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Behaviour of Cold-formed Thin-walled Steel Short Columns with Service Holes at Elevated Temperatures

M. Feng[1], Y.C. Wang[2], J.M. Davies[3]

Abstract

This paper presents the results of an experimental and numerical investigation into the axial strength of cold-formed thin-walled lipped channel sections with service holes under ambient and uniform high temperature conditions. Short columns of two different thickness with service holes under different temperatures have been tested, and analysed by using a variety of design methods and a commercial finite element program ABAQUS (1998). Three design methods (the British Standard BS5950 Part 5 (1987), Eurocode 3 Part 1.3 (CEN 1996) and the American Specification AISI (1996)) have been used in this paper. In the finite element analysis, both geometrical and material non-linearities are taken into account. The high temperature stress-strain relationships of steel are determined according to Eurocode 3, Part 1.2 (CEN 1995) and Outinen (1999, 2000, 2001). To enable BS5950 Part 5 (1987) and Eurocode 3 Part 1.3 (CEN 1996) to predict the ultimate strength of thin-walled columns with service holes, the AISI (1996) design method is introduced. To extend the capacity of the three design methods to deal with distortional buckling, the method of Young and Hancock (1992) for calculating distortional buckling capacity is introduced in these codes. The ambient temperature design methods for thin-walled columns in BS5950 Part 5 (1987), Eurocode 3 Part 1.3 (CEN 1996) and the AISI specification (1996) are modified to take into account changes in the strength and stiffness of steel at elevated temperatures. It is found that service holes can have a significant effect on the load capacity of a column regardless of the column temperature when thicker members are used. From extensive comparisons between the test results, modified codes' predictions and numerical analyses, it may be concluded that by adopting the aforementioned modifications, the current code design methods are suitable for evaluating the buckling behaviour of perforated short columns at elevated temperatures.

Keywords

Local buckling, distortional buckling, elevated temperature tests, design methods, perforated section, mechanical properties, fire resistance

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Introduction

Cold-formed steel members are used extensively in light steel construction as wall, roof and floor framing members. For easy installation of electrical wire and plumbing systems, pre-punched service holes are often introduced in the web of a beam or a column. The effect of a web opening in a column at ambient temperature has been investigated by many researchers (Yu and Davis 1973, Ritchie and Rhodes 1975, Loov 1984, Narayanan and Chow 1984, Sivakumaran 1987, Miller and Pekoz 1994, Pu 1999), however the structural performance of these kind of columns under high temperatures is not clear and there are very few studies of the fire performance of cold-formed thin-walled steel columns with holes. As a result, no design method is available for this type of construction.

In order to develop fire engineering design methods for cold-formed steel columns with service holes, a series of ambient and elevated temperature tests have been carried out at the Manchester Centre for Civil and Construction Engineering. This paper gives the results of a preliminary investigation into the axial strength of short cold-formed thin-walled channel columns with service holes under uniform high temperature conditions. After a description of the short column tests, this paper presents the results of theoretical studies using a number of modified current design methods and a commercial finite element package ABAQUS.

Short column tests

Test specimens

The ambient and elevated temperature tests were conducted in the fire-testing laboratory of the Manchester Centre for Civil and Construction Engineering. A total of 12 steady state tests were performed on lipped channels with service holes. All the channels were pre-hot dip galvanised to BS EN 10147 with a G275 coating. The steel grade is S350 GD+Z with a minimum yield strength of 350N/mm^2. The results of tensile coupon tests give much higher yield strengths. Figure 1 shows the profile of test specimens and also gives their nominal dimensions.

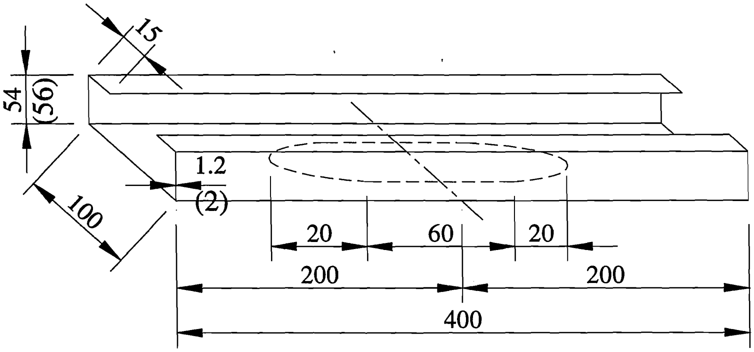


Figure 1: Dimensions of test specimens

The high temperature tests were conducted at 400°C and 550°C, and two replicate tests were performed for each high temperature and cross-section. Two ambient temperature tests were also carried out to provide reference data for the high temperature tests.

Test set up

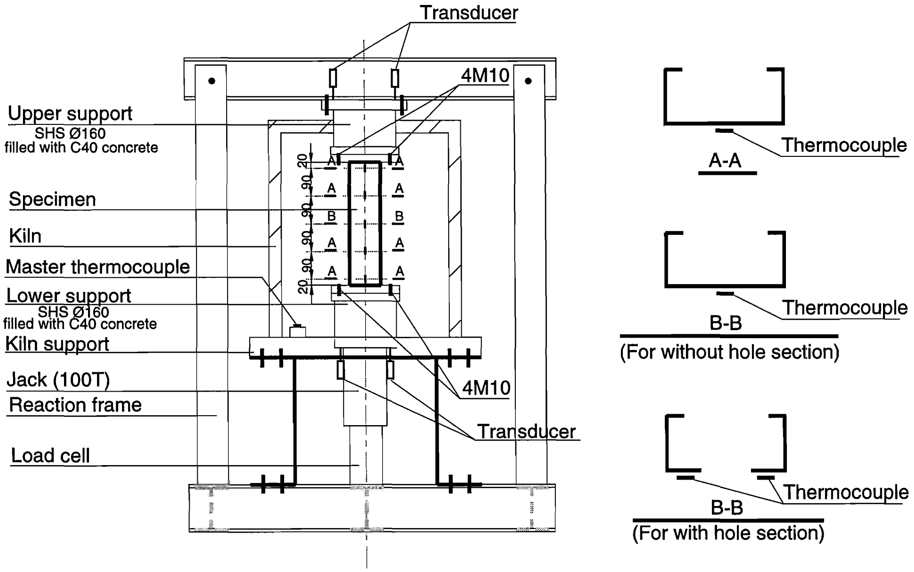


Figure 2: Test rig

The tests were conducted in a purposed built rig. As shown in Figure 2, the rig is made of a reaction frame, a loading jack and an electrically heated kiln. A 100T hydraulic jack was used to apply a compressive axial force to the test specimen. An electrically heated kiln was placed in the reaction frame to be used to increase the steel temperature. The specimen was fixed between the upper and lower supports, which were bolted to the reaction frame. The support end plates were in direct contact with the test specimen, allowing each individual plate of the test column to rotate out of plane but preventing the in-plane rotation. In each test four displacement transducers were used, two at the top and two at the bottom, as shown in Figure 2. It is assumed that due to the rigidity of the supporting blocks, relative to the test specimen, the measured displacements were those of the test specimen. To evaluate any rotation at the end of the test specimen, the displacement transducers at each end were placed at two opposite corners. Due to high cost and the perceived small benefit, no strain was measured except for the tests at ambient temperature.

In order to check whether the test specimens would be uniformly heated, an unloaded test was performed to monitor temperature distribution inside the kiln. Nine thermocouples were attached to a lipped channel specimen at three cross-sections. Every cross-section had three thermocouples, one at the centre of the web and two near the junctions of the lip and the flange, as shown in Figure 3.

During the temperature distribution test, the kiln temperature was raised to 200°C, 500°C and 700°C and then hold at these temperatures for a period of time to allow the kiln and specimen temperatures to reach equilibrium.

The results of the temperature distribution test show that the temperature distribution within the kiln was relatively even after 15 minutes. The difference between different measurements was less than 5%, as shown in Figure 3.

For the loading test, each test specimen was placed in the kiln and checked by eye to be square. However, due to inaccuracy in cutting and imprecision in placing the specimen, it is inevitable that the specimen may not be loaded exactly in the axial direction and sometimes an initial moment may be induced.

Elevated temperature tests were carried out under the steady state condition. The kiln temperature was raised to the desired level and then kept for about twenty minutes to ensure that the specimen reached uniform temperature. During the heating process, the specimen expanded almost freely without any restraint to its thermal expansion. When the specimen temperature reached the desired level, axial compression was applied slowly with an increment of 1kN. The test was terminated when the applied load could not be increased further, indicating that the ultimate load was reached.

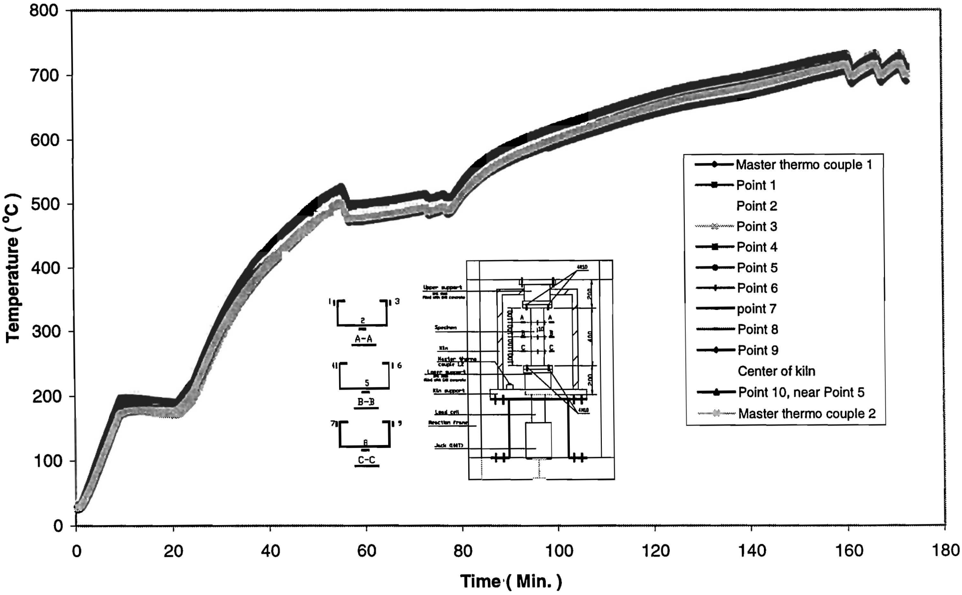


Figure 3: Temperature distribution inside kiln

Tensile coupon tests were carried out at ambient temperature to determine the mechanical properties of steel. For each type of channel section, two samples were taken from the web and one sample from each flange, not including the corner. From these tests, the mechanical properties, include elastic modulus and yield stress based on the 0.2% proof stress, were obtained. The results of the tensile coupon tests are given in table 1 and will be used to determine the appropriate stress-strain curves for numerical analysis at elevated temperatures.

Table 1: Tensile coupon test results

Test No.	Mean yield stress (N/mm^2)	Mean ultimate stress (N/mm^2)	Mean elastic modulus (N/mm^2)
Lipped 100x54x15x1.2	410.58	526.02	186.95
Lipped 100x56x15x2	406.00	494.59	186.65

Test results

Table 2: Critical Loads and Failure Modes for Test Specimens

Section type	**Temperature (°C)**	**Specimen ID.**	**Failure load (kN)**	**Failure mode**	**Average reduction in strength compared to solid section**
Lipped channel 100x56X 15X2	Amb	Lip2a3	111.1	Local buckling	10%
		Lip2a4	116.94	Local buckling	
	400	Lp2bh140	73.62	Distortional buckling and bending	20%
		Lp2bh240	83.78	Distortional buckling and bending	
	550	Lp2ch155	48.01	Distortional buckling	-5%
		Lp2ch255	47.99	Distortional buckling	
Lipped channel 100x54X 15X1.2	Amb	Lip12a3	54.86	Local buckling	0%
		Lip12a4	53.48	Local buckling	
	400	Lp12ch140	39.93	Local buckling and bending	10%
		Lp12ch240	43.02	Local buckling and bending	
	550	Lp12bh155	22.64	Local, distortional buckling and bending	5%
		Lp12bh255	25.17	Local, distortional buckling	

The failure loads and failure modes are given in Table 2. The replicate tests produced very similar behaviour, both in terms of the failure load and the failure mode. For comparison, table 2 also gives the average reduction in strength relative to that of a solid section (Feng el et 2001). For lipped channels 100x56x15x2, the load capacity of a solid section is about 10%, 20% and -5% higher than the one with a service hole. The load capacity of lipped channel 100x54x15x1.2 with a service hole is about 0%, 10% and 5% lower than that without a service hole. The difference for the thinner section is smaller because the service hole is almost entirely within the ineffective section of the solid section. For both sections, the effect of a service hole at 400°C appears to be particularly large. This may be due to the relatively higher residual elastic modulus compared to the yield stress of steel at this temperature, thus increasing the effective area of the web. At 550°C, the failure loads of lipped channel 100x56x15x2 with holes are slightly higher than those without holes, and the failure modes for sections with holes are distortional buckling and for solid sections are a combination of local buckling, distortional buckling and bending due to initial imperfections. The initial imperfect contact at boundary, which induced an initial moment on the specimen, is the main reason to lead to a different failure mode and a lower load capacity for solid lipped channels 100x56x15x2.

Design Calculations

At present, there is no direct design method to deal with the strength of cold-formed thin-walled columns with service holes. All existing design methods need some modification. This paper will use the British Standard BS5950 Part 5 (1987), Eurocode 3 Part 1.3 (CEN 1996) and AISI (1996) with the following modifications.

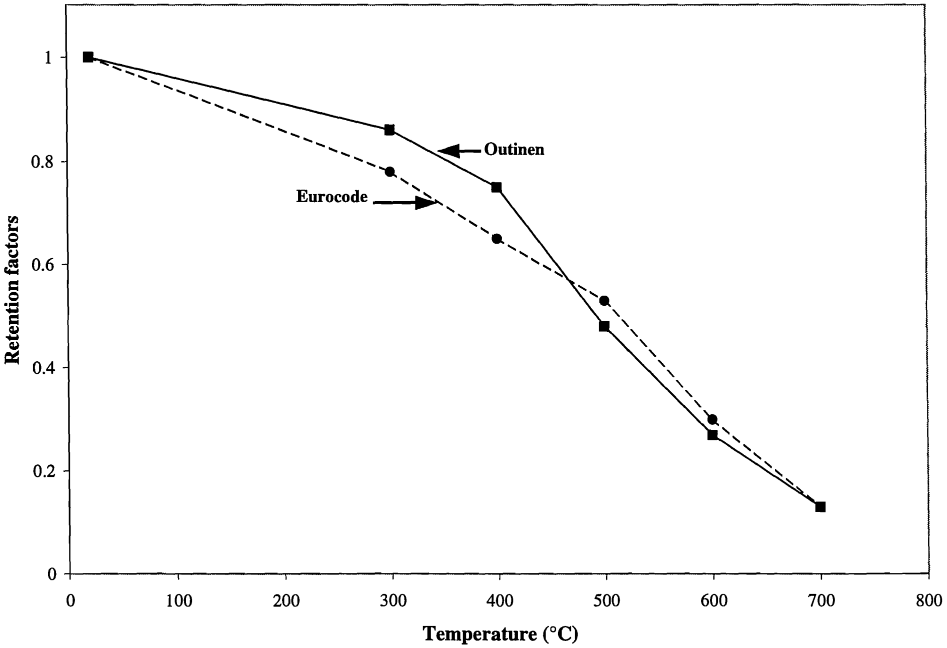


Figure 4: Strength retention factors for 0.2% proof stress

Elevated temperatures

According to Ranby (1998), when predicting the column failure load under a uniform elevated temperature, the reduced 0.2% proof stress and the reduced elastic modulus should be used. Figure 4 shows the strength retention factors for the 0.2% proof stress of Outinen et al (1999, 2000, 2001) and Eurocode 3 Part 1.2 (CEN 1995), which are used in this study. This modification applies to all design codes. Outinen et al (1999, 2000, 2001) and Eurocode 3 Part 1.2 (CEN 1995) use the same reduced elastic modulus at elevated temperatures. Although not shown here, these reduced elastic modulus at elevated temperatures have been used in this study.

Distortional buckling

Distortional buckling in a compression member such as a lipped channel section usually involves rotation of the flanges and the lip around the flange-web junctions. In BS5950 Part 5 (1987), Eurocode 3 Part 1.3 (CEN 1996) and AISI (1996), distortional buckling is not explicitly considered. In this study, the method of Young, Kwon and Hancock (1992) is introduced to the three design methods for thin-walled structures in order to predict the distortional buckling load. In this method, the flanges are assumed to be undistorted and can be considered in isolation. The design equations are:

$$\frac{b_e}{b} = 1 \quad \text{for } \lambda \leq 0.673 \qquad (1)$$

$$\frac{b_e}{b} = \sqrt{\frac{\sigma_{de}}{f_y}}\left(1 - 0.22\sqrt{\frac{\sigma_{de}}{f_y}}\right) \quad \text{for } \lambda \geq 0.673 \qquad (2)$$

where, b is the width of the flange plate, b_e is the effective width of the flange plate due to distortional buckling, f_y is the yield stress and σ_{de} is the elastic distortional buckling stress. The distortional buckling stress may be calculated according to Lau and Hancock (1987). The plate slenderness for distortional buckling is calculated using

$$\lambda = \sqrt{\frac{f_y}{\sigma_{de}}} \qquad (3)$$

Service hole

Of the three different design methods, only the AISI method (1996) considers plates with one service hole. Refer to Figure 5, the AISI recommendations are:

- if $a/h < 0.38$, the effective width should be determined by assuming a solid web;
- if $a/h \geq 0.38$, the effective width of the web should be determined by assuming that the web consists of two unstiffened elements adjacent to the hole and their effective widths calculated accordingly.

These recommendations will be adopted in calculations using BS5950 and Eurocode 3.

Figures 6-8 show comparisons between the test failure loads and various predictions using retention factors for the 0.2% proof stress of Outinen et al (1999, 2000, 2001) under steady state test condition and the strength retention factors of Eurocode 3 Part 1.2 (CEN 1995). The elastic modulus is reduced according to Eurocode 3 Part 1.2 in all calculation. From these results, it can be found that the predicted failure loads based on the Outinen (1999, 2000, 2001) property model give a slightly better aggreement with the test results than the EC3 (CEN 1995) property model. Considering different design methods, the predicted results indicate very good agreement, less than 10% in difference, between the three codes, as shown in Figure 9

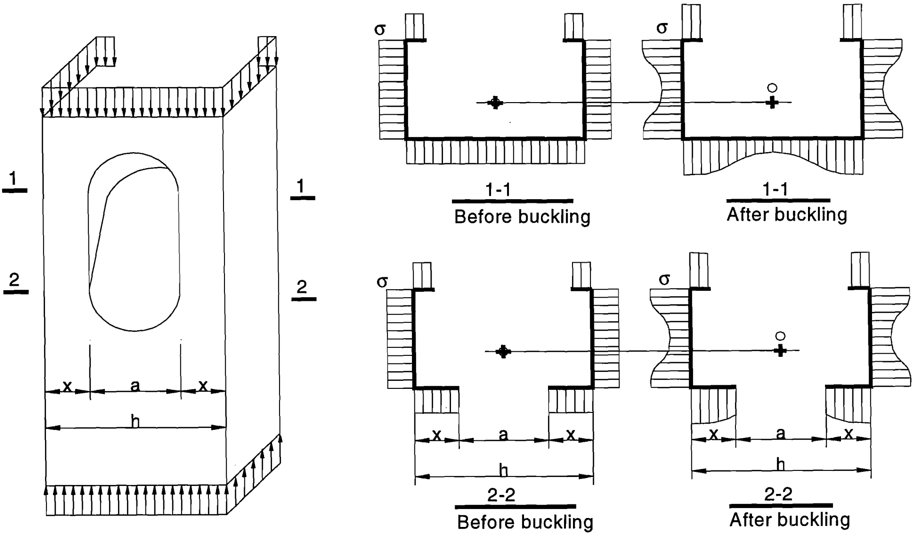


Figure 5: Lipped channel with a service hole

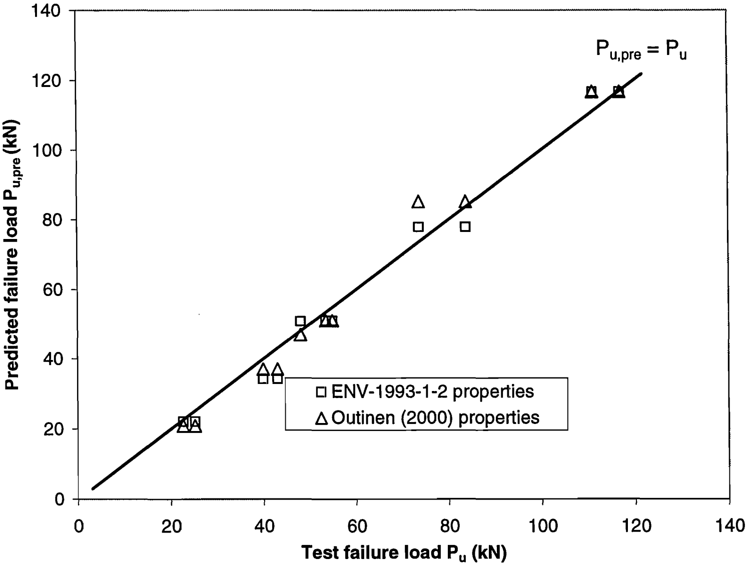


Figure 6: Comparison between test failure loads and BS5950 predictions

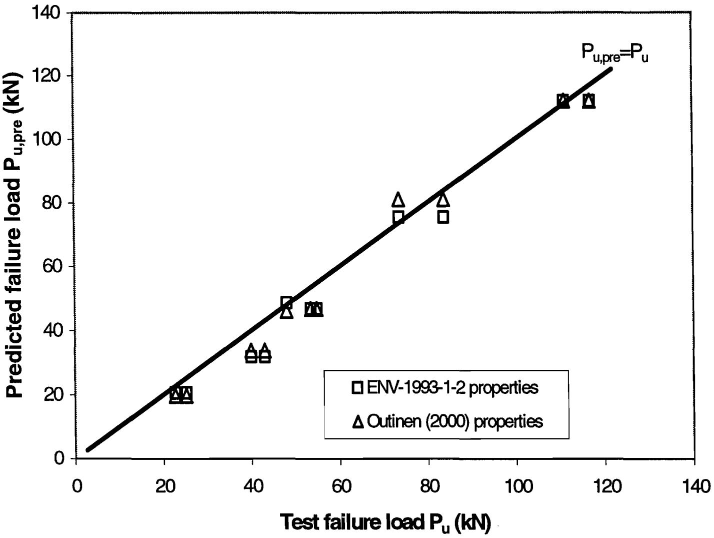


Figure 7: Comparison between test failure loads and Eurocode 3 predictions

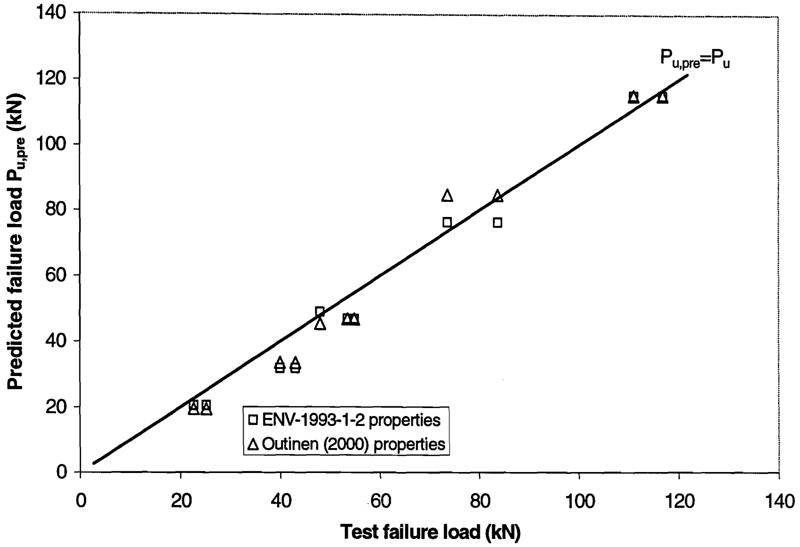


Figure 8: Comparison between test failure loads and AISI predictions

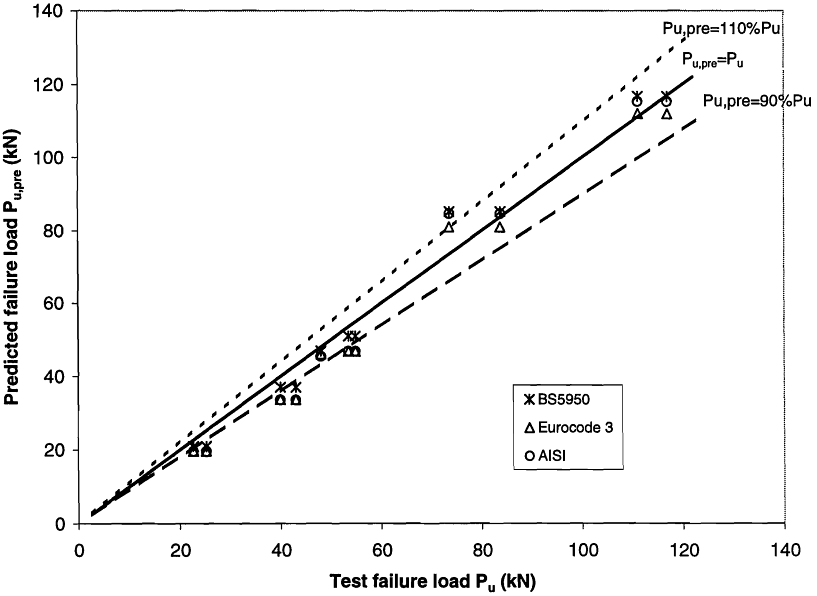


Figure 9: Comparison between test failure loads and predictions of BS5950, Eurocode 3 Part 1.3 and AISI, using Outinen properties

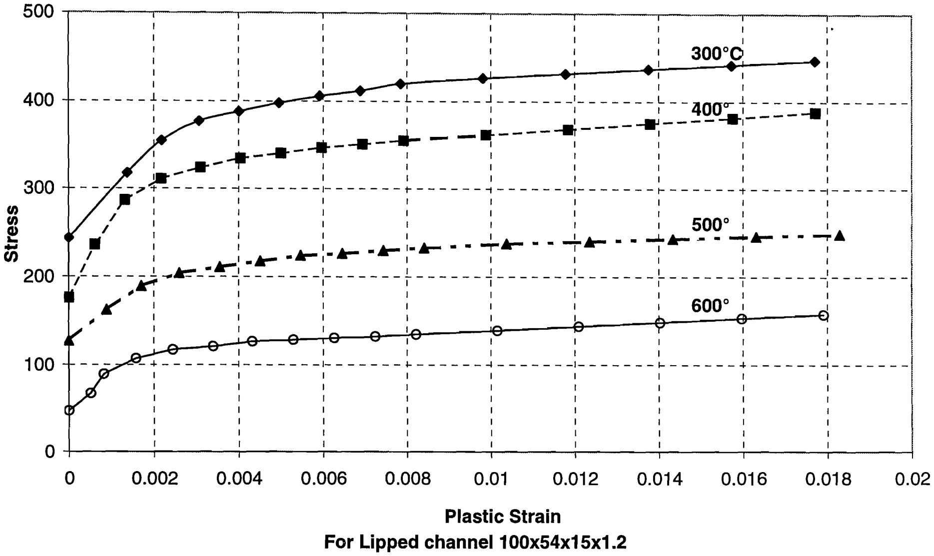
Finite element analysis

The tests were also simulated by a commercially available FE package ABAQUS in which both material and geometric non-linearities were considered. Since the tests were conducted under the steady state condition, the following assumptions were adopted in finite element analyses:

- The cross-sectional properties were modelled using the measured centre line dimensions.
- The steel column was at the same temperature.
- All lateral displacements of the column ends were prevented. One end of the specimen was free to move axially, the other end being fixed. In-plane rotations of each plate at the ends were prevented, but out-of plane rotation was allowed and twist was prevented at both ends.
- Only uniform axial compressive loads were imposed to the ends of the specimens.
- The stress-strain relationships at high temperatures used in finite element analyses are based on the models in Eurocode 3 Part 1.2 and Outinen(1999, 2000), but modified by the appropriate measured yield stress and elastic modulus. Eurocode 3 Part 1.2 gives mathematical equations for the stress-strain relationships of steel at elevated temperatures and can be directly used in this study if the yield stress is based on the stress at 2% total strain. Since Eurocode 3 Part 1.2 only given retention factors of the 0.2% proof stress for cold-fored steel, a suitable modification has been done so that the mathematical equations for the stress-strain relationships of steel at elevated temperature in Eurocode 3 Part 1.2 can be used directly. The modification is to select appropriate stresses at 2% total strain so that retention factors for the 0.2% proof stress obtained from using the mathematical stress-strain relationships become equal to the Eurocode 3 Part 1.2 values for cold-formed steel. To use the stress-strain relationships of Outinen, since the ambient temperature strengths of steel from this study are different from those used by Outinen, modifications are necessary. The final stress-plastic strain curves to be used in ABAQUS at different temperatures are given in Figure 10. To obtain these curves, the plastic strains were extracted from the stress-total strain curves reported in Outinen (1999). At the same plastic strain, the stress of steel used in ABAQUS simulations was obtained by multipling the stress in the Outinen stress-strain curve by the ratio of the test coupon 0.2% proof stress to the 0.2% proof stress of Outinen.
- The initial imperfection of each column were according to the eigenvalue that gives a deformation pattern similar to that observed, with the maximum value as the section thickness.

The numerically simulated failure loads obtained from ABAQUS are compared with the test results in Figure 11.

Table 3 shows a comparison of the simulated failure modes with observed failure modes. From this table, it can be seen that ABAQUS can simulate the failure modes accurately provided the appropriate boundary conditions, material properties and initial imperfections are used.



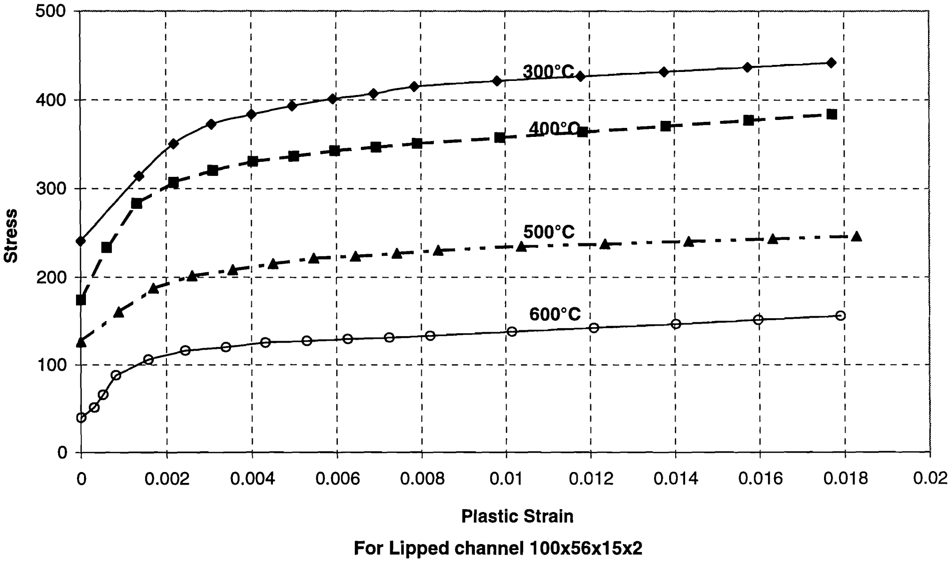
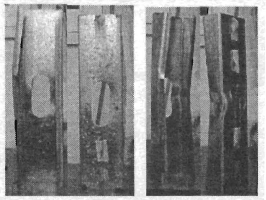
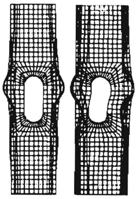
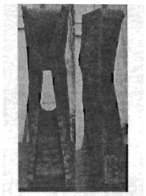
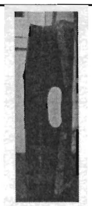
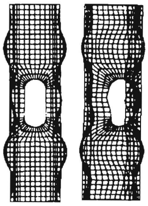
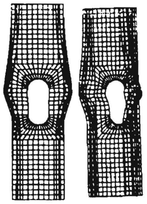
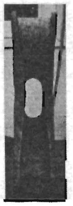


Figure 10: Input stress-plastic strain relationships according to Outinen (1999, 2000, 2001)

Table 3: Comparison of test failure modes and ABAQUS simulations

	Observed failure modes		**ABAQUS simulation failure modes**	
	Case 1	**Case 2**	**Case1**	**Case 2**
Lipped channel 100x54x15x 1.2 with hole at 400°C	 **Lp12ch140 Lp12ch240**			
Lipped channel 100x54x15x 1.2 with hole at 550°C	 **Lp12bh155**	 **Lp12bh255**		
Lipped channel 100x56x15x 2 with hole at 400°C	 **Lp2bh140**  **Lp2bh240**			
Lipped channel 100x56x15x 2 with hole at 550°C	 **Lp2ch155**  **Lp2ch255**			

Note: 1. Cases 1 and 2 in observed failure modes show different failure modes from replicate tests with the same conditions.

2. Cases 1 and 2 in ABAQUS simulations show different failure modes with different initial imperfections.

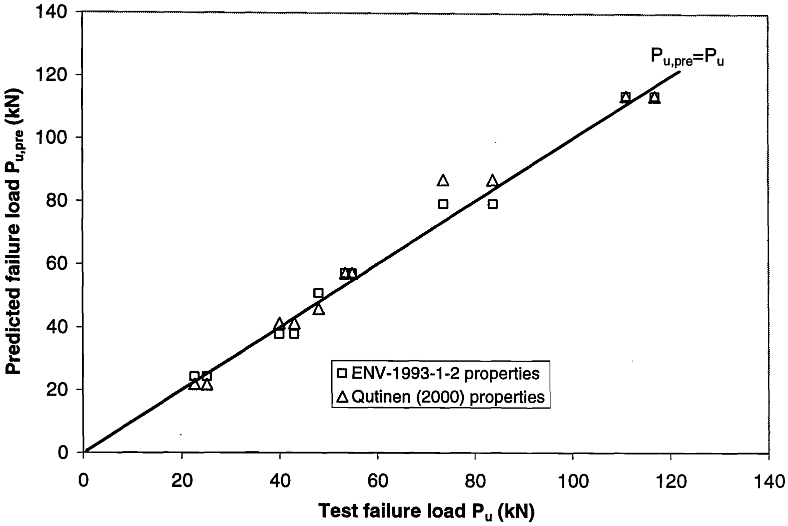


Figure 11: Comparison of failure loads between test results and ABAQUS simulations

Conclusion

In this paper, the behaviour of cold-formed thin-walled steel short columns with service holes under different uniform high temperatures has been studied. A total of 12 short column tests, including 4 ambient tests and 8 high temperature tests, were conducted to evaluate their local and distortional buckling behaviour. The results of the high temperature tests were analysed using the finite element method ABAQUS, in which both geometrical and material non-linearities were included, and also compared with predictions using three modified code methods. The following conclusions may be drawn:

- Service holes can have a significant effect on the load carrying capacity of a column when large holes and thicker members are used. It is suggested that the effective width of a perforated column may be calculated as in AISI (1996).
- Using the Outinen (1999, 2000, 2001) material properties, the modified code methods and ABAQUS simulations give accurate predictions. However, predictions using the Eurocodes 3 value are also acceptable.
- The FEM program ABAQUS can be used to simulate detailed behaviour of cold-formed steel columns with holes accurately, provided the appropriate boundary conditions and material properties are adopted.

Notation

a	width of opening
b	width of the flange plate
b_e	effective width of the flange plate due to distortional buckling

f_y yield stress
h width of web
σ_{de} elastic distortional buckling stress

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