Experimental behaviour of stainless steel cellular beam in fire

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ABSTRACT

This paper presents a description and the analysis of a fire test on a cellular beam made from grade 1.4301 stainless steel. Cellular beams are increasingly popular in the construction as they provide a structurally and materially efficient design solution as well as allowing the passage of services. In addition, stainless steel is also increasing in popularity for structural applications owing to its inherent durability and ductility, as well as other attractive properties such as structural efficiency and low maintenance requirements. However, the behaviour of stainless steel cellular beams in fire has received little attention from the research community until recently. In the current paper, a description is presented of an experimental investigation into the fire behaviour of grade 1.4301 stainless steel cellular beams. The experimental arrangements are described together with the details of the specimen. The test occurred at the fire testing laboratory at Tampere University, Finland. For the member test, the beam spanned 4,3 m, with an overall depth of 290 mm and 200 mm diameter openings along the span. It was found that the unprotected beam lasted for 29 minutes during the test, after being exposed to a standard fire, and the experiment was eventually stopped due to excessive rate of deflection. The test specimen has been analysed using available design methods and the results are presented herein.

Keywords: stainless steel, cellular beam, fire, web post, buckling

1 INTRODUCTION

Cellular beams are widely used to facilitate lightweight structures and long beam spans resulting in column free internal spaces, high degree of flexibility in service routing and reduced floor-to-floor height. Stainless steel structural members exhibit very good corrosion resistance, ease of maintenance and better fire resistance and stiffness than carbon steel structural members at elevated temperatures (1). Previous research has also shown that the heat transfer coefficient and emissivity values of structural stainless steel members exposed to fire are significantly better than those for carbon steel members (2). Cellular beams fail typically either by web post buckling or Vierendeel bending associated with the buckling of the web posts (3). In the fire situation, the temperature of the web post in a cellular beam increases at a faster rate compared to an equivalent solid beam and members with web openings therefore require more passive fire protection (4). Total elimination for the need of this protection would offer substantial economic incentives including lower construction and maintenance costs, and a shorter construction period.
As the retention of strength and stiffness is greater for stainless steel at elevated temperatures compared to carbon steel, stainless steel structures have the potential to increase the fire resistance time of unprotected cellular beams up to levels of practical significance. Stainless steel is more expensive than carbon steel in terms of initial cost, but the elimination of the fire protection would offset some of the costs. This paper briefly describes the experimental study carried out at the Fire Laboratory of Tampere University in collaboration with Brunel University London to investigate the performance of stainless steel cellular beams in fire conditions. A full-scale fire resistance test was conducted to assess the temperatures and resistance of the cellular beam and to produce experimental data for the validation of FEM simulations, which are described in detail in a companion paper (5). The test was designed to investigate:

- *Beam deflections*
- *Beam fire resistance in minutes*
- *Failure mode*
- *Temperature profile of the cellular beam*

2 EXPERIMENTAL PROCEDURE

2.1 Test specimen and set-up

The experimental research was conducted in accordance with European test standards SFS-EN 1365-3 (6) and EN 1363-1 (7). The steel beam was installed across the longer span of the 3 m × 4 m furnace chamber. The total length and span of the beam were 5000 mm and 4300 mm, respectively, and the length exposed to fire was 4000 mm. Both beam-ends were simply supported and one end on roller support. The symmetrical 290 mm deep by 300 mm wide beam section was fabricated from stainless steel plates of grade 1.4301. The beam flange and web thicknesses were 14 mm and 8 mm, respectively. The size of the web to flange welds were 5 mm. Web stiffeners 8 mm thick were provided at the beam supports and at the load application points on both sides of the web. The diameter of circular openings were 200 mm and they were located at 300 mm centers. *Fig. 1a)* shows the beam and opening geometry. The beam was not fire protected.

The horizontal slab construction over the furnace chamber and the test beam was made up of 250 mm thick aerated concrete blocks and elements. Concrete blocks were placed on the upper flange of the beam, in order to simulate the floor and provide three sided heating. The 1200 mm long blocks were installed with their longer dimension perpendicular to the beam span, see *Fig 2a)*. The remaining area of the furnace chamber was covered with aerated concrete elements spanning parallel to the steel beam.

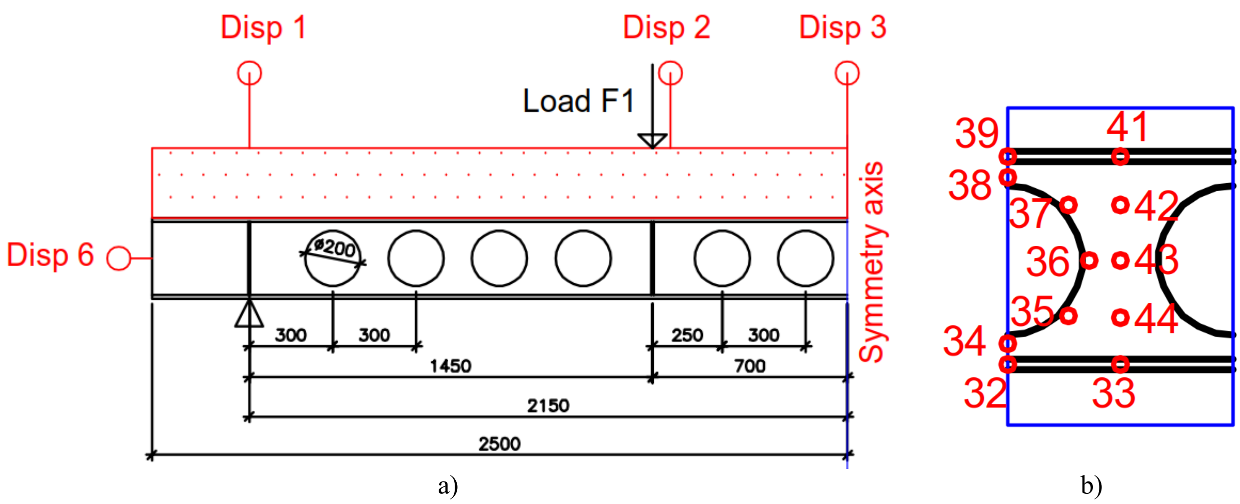


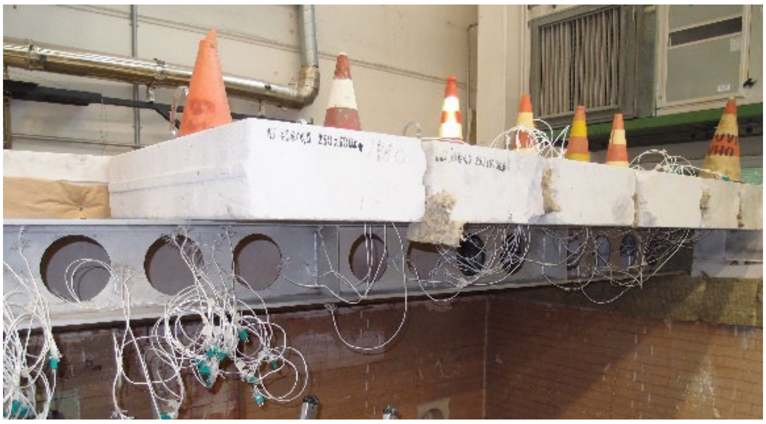
Fig. 1. a) Detail information of the beam and cell geometry, left half of the beam b) Thermocouple positions at beam mid-span.

2.2 Mechanical and thermal loading

The beam was tested under two point-loading. Constant loads of 58 kN were applied through hydraulic loading jacks fixed to a load application frame above the test furnace, as shown in *Fig. 2b)*. The test load was considered to be approximately 30 % of the ultimate load found from pre-design calculations made at ambient conditions. In addition, the self-weight of the concrete blocks bearing on the beam was approximately 1.5 kN/m. The beam was continuously loaded to the test load for over an hour before the elevated temperature loading was applied through ignition of the furnace. The fire load was applied in accordance with the standard ISO 834 fire curve, described in EN 1363-1 (7).

2.3 Instrumentation

The furnace temperature was measured using 8 plate thermometers, in accordance with EN 1363-1 (7). The temperature distribution in the cellular beam was measured using 70 thermocouples, which were installed at various locations along the beam span. K20-2-350 K-type thermocouple wires were installed in pre-drilled holes in the steel section. *Fig. 1b)* shows the thermocouple locations at the beam mid-span. The vertical beam deflections and axial displacements were recorded using six linear differential transducers connected to the specimen through steel wire ropes. Deflections were measured at the mid-span and also at the load application points.



a)

b)

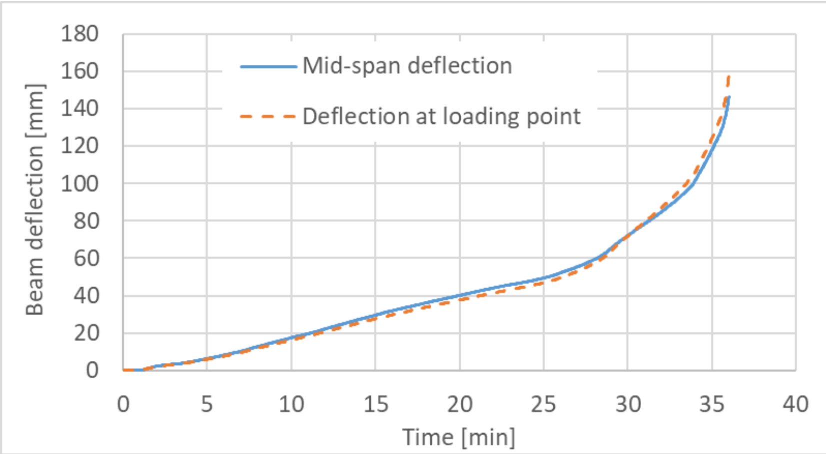
Fig. 2. a) Beam and slab construction during installation; b) Test set-up during the test.

The fire test was performed in accordance with SFS-EN 1365-3 (6). *Fig. 2b)* shows the test set-up during the fire test.

3 FIRE TEST RESULTS

3.1 Recorded deflections

The performance criteria for the beam load-bearing capacity is defined by the limiting value of deflection and limiting rate of deflection (7). In this test the limiting values were 159 mm and 7,1 mm/min, respectively. The measurements taken during the tests are presented in *Fig. 3*. It is shown that in terms of the mid-span vertical deflections, the beam responded linearly until about 24 minutes by which time the furnace temperature had risen to over 800 °C. After this point, the rate of deflection began to gradually increase due to the deterioration of the beam properties. At about 28 min the rate of deflection started to increase and the limiting value for the rate of deflection was exceeded 29 minutes after ignition. By that time, the beam had deflected 65 mm and the furnace temperature was around 840 °C. The rate of beam deflection started to increase rapidly 34 minutes after ignition and the burners were shut off 36 minutes after ignition when the maximum beam deflection exceeded the limit value of 159 mm. The maximum deflection occurred at the load application point. The testing standard EN 1363-1 (7) and the fire resistance classification standard EN 13501-2 (8) give two different assessments for the beam loadbearing capacity R. The first standard states that the capacity is reached as soon as one of the two criteria is exceeded, which in this test gives fire resistance classification R20. In accordance with the classification standard failure to support the load is deemed to have occurred when both of the criteria have been exceeded, leading to classification R30 in this test.



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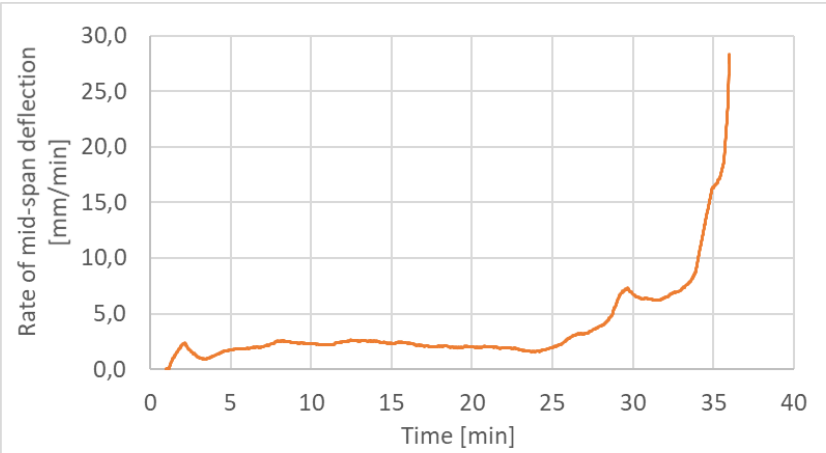

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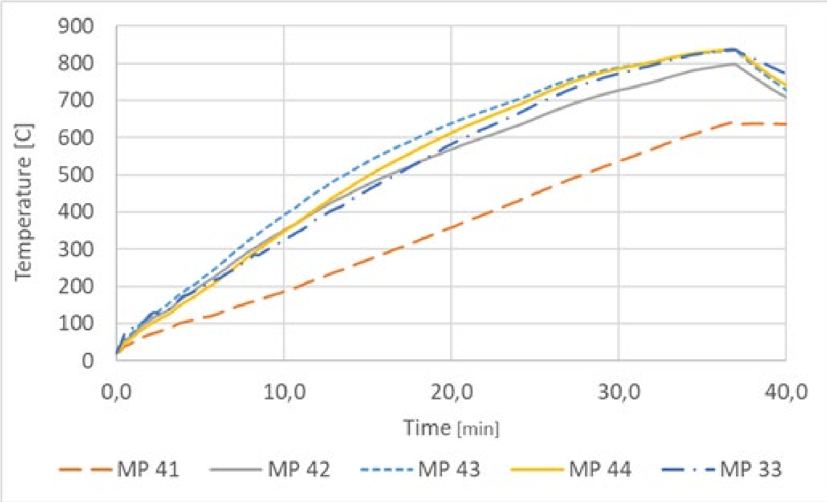
Fig. 3. a) Beam deflection at mid-span and loading point; b) Rate of mid-span deflection

3.2 Recorded steel temperatures

The steel temperature development at mid-span is shown in *Fig. 4*. The corresponding thermocouple locations are shown in *Fig. 2*. At failure (29 min) the steel temperatures at beam mid-span varied between 529 °C and 785 °C and the maximum temperatures were recorded in the web. The difference between bottom and top flange temperatures was about 250 °C. Similar temperature development was recorded in all beam sections. At 36 minutes steel temperatures at mid-span varied between 632 °C (top flange) and 834 °C (bottom flange and web).



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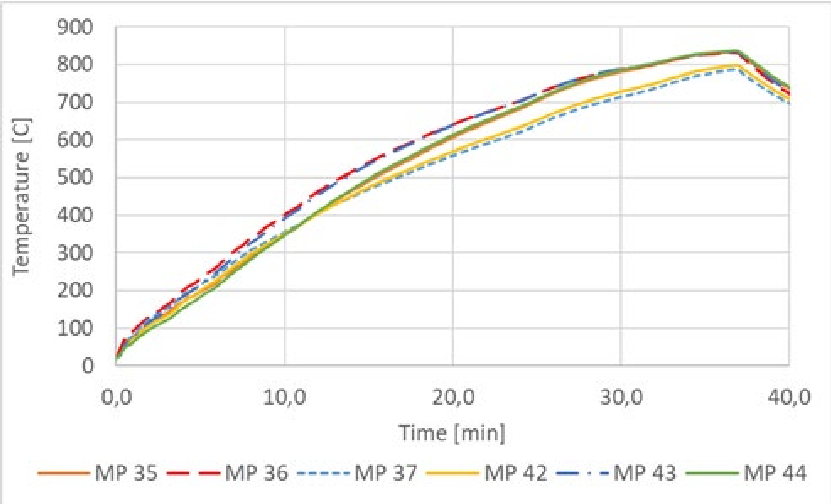

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Fig. 3. Steel temperatures at mid-span a) Over beam cross-section; b) Web temperatures. For thermocouple positions refer to Fig. 1b).

3.3 Failure mechanism

The failure mechanism of the beam was buckling of the web posts between the load application point and the beam support. *Fig. 4* shows the deflected shape of the beam after testing and the failure mode forming an S-shape on the web between openings. As described above, the beam responded linearly until about 24 min at which point the maximum and average beam web temperatures were 703 °C and 672 °C, respectively. Failure occurred around 5 minutes later when the maximum web temperature had increased to 785 °C and the average web temperature was 759 °C. At this average temperature, Youngs modulus and the material strength ($f_{2,\theta}$) are reduced to 66% and 43%, respectively, of their value at 20 °C (9). For carbon steel at 759 °C temperature the corresponding reduction factors are significantly lower being 16% and 11% for the effective yield strength and the slope of the linear elastic range, respectively (10).

a) b)

Fig. 4. a) Steel beam after testing; b) Web post buckling failure mechanism

4 SUMMARY AND ACKNOWLEDGMENT

The experimental fire research on stainless steel cellular beam conducted at Tampere University in collaboration with Brunel University London, and the results and observations have been summarised in this paper. A full-scale fire resistance test was conducted on a stainless steel cellular beam subject to pure bending. Based on the performance criteria of EN 1363-1, the beam failed by web post buckling 29 minutes after the ignition of the furnace, despite having no fire protection. At failure, the furnace and the average web temperatures at mid-span were 840 °C and 759 °C, respectively. In accordance with the classification standard EN 13501-2 (8) the loss of load bearing capacity occurred 34 minutes after the ignition. The research is ongoing with the aim to analyse further the temperature development of stainless steel section and the fire resistance design of stainless steel cellular beams.

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