FIRE TESTS ON BEAMS WITH CLASS 4 CROSS-SECTION SUBJECTED TO LATERAL TORSIONAL BUCKLING

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Abstract

This paper describes experimental research in behaviour of laterally unrestrained beams (I or H section) of Class 4 constant or variable cross-sections at elevated temperatures. Preparation and design of experiments is described. The design of the test set-up was made by FE modelling and the experiments followed. The test results are given. Future numerical investigation is planned for full understanding of the fire behaviour of steel members of Class 4 cross-sections considering both welded and hot-rolled I or H shape steel profiles.

Keywords: steel structure, beam, slender section, lateral torsional buckling, fire design

INTRODUCTION

In the last decade, structural fire design became an inseparable part of structural design. The accuracy of design is essential regarding safety of the structure as well as its economy, concerning also possible additional fire protection costs. Therefore, well representing design models, which simulate the actual behaviour of the structures exposed to fire, are crucial as a base of such design.

Recent design standard EC3 part 1-2 (EN 1993–1–2) contains simple rules for design of Classes 1 to 3 cross-sections under the fire. These rules were based on many experimental and numerical analyses and modified during last decade.

Determination of the bending resistance for members subjected to lateral torsional buckling of Classes 1to 3 cross sections at elevated temperature is based on the same principles as the design at room temperature according to EC3 part 1-1 (EN 1993–1–1). However it differs in using one imperfection factor only for all types of cross-sections. Informative Annex E of the standard recommends using the design formulas for slender (Class 4) sections as well. But there is a restriction of critical temperature value and different reduction of yield strength is used (0.2 % proof strength for Class 4 instead of 2.0 % proof strength for stockier Class 1 to 3 sections).

Only few experimental data on which the potential refining of the provisions could be base on have been collected until now. Therefore, further numerical investigations in lateral-torsional buckling at fire will be made for the slender sections. For the non-uniform members (variable section height), a limited procedure for lateral torsional buckling verification is given in EC3 part 1-1. This is applicable for room temperature only. A development of more general design model is planned to be published for elements at elevated temperature.

1 DESCRIPTION OF THE SPECIMENS

The three tests vary in the cross-sections and considered temperature. Table 1 presents the tests, two beams with constant cross-section and one with variable cross-section (height of the web varies linearly from one end to another). The temperature was chosen based on the most significant changes of plate slenderness calculated using the elevated temperature reduction factors.

Tab. 1 Tested sections

Test number	Figure	Web*	Flange*	Temp [°C]	Non-dimensional slenderness	
					**	***
Test 1 **IW460/150/4/5**	1a	Class 4 $\bar{\lambda}_{\mathrm{P}} = 1.33$	Class 4 $\bar{\lambda}_{\mathrm{P}} = 1.13$	450	1,06	0.86
Test 21 **IW460/150/4/7**	1b	Class 4 $\bar{\lambda}_{\mathrm{P}} = 1.23$	Class 3 $\bar{\lambda}_{\mathrm{P}} = 0.81$	450	0.97	0.79
Test 3 **IW585-495/150/4/5**	1c	Class 4 $\bar{\lambda}_{\mathrm{P}} = 1.45 - 1.76$	Class 4 $\bar{\lambda}_{\mathrm{P}} = 1.13$	650		

NOTE * Classification and plate slenderness - according to EN 1993-1-2 ($\varepsilon = 0.85[235/f_{\mathrm{y}}]^{0.5}$)

** Reduction of material properties - according to EN 1993-1-2 tab. 3.1. ($\bar{\lambda}_{\mathrm{LT},\theta} = \bar{\lambda}_{\mathrm{LT}}[k_{\mathrm{y},\theta}/k_{\mathrm{E},\theta}]^{0.5}$

where $k_{\mathrm{y},\theta}$ is is reduction factor (relative to fy) for effective yield strength of Class 1 to 3 sections)

*** Reduction of material properties - according to EN 1993-1-2 Annex E ($\bar{\lambda}_{\mathrm{LT},\theta} = \bar{\lambda}_{\mathrm{LT}}[k_{0.2\mathrm{p},\theta}/k_{\mathrm{E},\theta}]^{0.5}$

where $k_{0.2\mathrm{p},\theta}$ is reduction factor (relative to fy) for the design yield strength of hot rolled and welded class 4 sections)

1 To avoid shear failure, a thicker plate was used for the side spans. Therefore, two thicknesses were used for the tested beam. 4 mm in the middle span and 5mm in the sidespan.

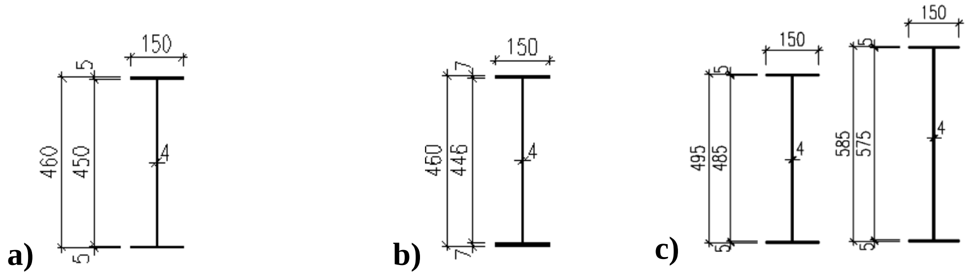


Fig. 1 Cross-section: (a) Test 1; (b) Test 2; (c) Test 3

2 NUMERICAL MODEL DEVELOPMENT

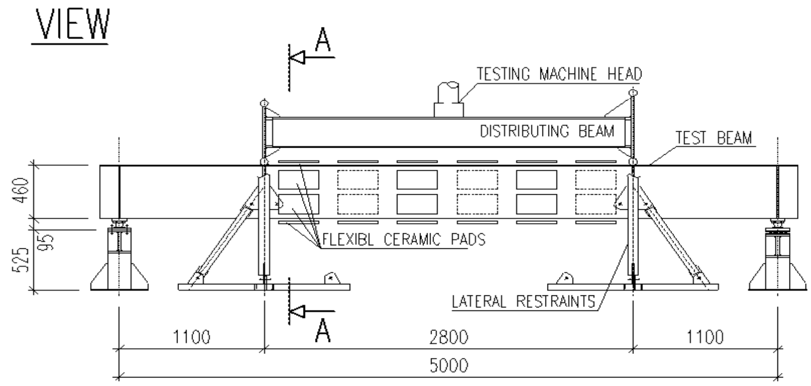
First of all, preliminary numerical model for calibration of experiments was made using FE software ABAQUS. The beam was meshed using rectangular shell elements type S4.
Failure mode obtained from elastic buckling analysis was used as the initial geometric imperfection shape for post buckling analysis. The initial local and global imperfections were considered using following amplitudes:

- global = L/1000 (where L is distance between lateral supports)
- local = B/200 (where B is flange width)

In order to achieve LTB failure mode as main failure mode, different boundary condition and load distributions were modelled. The introduction of stiffeners and different thickness of stiffeners were considered too. Finally, in the location of supports, the pin point supports (one node only) were proposed. The point support allows no displacement in transverse direction as it is much easier to reach in the test and free torsion of the end sections. It has a negligible influence on the resistance and buckling shape. Significant lateral displacement could be observed as result of using pin supports. In the locations of load application, the top and bottom flange were provided with lateral restraints. Elevated temperature was used for the internal span only. Adjacent cross-section and stiffeners were considered at room temperature.

3 DESCRIPTION OF THE EXPERIMENTS

During the experiments a simply supported beam with two equal concentrated point loads applied symmetrically was tested. The heated central part of beam where the temperature was aimed to be constant and uniform was therefore subjected to a uniform bending moment. The fire test was performed on steady state, it means that the beam was first heated and then the loads were applied, until failure. The test was controlled by deflection which was estimated as 3.5mm per minute. Final deformation at the end of experiment was 50 mm at midspan. This procedure was the same for all three beams. Figure 2 shows a scheme of experiment.



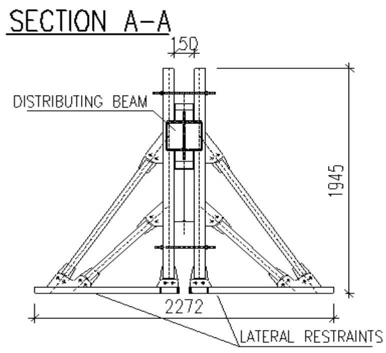


Fig. 2 Scheme of experiment

Fig.3 Lateral restraints

3.1 Test set up equipment

Test equipments respected boundary conditions based by the numerical analyses. Their implementation is described below. Figure 3 shows the lateral restraint of the top and bottom flanges in the locations where the load is application (at the edge of heated part).The end supports were considered just by one point support. It was done using a steel sphere bearing placed between two steel plates. As was already described, both end supports allowed free torsion of the end cross-section. One restrains deformations in all directions. The second allows free horizontal displacement in the direction along the beam axis. Figure 4 and 5 shows the fixed pin point support of the beam.

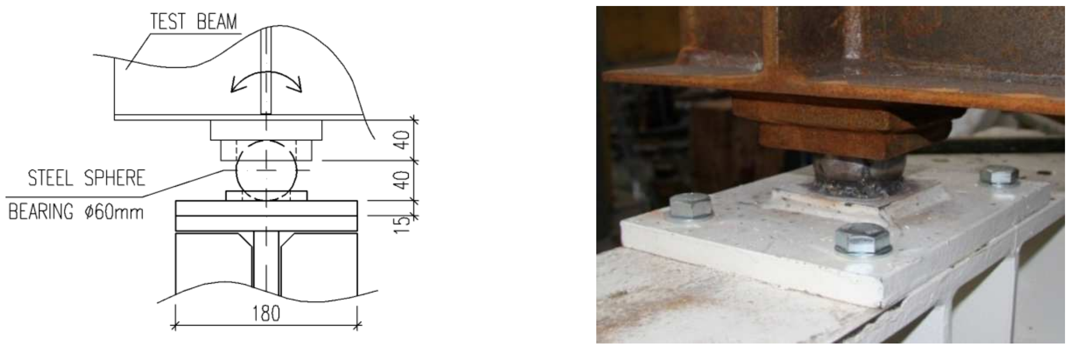


Fig. 4 Fixed pin point support

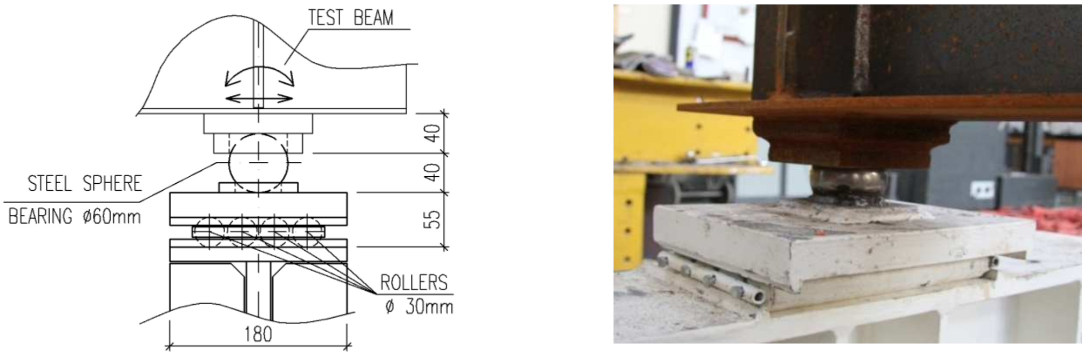


Fig. 5 Free pin point support

3.2 Measuring of initial imperfections

The initial geometry of the specimens were established using the two methods, namely laser scanning and manual measurements. The first method - the laser scanning (see Fig. 6) was used for determination of global and local initial imperfections. The second method consists of manual measurement of the exact dimensions of the specimens (width, depth, flange thickness, web thickness) and manual measurement of the amplitude of the local imperfection of the web and the top compression flange (see Fig. 7). The manual measurement was used jut to validate the more precise, but not experienced laser-scanning method.

Fig. 6 Laser scanner

Fig. 7 Manual measurement

3.3 Heating of specimens

Mannings 70 kVA heat power units with 6 channels were used to heat the specimens. Cable connection of 70 kVA consists of 6 triple cable sets and 4-way splitter cables can accommodate 24 flexible ceramic pads attached. Maximum connected load for the 70 kVA unit is 64.8 kW. One size of the ceramic pads was used: 305 x 165 mm. The power output of the pad was 2.7 kW. Ceramic pads were placed as shown in Fig. 8.

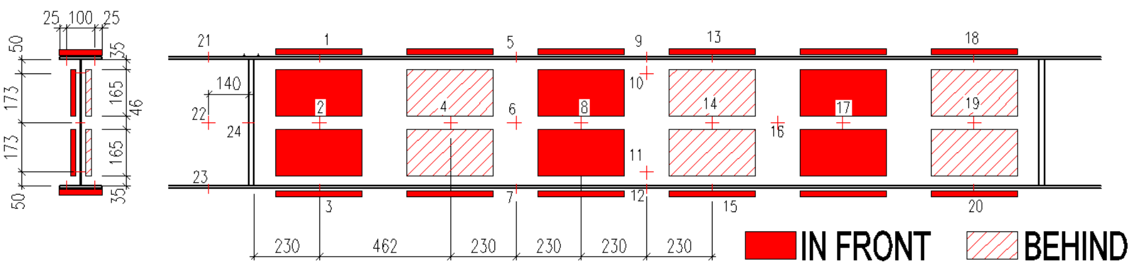


Fig. 8 Layout of flexible ceramic pads and thermocouples

In the first step, the pads were put on the rod rack in order to maintain the position of the heating elements on the web then were fixed by paper adhesive tape on the beam.On the bottom flange, the pads were fixed with the steel wires. On the top flange, the pads were fixed only by adhesive tape to the top of the section.

3.4 Measuring of temperatures

Twenty-four thermocouples were used for the temperature measurement. Twenty were placed in the middle span and four were placed in the side spans for monitoring of temperature in not-heated section. The thermocouples were distributed on the beam according to position of ceramic pads, as shown and numbered in Fig. 8. Beam temperatures were recorded from the beginning of heating to the end of experiment.

3.5 Measuring of strains

High temperature strain gages were used to measure strain distributions across the depth in the heated section. There were 4 high temperature strain gages attached to the beam at the midspan. Two were in the middle of the top flange and the other two in the middle of the bottom flange. At the side spans, there were 4 room temperature strain gages always one in the middle of the top flange and the second in the middle of the bottom flange. These 4 were attached to control the reactions in the supports and to monitor any frictional losses.

3.6 Displacements

The displacements were measured by potentiometers. Two potentiometers were used for measuring displacement in the locations of load application. Vertical (VD), see Fig. 11, and horizontal (HD), see Fig. 12, deflection of the bottom flange centre and lateral rotation (R), see Fig. 13, of the beam at midspan were calculated based on measurement of four potentiometers. Two measured relative vertical deflection and rest of them measured relative horizontal deflection (see Fig.9).

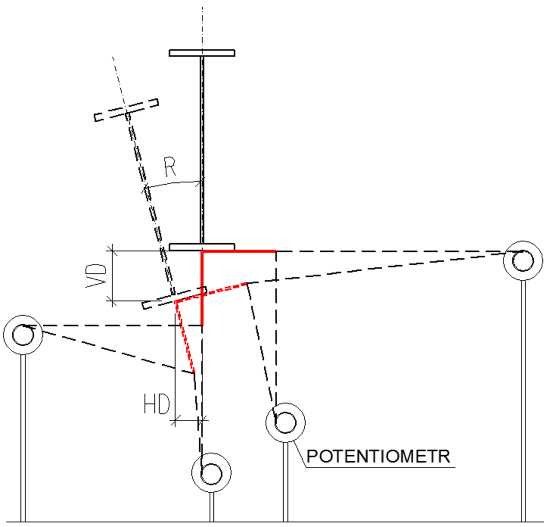


Fig. 9 Measuring of displacement at midspan

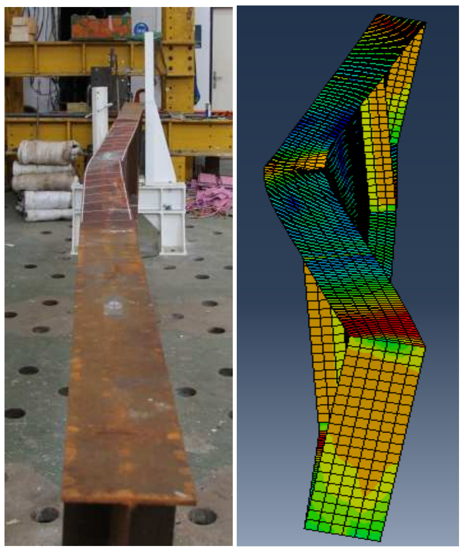
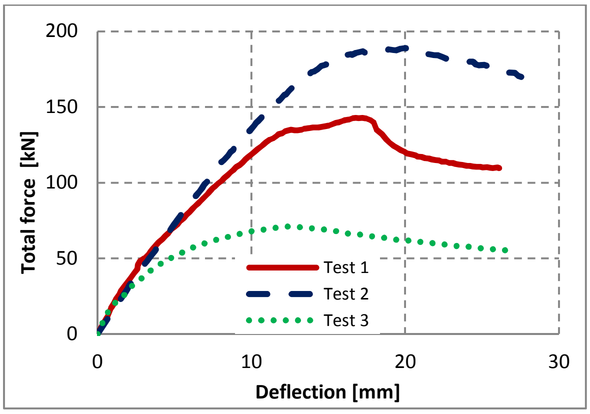


Fig. 10 Comparison of deformed shape (Experiment vs. FEM; test 2)



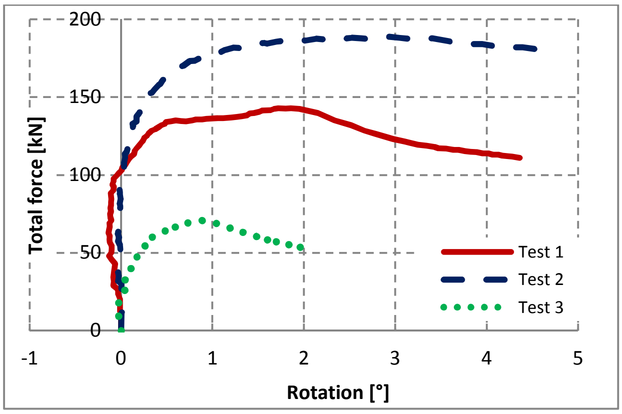


Fig. 11 Vertical deflection of bottom flange at midspan

Fig. 12 Rotation about longitudinl axis at midspan

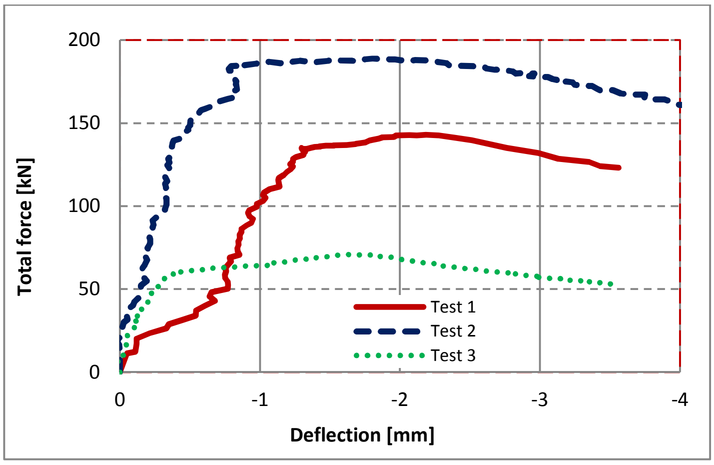


Fig. 13 Horizontal deflection of bottom flange at midspan

4 SUMMARY

In this paper, three experimental tests of laterally unrestrained beams (I or H section) of Class 4 cross-sections at elevated temperatures were described (two beams with constant cross-section one beam with variable cross-section). Several types of displacement and the beam temperatures were measured. Now, these results are used for calibration of numerical model. A numerical validation for beams is currently being carried out (see Fig. 10). Future numerical investigation is planned for full understanding of the fire behaviour of steel members of Class 4 cross-sections considering both welded and hot-rolled I or H shape steel profiles.

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