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High-Temperature Tests on Joints to Steel and Partially-Encased H-Section Columns

Shan-Shan Huang[a,*], Buick Davison[a] and Ian W. Burgess[a]

[a] Department of Civil and Structural Engineering, The University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield, S1 3JD, UK

* Corresponding author. Tel.: +44 114 222 5726; fax: +44 114 222 5793. E-mail address: s.huang@shef.ac.uk (S.-S. Huang).

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Abstract

This paper reports on a series of tests at elevated temperatures on connections between steel beams and H-section columns, both unfilled and partially-concrete-encased. Reverse-channel connections to both types of column, as well as flush endplate connections to partially-encased H-section columns, were studied. The experiments aimed to investigate the behaviour of beam-to-column connections subject to significant tying forces and large rotations in fire situations, and to provide test data for development and validation of simplified component-based connection models. It has been found that reverse-channel connections provide not only high strength, but also the high ductility which is required to reduce the possibility of connection fracture and to improve the robustness of buildings in fire.

Key words: Connection, High Temperature, Experiment, Robustness, Reverse-Channel, Endplate.

1 Introduction

Connections between columns and beams are vulnerable parts of a multi-storey building frame under accidental actions. Connection failure in fire was the cause of the well-documented total collapse of a 47-storey building in the World Trade Center, New York City [1, 2] on 11 September 2001. Under fire exposure, large additional forces and rotations can be generated in connections, due to a combination of restraint to thermal deformation and degradation of the mechanical properties of the construction materials at high temperatures. These forces are neglected by current robustness design rules, which are solely based on ambient-temperature behaviour. It is clearly important that design for robustness should prevent the fracture of connections, which could potentially cause disproportionate overall building collapse.

An effective way of preventing fracture of a connection is to enhance its ductility rather than its strength. Allowing connections to deform so that they accommodate the large axial deformations arising from thermally-induced changes in beam length reduces the internal forces which are caused if these changes are resisted. Reverse-channel connections (which connect the ends of a beam provided with flush endplates to channels which are welded at their toes to the outer faces of the supporting columns) have previously been suggested [3] as a practical method of connecting a steel beam to a column with access only to its outer face. It allows nuts and bolts to be placed and tightened on site. Apart from their practicality, recent experimental work on the use of these connections with concrete-filled tubular columns has also shown a ‘bonus’ of high ductility, which actually enhances the robustness in fire of the connections without requiring them to be stronger.

The Structural Fire Engineering Research Group of the University of Sheffield has collaborated with research teams at the universities of Manchester, Coimbra, Luleå and Prague, as well as with Tata Steel RD&T, in the European-funded project, COMPFIRE [4], which concerned the behaviour, and the robustness, in fire of practical connections between steel beams and two types of composite column. These were (i) concrete-filled steel tubes and (ii) partially-encased steel H-section columns. This paper reports on the experimental investigation of flush endplate and reverse-channel connections to partially-encased columns at elevated temperatures, together with three additional tests conducted on reverse-channel connections to bare steel H-section columns.

2 Test Setup & Measurements

2.1 *Furnace and Specimen Setup*

An existing furnace, reaction frame and loading device [5] at the University of Sheffield was used, with slight alterations to the previous setup in order to accommodate these tests. The electric furnace has an internal volume of 1.0m^3 and has one 300mm diameter hole on each side; the test setup is shown in Figure 1. The tests were designed to load full-size connections, which represent practical designs, by a combination of axial and shear forces and moment, and to allow adequate space in the furnace for the specimens to deform until failure occurred.

The beam-to-column connection was placed in the middle of the furnace. A cantilevered support beam of UC203×86 kg/m section extended from the left-hand hole in the furnace wall, and was connected to the column via an oversized endplate. For this connection, bolts were partially cast into the concrete infill when specimens using composite steel-concrete columns were tested. Two *Φ*25mm Grade 1030 Macalloy bars from the reaction frame were additionally used to support the column top.

The loaded end of the beam, the end connector and the bottom of the column were wrapped in thermal insulation blanket. The support bars and the support beam, as well as its connection to the column, were also protected by thermal blanket, and the two openings were filled with thermal insulation to prevent heat leakage. The connection, the column, and a significant length of the beam were left unprotected.

2.2 *Testing Procedure*

Steady-state elevated-temperature tests were conducted with the specimen heated until the temperatures of the exposed steel parts reached, and stabilised at, the specified temperature. Loading (under displacement control) was then applied at constant temperature until fracture occurred.

In the first test (a flush endplate connection to a partially-encased column), 12 thermocouples were installed to monitor the temperature distribution in the connection, as shown in Figure 2. From this test, differences in temperature between various locations of the exposed steel parts were determined to be less than 25°C before load was applied. It was not possible to achieve such small differences within the concrete infill of the composite column within any reasonable heating time, but the distribution was found to be reasonably symmetric throughout the cross section from the front to the back of the furnace, and reasonably uniform along the column length.

The load was applied through three *Φ*26.5mm Grade 1030 Macalloy bars, which were all connected to a central pin. One bar went into the furnace (hereafter referred to as the furnace bar) and was pin-connected to the beam end. The second (the link bar) was pin-connected to the reaction frame. The third (the jack bar) was connected to the head of the displacement-controlled loading jack. When the jack moved downward, the central pin was pulled down, thus applying an inclined tensile force to the beam end through the furnace bar. The angle α between the furnace bar and the axis of the beam determined the ratio of shear to tensile force applied to the connection. The initial value of α before testing was 55° for all tests. This angle was chosen from experience gained in previous experimental programmes [6, 7] using the same setup. To allow free movement of the furnace bar through the hole in the right-hand side of the furnace, the whole specimen was tilted backward by 25° in the furnace, and the clearance for the furnace bar in the right-hand hole in the furnace wall allowed large rotation at the connection.

2.3 *Instrumentation*

Measurement of specimen deformations in fire tests is not easy, because conventional approaches to measuring strain or displacement tend to lose reliability at high temperature. Digital cameras, together with image correlation techniques, offer a useful alternative to conventional methods, and can overcome many of these difficulties [8]. The furnace has two 100mm high x 200mm wide observation windows, one at the front and one on top. The specimen deformations were measured with two digital cameras, which conducted interval shooting (once per minute) through the two windows throughout a test. The cameras were synchronized to each other and to the data logging system. To ensure high-quality digital images, extra lighting was provided in the furnace through half of each observation window, and fans were used to prevent damage from over-heating of the cameras. Figure 3 shows examples of the images taken by the two cameras. Marks (*Φ*3mm ceramic rods inserted in drilled holes) were made on the column, beam web and reverse channel, from which rotations and displacements were calculated by processing the interval-shot images and tracking the movements of the marks.

The forces in the link and jack bars were determined from the strains measured by strain gauges attached to these two bars, which had been calibrated beforehand. In a previous test [5], in which the furnace was heated to 700°C and kept constant at this temperature for two hours, the temperature of the furnace bar had reached 120°C, but the other two bars remained near ambient temperature when a cooling fan was provided. At elevated temperatures the strain-gauge readings can be affected by temperature change, and the gauges themselves can be damaged by high temperatures. Therefore the force in the furnace bar was resolved from equilibrium of the forces in the link and jack bars. This approach had been validated against an ambient-temperature test, in which all three bar forces were monitored, showing calculation of the furnace-bar force to have a maximum discrepancy of 5%.

To calculate the force equilibrium, the inclinations of the three bars were measured by inclinometers and double-checked using a digital camera facing the central pin, as shown in Figure 4. This camera also performed interval-shooting, simultaneously with the other two cameras and with the data logging, throughout the tests. Marks (Φ3mm black dots) for image processing were made on the plates attached to the bars.

3 Test Programme and Specimens

Table 1 summarises the series of tests reported in this paper. Tests 1-4 tested two types (reverse-channel and flush-endplate) of connection to partially-encased H-section columns, as shown in Figure 5. Tests 1 and 2 were compared with 3 and 4 to assess the effect of connection type. For each type, two specimens of identical dimensions were tested at different temperatures to examine the influence of temperature increase. Tests 5-7 were conducted on reverse-channel connections to steel columns. The dimensions of the specimens in these three tests were identical, except that the widths and thicknesses of the reverse channels differed. These aimed to examine the effects of the thickness and the width/depth ratio of the reverse channel. The details of the specimen of Test 6 are shown in Figure 6. Comparing Tests 1-4 with 5-7 enabled investigation of the influence of the concrete infill of partially-encased columns and the effect of the reverse channel type (hot-rolled parallel-flange channel or channel cut from an RHS tube).

All columns were 254UKC89 kg/m, four of which were filled with concrete between their flanges to form the composite columns. The concrete infill was reinforced according to Eurocode 4 [9]. All beams were 305×165UKB40 kg/m, whilst their lengths differed to ensure that the initial position of the loaded end of the beam before testing was approximately the same for all tests. The beams connected to reverse channels were further shortened (by 20mm for hot-rolled channels and 40mm for those cut from tubes) because the reverse-channel connections were expected to have higher deformability than the flush endplates. A custom-made connector was bolted to the end of the beam, and the load was applied to it through a hinge. All steel parts were Grade S275, except for the UKC sections which were Grade S355. Differences between the actual dimensions of the steel sections and their nominal dimensions, given in the “Blue Book” [10], were negligible. Hexagon-head screws to ISO4017-M20x90-8.8 [11], hexagon nuts to ISO4032-M20-10 [12] and washers to ISO7091-20-100HV [13] were used. All bolt holes were 22mm in diameter. The cube strength of the concrete was measured on the day of testing.

When designing the reverse-channel connections, care was taken to ensure that the designs would be feasible and easy for practical on-site installation, by leaving enough clearance for site workers to fix bolts. For the reverse-channel connections to partially-encased columns, a narrow reverse-channel section was selected to avoid bending of the column flange. For all the reverse-channel connections, the beams were connected to reverse channels with a thick (20mm) endplate to ensure that the reverse channel was the most flexible and weakest component, as is desirable for ductility. The standard design of a flush endplate, according to the UK “Green Book” [14] was adopted, except that the bolt spacing was decreased to 70mm for connecting to the UKPFC150x75x18 on partially-encased columns. The same detail was used for the flush endplate connections to partially-encased columns, because the behaviour of flush endplates had previously been investigated [7]. Double nuts were used to bolt the beam endplate to the reverse channel, or directly to the column, in all cases except for the endplate connection to partially-encased column (Test 1) tested at 550°C. The fourth column of Table 1 indicates the number of nuts adopted in each bolt assembly.

4 Test Results

4.1 *Endplate/Reverse-Channel Connections to Partially-Encased Columns*

The results of the four tests on connections to partially-encased columns are given in Table 2. The ID numbers of the tests in this Table correspond to those in Table 1. The cube strength of concrete on the day of testing is denoted as σ_c. The load angle α is actually the sum of the inclinations of the axes of the beam and the furnace bar to the horizontal axis, measured photographically. It was not possible to set α to exactly the same value at the start of each test, and so the exact initial value is given in the Table as "Initial α". During each test the angle α changed progressively from its initial value, due to the re-alignment of the loading system and the rotation of the beam itself. Its value at the end of each test is shown as "Final α". The final two columns show the maximum resultant applied force and the connection rotation at maximum resistance.

Plots of the furnace-bar force versus the connection rotation for the four tests are given together for comparison in Figure 7, and Figure 8 shows the failure modes of the two endplate connections. The rotation of the connection is calculated as the rotation of the beam minus the rotation of the column. In the first test, on an endplate connection at 550°C, the specimen failed by thread-stripping on all the bolts. For this reason the force can be seen to decrease very rapidly after a rotation of 1.07°. To avoid similar behaviour in the remaining tests, double nuts were used to bolt the beam endplate to the column or to the reverse channel.

At 650°C the failure was also controlled by bolt behaviour, but the failure mode switched to tensile fracture due to the use of double nuts. For both tests, apart from the bolts, the specimen barely deformed. At 650°C the concrete cracked around the connection, but these cracks were modest and seemed to initiate from the holes accommodating the thermocouples. The resistance of the connection reduced rapidly with increase of temperature. Compared with the previous tests on specimens of similar dimensions [7], the use of a relatively thick (20mm) endplate enhances the resistance but significantly reduces the ductility.

The failure of the reverse-channel connections to partially-encased columns is shown in Figure 9. The ductility induced by the reverse channel gave this connection type around three times more rotational capacity, with comparable ultimate strength, than the flush endplate connections tested at the same temperature. For both of Tests 3 and 4, there was no noticeable deformation in the partially-encased columns or in the steel beams; neither was any damage found in the connection welds. The failure was controlled by the reverse channel. In both cases, the web of the reverse channel was pulled outwards at the top. Since the flanges of the hot-rolled channel were significantly thicker than the web, they remained straight, but the two flanges moved slightly towards each other at the top, due to the bending deformation of the channel web. Unsurprisingly, these deformations of the channel web and flanges became more severe with increasing temperature. The failure modes of these two tests differed. At 550°C the web of the reverse channel fractured in the regions adjacent to the flanges, whereas at 650°C the top rows of bolts punched through the bolt holes in the web of the reverse channel, and the channel web fractured around the bolt holes; these fractures eventually spread to the regions adjacent to the flanges.

4.2 *Reverse-Channel Connections to Steel Columns*

Figure 10 shows the aftermath of these tests. The reverse channels which were cut from SHS tube provided extremely high deformability (even higher than that of the hot-rolled channels) because their flanges were considerably thinner than those of the hot-rolled channels. In all three cases, the channel web was pulled outwards and the flanges turned inwards at the top, with deformation so large that the corners of the channel effectively unfolded. The bolts, especially those on the top rows, were stretched and bent. The column flange was also pulled outwards when this large deformation took place. These deformations of the column flanges increased as the channel width increased. At the bottom the channel web was pushed inwards, which bent the channel flanges as well, due to the rotation of the connection. There were no noticeable deformations in the steel beams and their endplates, because of the use of very thick endplates.

Tests 6 and 7 were successfully continued to failure. For both cases, the failure occurred at very large connection rotation, and was controlled by the top rows of bolts punching through their bolt holes in the reverse-channel web, which deformed significantly and locally around the holes. The global deformability of the reverse channel increases with increase of the channel width. The specimen with the widest reverse channel (Test 5) deformed so highly that it exceeded the space limits of the furnace (the furnace bar touched the furnace wall) and hence this test had to be stopped before failure occurred. It can be anticipated that its failure mode would either be the same as that of Tests 6 and 7, or be controlled by the tensile fracture of the top row of bolts as experienced in previous tests.

In addition, for the two tests using wider reverse channels (Tests 5 and 6), the welds between the top of the channels and column split. It should be noted that these did not occur during testing but were caused by the rapid drop of temperature after opening the furnace.

The results of these three tests are shown in Table 3, whose column titles are as defined for Table 2. Since Test 5 was stopped before failure, the values of force and rotation given for this test are the final measurements rather than those at maximum capacity. The relationship between the furnace-bar force and the connection rotations in these tests are compared in Figure 11. The width of the reverse channel of each specimen is marked on the corresponding curve on this figure. The curves for the two tests with wider channels do not have descending post-failure parts. This is because these two tests were stopped either at failure (Test 6) or before failure (Test 5), due to the excessively large deformations of the specimens which reached the space limit of the furnace. It is nearly certain that Test 5 would have carried on if this had been possible, which means that both the rotation capacity and ultimate strength would definitely have been higher than the final measurements. As observed from the tests, both the deformability of the reverse channel and that of the column flanges increase as the channel width increases. This is reflected by an increase of the rotational capacity of the whole joint as the channel width increases.

This set of tests was compared with Test 3 to assess the influence of the type and width of reverse channel, and the effect of the concrete infill on the performance of connections to partially-encased columns. These three specimens demonstrated both higher ductility and ultimate strength than those of Test 3. The rotational capacities of Specimens 5-7 were at least seven times greater than that of Specimen 3. This extremely large difference is due to:

- The greater deformability of the wider tube-cut reverse channels of Specimens 5-7 than that of the narrower hot-rolled channels used in Test 3;
- The high deformations of the flanges of the steel columns of Tests 5-7 compared to the minimal deformation of the composite column of Test 3.

5 Conclusion

This paper presents the results of an experimental investigation of the robustness at elevated temperatures of steel connections to two types of H-section column; (i) flush endplate and reverse-channel connections to partially-encased H-section columns, and (ii) reverse-channel connections to unfilled steel H-section columns. The two key parameters studied are the ultimate strength and rotational capacity of these connections, subject to combinations of tension, shear and bending moment. The test results showed that:

1. tying capacities decreased rapidly with increase of temperature, and the connections had little residual resistance at 650°C;

2. double nuts were necessary for the bolted connections to avoid thread-stripping failure at high temperature;

3. due to the use of a relatively thick (20mm) endplate, the failure of the endplate connections was controlled by bolts; thread-stripping with single nuts, and tensile bolt fracture when double nuts were used;

4. the use of thick endplates enhanced the ultimate strength of the end-plate connections but significantly reduced their ductility;

5. reverse-channel connections provided significantly enhanced ductility compared to flush endplate connections, without compromising the ultimate strength;

6. comparing the two types of reverse-channel connections tested (hot-rolled parallel-flange sections and those cut from tubes), the latter provided even higher ductility than the former with comparable tying capacity;

7. the failure of the reverse-channel connections was controlled by the reverse channel web, which fractured or deformed in different ways, depending on the test temperature, channel type and dimensions;

8. the global deformability (ductility) of reverse-channel connections increased with increase of the channel width;

9. when connecting reverse channels to H-section columns, the deformability of the column flange provided extra ductility, but this deformation of the column may not be desirable.

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Figure Captions

Figure 1	The test setup.
Figure 2	Temperature distribution during loading in Test 1.
Figure 3	Camera measurement of the specimen deformation.
Figure 4	Measurement of the load-bar alignment.
Figure 5	Geometry of connections to partially-encased H-section columns.
Figure 6	Geometry of the reverse-channel connection to steel column tested in Test 6.
Figure 7	The force-rotation relationships of the connections to partially-encased columns.
Figure 8	Failure of the flush endplate connections to partially-encased columns.
Figure 9	Failure of the reverse-channel connections to partially-encased columns.
Figure 10	Post-test photographs of the tests on the reverse-channel connections to steel H-section columns.
Figure 11	The force-rotation relationships of the reverse-channel connections to steel H-section columns.

Table Captions

Table 1 The test programme.

Table 2 Results of the tests on connections to partially-encased columns.

Table 3 Results of the tests on reverse-channel connections to steel columns.

Table 1

No.	Column	Connection Type	No. of Nuts	Temperature (°C)
1	P/E[1]	Flush endplate	1	550
2	P/E	Flush endplate	2	650
3	P/E	UKPFC[3]150x75x18	2	550
4	P/E	UKPFC150x75x18	2	650
5	UKC[2]	r/c[4] cut from SHS[5]250x8	2	550
6	UKC	r/c cut from SHS200x6	2	550
7	UKC	r/c cut from SHS180x6	2	550

[1] Partially-encased flange-infilled H-section column

[2] UK column

[3] UK parallel flange channel

[4] Reverse channel

[5] Square hollow section

Table 1 The test programme.

Table 2

No.	σ_c (MPa)	Initial α (°)	Final α (°)	Force (kN)	Rotation (°)
1	24	59.65	46.04	100.32	1.07
2	22	58.86	46.94	49.39	1.96
3	48	50.61	43.46	80.90	2.66
4	50	51.31	39.46	37.76	6.53

Table 2 Results of the tests on connections to partially-encased columns.

Table 3

No.	Initial α (°)	Final α (°)	Force (kN)	Rotation (°)
5	52.01	29.56	132.66	20.08
6	49.53	21.79	168.6	20.56
7	49.20	23.49	131.01	19.71

Table 3 Results of the tests on reverse-channel connections to steel columns.

Figure 1

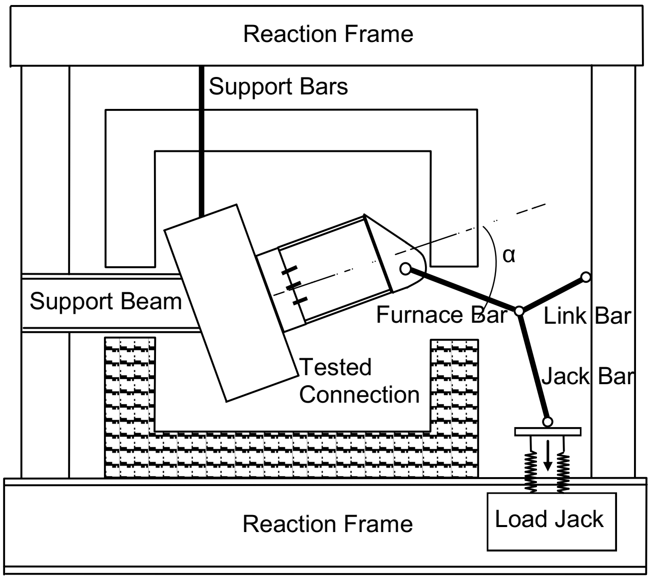
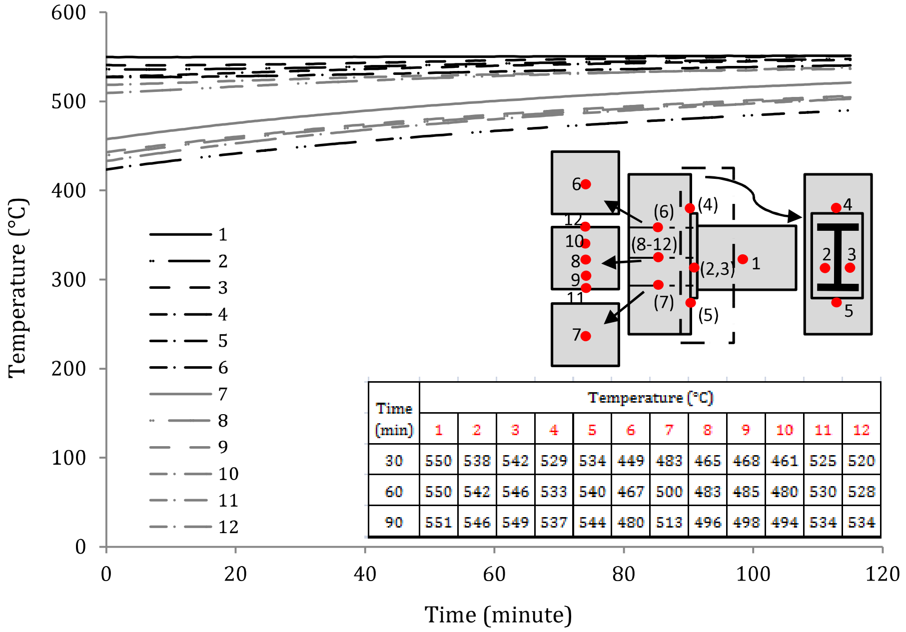


Figure 1 The test setup.

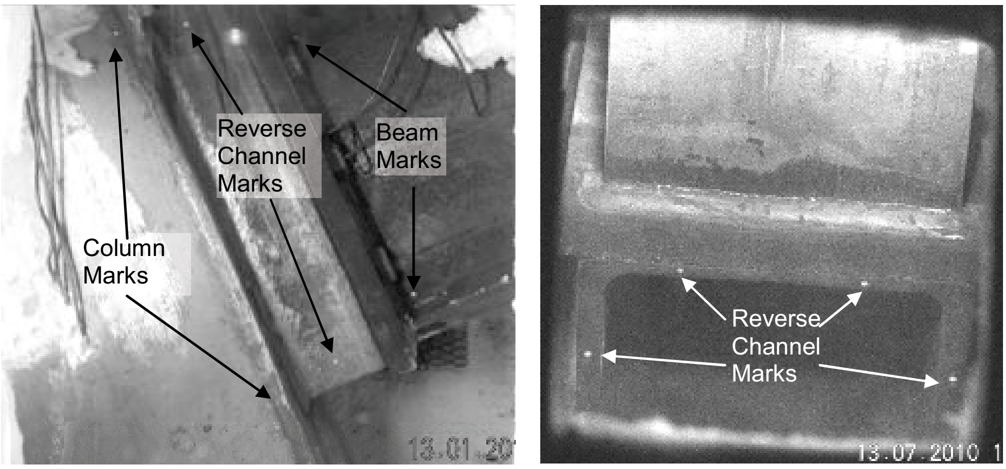
Figure 2



Time (min)	Temperature (°C)											
	1	2	3	4	5	6	7	8	9	10	11	12
30	550	538	542	529	534	449	483	465	468	461	525	520
60	550	542	546	533	540	467	500	483	485	480	530	528
90	551	546	549	537	544	480	513	496	498	494	534	534

Figure 2 Temperature distribution during loading in Test 1.

Figure 3



(a). View from the front window (b). View from the top window

Figure 3 Camera measurement of the specimen deformation.

Figure 4

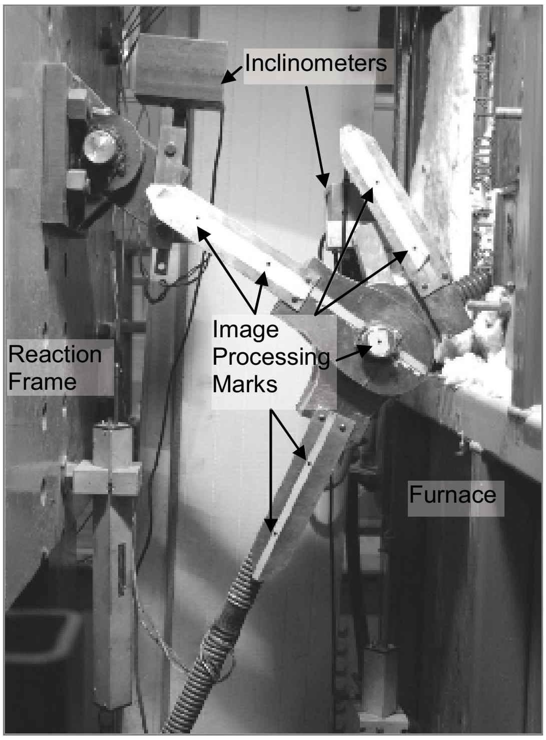
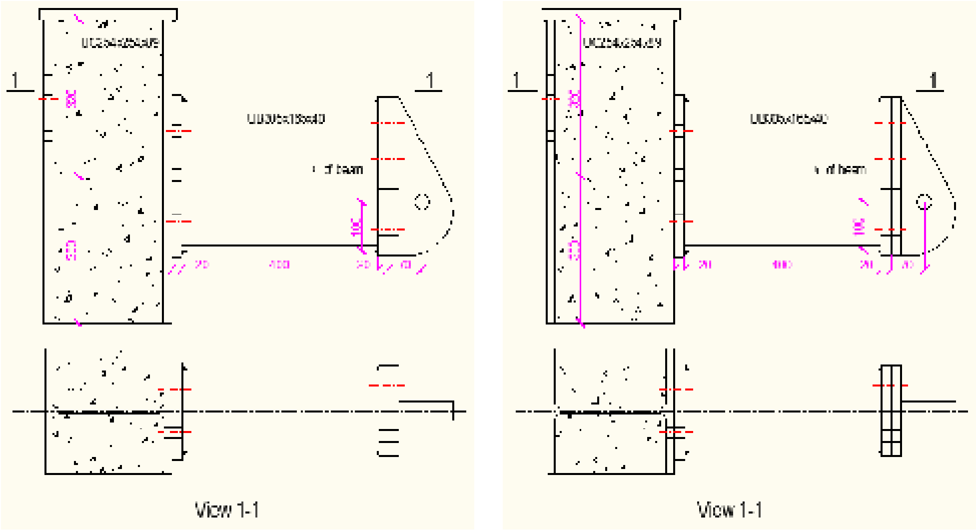


Figure 4 Measurement of the load-bar alignment.

Figure 5



(a). Flush endplate connection (b). Reverse-channel connection

<u>Figure 5</u> Geometry of connections to partially-encased H-section columns.

Figure 6

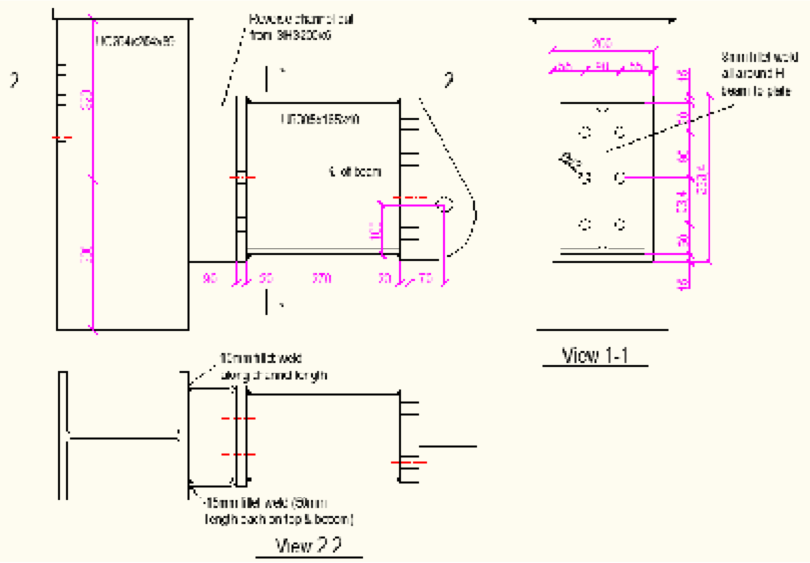


Figure 6 Geometry of the reverse-channel connection to steel column tested in Test 6.

Figure 7

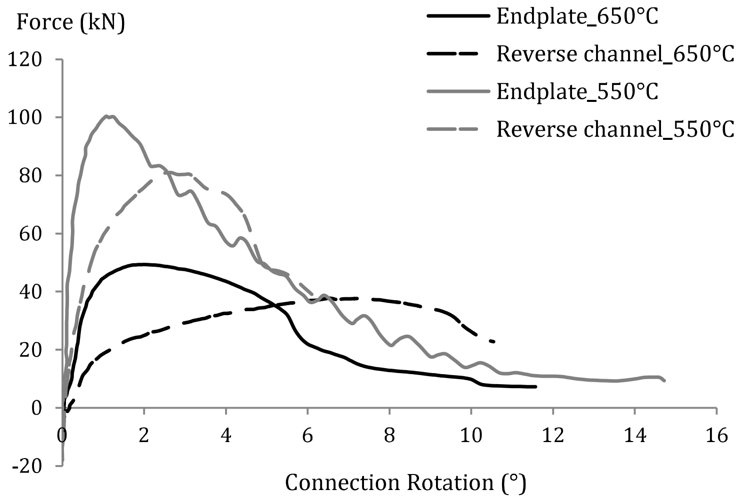
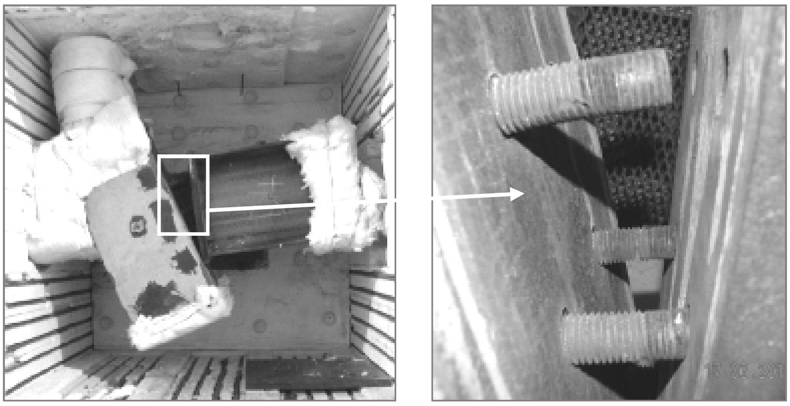
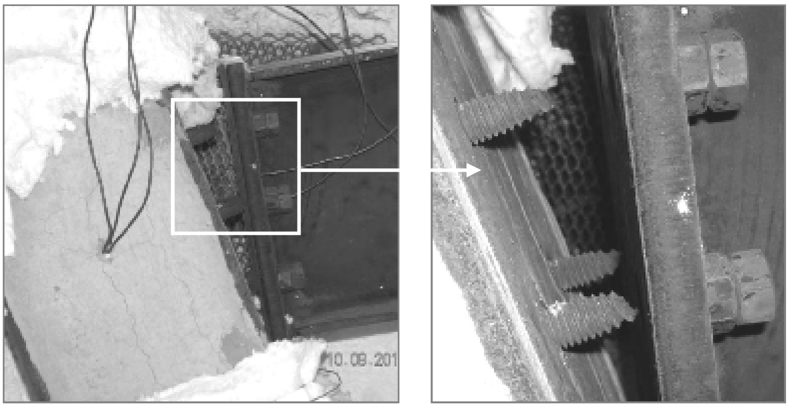


Figure 7 The force-rotation relationships of the connections to partially-encased columns.

Figure 8



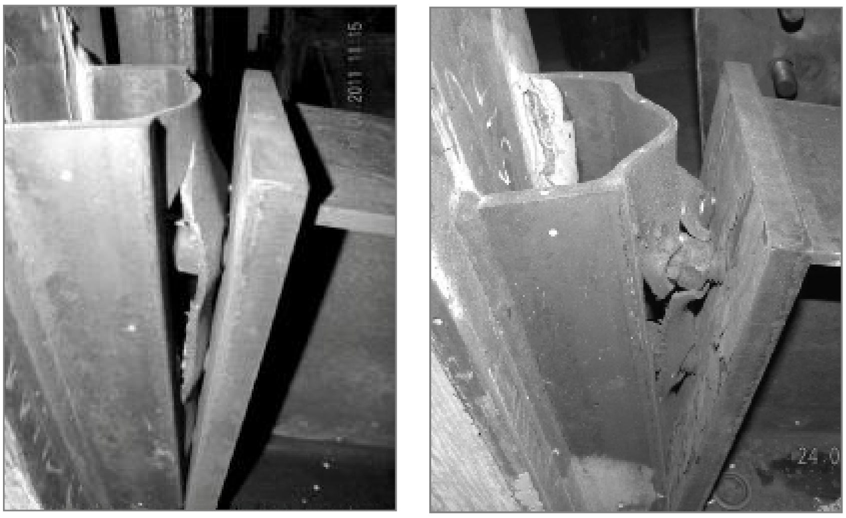
(a). Tested at 550 °C (Test 1)



(b). Tested at 650 °C (Test 2)

Figure 8 Failure of the flush endplate connections to partially-encased columns.

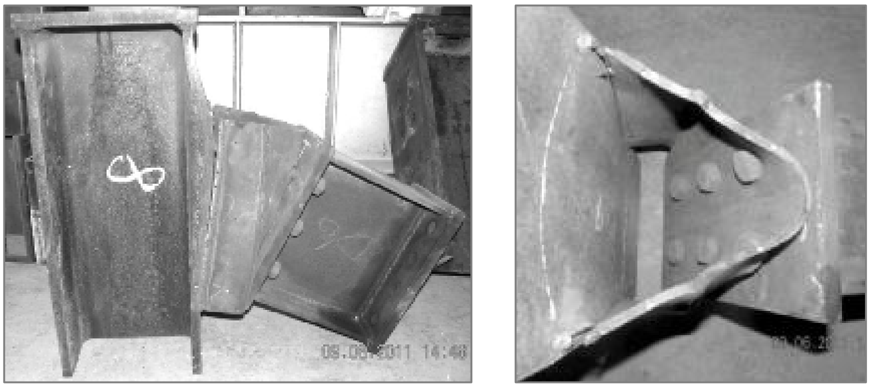
Figure 9



(a) Tested at 550 °C (Test 3)　　(b) Tested at 650 °C (Test 4)

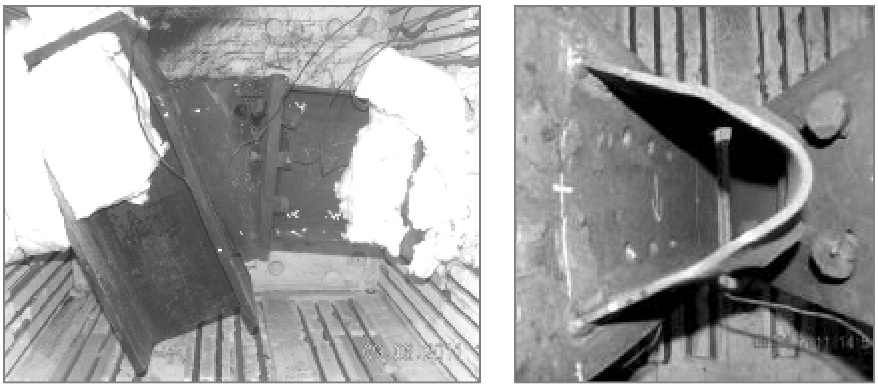
Figure 9 Failure of the reverse-channel connections to partially-encased columns.

Figure 10



(a) Reverse channel cut from SHS250x8 (Test 5)

(b) Reverse channel cut from SHS200x6 (Test 6)



(c) Reverse channel cut from SHS180x6 (Test 7)

Figure 10 Post-test photographs of the tests on the reverse-channel connections to steel H-section columns.

Figure 11

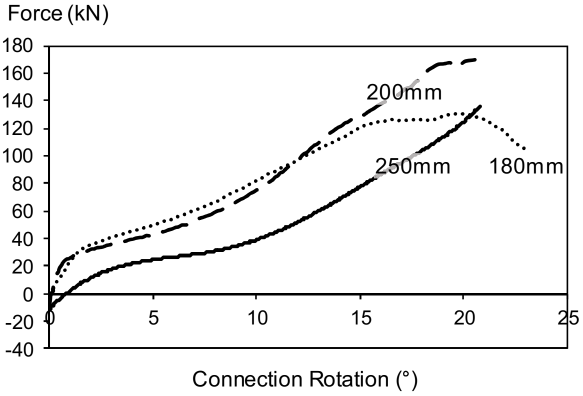


Figure 11 The force-rotation relationships of the reverse-channel connections to steel H-section columns.