through-bolt connections.

3.3. Behavior of displacements

The variation in the beams deflections measured along the beams at several points is shown in Fig. 14, and it is clear that the bolt-concrete bearing caused changes on vertical displacements values. For the C1 detail, displacements are slightly higher than for the C2 detail, and they also have a different behavior for beams on both left and right sides. For the C2 detail the behavior of displacements is similar for both beams. This was attributed to the absence of bolt-concrete bearing. Displacements for the C3 detail are much greater than the displacements registered for both beams for the C4 detail. Displacement values were reduced due to the stiffening in the connection region caused by the angles welded inside the steel profile.

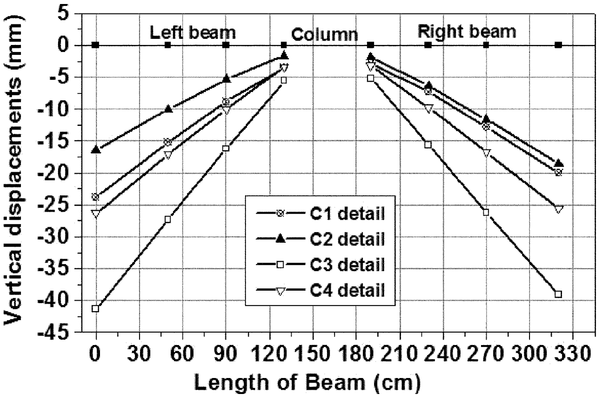


Fig. 14 Vertical displacement of beams

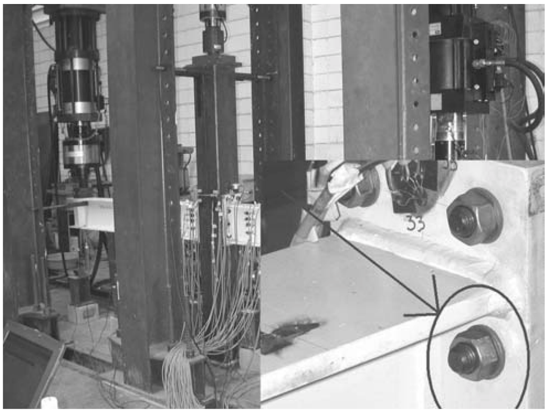


Fig. 15 Typical failure mode for C1 and C2 through -bolt details

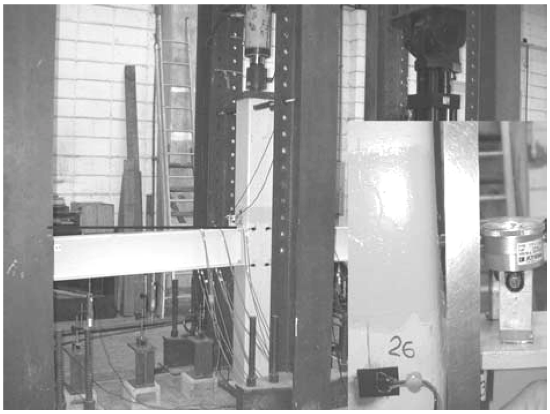


Fig. 16 Typical failure mode for the C3 welded detail

3.4. Failure of specimens

The typical failure mode for C1 and C2 details are given in Fig. 15. A typical failure mode for through-bolt connections was nut-bolt sliding, which occurred in P5 bolt for C1 and C2 details. For the C2 detail, the sliding was abrupt due to the absence of boltconcrete bearing. A soft sliding was observed for the bolts of C1 detail, as a consequence of bearing existence. This behavior can also be observed from the measured strains at various components of the detail connection. The nut-bolt sliding is not visible in the figure.

Fig. 16 indicates that for C3 and C4 details, the typical failure mode was the very large strains of the profile wall near the beam-column weld. These large strains and large distortion occurred on the profile wall around the connection region. For C4 detail the strains and distortion on the profile wall were reduced by the presence of the angles. Therefore, internal angles transfer beam forces into to the concrete core and reduce local stresses on the profile wall.

4. Conclusions

Several details to connect I-beams and concrete filled steel tubular columns were investigated by experimental work. The connection details studied were through-bolt and extended endplate, simple welding of the beam to the outside wall of the steel profile and angles welded in the interior of the profile wall. Four connection details were tested in a cruciform loading arrangement with variable monotonic loading on the beams and constant compressive load on the composite column. For the through-bolt connection details, the influence of the bolt-concrete bearing was evaluated and for the welded connections the contribution of the internal angles to the connection moment capacity and moment-rotation behavior was analyzed. The following observations and conclusions were made based on the limited research reported in the paper:

1. Bearing bolt-concrete core does not change the moment-rotation behavior of the through-bolt connection details (C1 and C2 details). An influence of the bearing is present only on the bolt strains behavior. For the through-bolt connection, the moment connection capacity is not changed by the bolt-concrete bearing. However, internal angles contribute to reduce the beams displacements and to

increase the moment connection capacity of the welded connections.

2. The effect of bolt-concrete core bearing on the stiffness connection is not significant. However, internal angles contribute to the increase of the stiffness of the welded connections investigated.
3. The slip nut-bolt was the failure mode to the through-bolt connections. This slip was abrupt for the non-bearing through-bolt connection (C2 detail) and soft for bearing through-bolt connection (C1 detail).
4. For welded connections, the failure mode was characterized by large strains on the profile wall near the tensioned region of the connection. The C3 and C4 details were designed to investigate the contribution of the internal angles to transfer part of the flange forces directly to the concrete core. This contribution can be seen from both moment-rotation curves. Small angles increase the stiffness of the welded connection and reduce the strains values on the profile wall.
5. Due to the presence of angles, the neutral axis is positioned below the centerline of the steel beam web but nearer this centerline for the C3 welded detail.

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