Numerical analysis of the behaviour of stainless steel cellular beam in fire

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ABSTRACT

This paper is concerned with the behaviour of stainless steel cellular beams during a fire. Stainless steel has become increasingly popular in recent years for structural applications, mainly due to its excellent corrosion resistance, as well as its other attractive physical and mechanical attributes. During a fire, stainless steel generally retains a higher proportion of their room temperature strength (above temperatures of 550°C) and stiffness (all temperatures) compared with carbon steel. In the current paper, the focus is on the fire behaviour of stainless steel cellular beams. There are no specific design rules available for these members and the carbon steel design rules for cellular beams are typically used with the stainless steel material properties. This work aims to investigate the validity of this approach by analysing the behaviour of stainless steel cellular beams with stiffened webs under fire conditions. A nonlinear finite element (FE) model is developed using the ABAQUS software, and is validated using fire test data. Then, the model is employed to conduct parametric studies in order to determine the most salient factors. Finally, design guidance is provided for stainless steel cellular beams in fire conditions, which consider the most influential geometric and material characteristics.

Keywords: Cellular beams, stainless steel, finite element analysis, ABAQUS.

1 INTRODUCTION

1.1 Background

This paper is concerned with the behaviour of stainless steel cellular beams under fire conditions. This is a relatively new concept, which has largely come about owing to the ever-increasing demands for structures to be more environmentally sustainable, robust and versatile. Cellular beams are a very efficient structural option for long-spanning members (1) whilst stainless steel is widely used for load-bearing applications in structural engineering, largely owing to its excellent corrosion resistance, long life-cycle, excellent mechanical characteristics, good formability and recyclability and very low maintenance requirements (2). In this context, a relatively logical but new application is to use stainless steel in the manufacturing of cellular beams. However, a key inhibitor of this application is a lack of information on the way these elements behave in fire. Given that stainless steel is often specified because of its attractive appearance, covering the beams in intumescent paint is not likely to be a popular recommendation. Hence, the aim of this work is to assess the behaviour of unprotected stainless steel beams with a view to providing designers with the information that they require to reliably use these members.

Cellular beams have become more and more popular for long-spanning structural elements in various applications such as multi-storey buildings, sports arenas and terminals. Cellular beams are regular I-shaped girders which have circular openings in the web along the length of the member. They are typically made either from rolled sections (universal beams, UB's, or universal columns, UC's) or by fabricating the member by welding plates together into the desired shape. For the former method, the cellular beam is produced by cutting the rolled steel sections longitudinally and then re-welding the two portions together to create a deeper beam with a series of circular holes (1). Using the plate girder approach, the flange and web dimensions can be selected to be the most efficient for the applied loading, form of construction and opening requirements. The main advantages of cellular beams are that long span construction can be achieved with fewer columns required, the services can be integrated through the floor beams in multi-storeys leading to reduced floor depths and lower building heights and construction is typically faster compared with using regular steel beams. The costs of producing these sections is reducing as they increase in popularity and therefore they can provide a very efficient solution in modern construction.

As mentioned previously, stainless steel is a very durable material, and also offers excellent mechanical and thermal properties, relative to other structural metals. It also offers excellent ductility and strain hardening capacity compared with traditional carbon steel, which is particularly desirable in design as a ductile section provides more warning of imminent collapse compared with brittle arrangements. There are many different grades of stainless steel, and these are typically categorised into five different families, according to their metallurgical composition. These include the austenitic, ferritic, duplex, martensitic and precipitation hardened grades. The austenitic and duplex grades are most common in structural applications and they comprise 17-18% and 22-23% chromium, respectively. Both austenitics and duplex stainless steels offer excellent corrosion resistance and mechanical properties.

In terms of the fire performance, there has been considerable research done on the effect of elevated temperature on various grades of stainless steel in recent years, e.g. (3, 4). Generally, it has been found that austenitic stainless steels perform at least as well as carbon steel under fire conditions in that they generally retain a higher proportion of their room temperature strength than carbon steels above temperatures of about 550 °C, and a higher proportion of their stiffness at all temperatures (5) Stainless steel also has greater thermal expansion than carbon steel. Eurocode 3 Part 1-2 (6) currently provides eight sets of strength and stiffness reduction factors for different grades of steel. In this context, the current paper aims to develop and validate a numerical model, which can then be used to conduct a detailed and fundamental investigation into the performance of stainless steel cellular beams under fire behaviour

2 DEVELOPMENT OF THE NUMERICAL MODEL

A numerical study is performed to understand the behaviour of stainless steel cellular beams in fire, and to investigate the influence of key parameters. The finite element software package ABAQUS is employed to model the stainless steel cellular beams. The details of the cellular beam which are employed in the model are based on the fire test which was conducted at Tampere University in 2018, and is discussed in an accompanying paper (7). In addition, and to begin with, the model is validated using the details of a published test programme (8).

The cellular beam is modelled using shell elements which are available in the ABAQUS library (S4R). These have four corner nodes, each with six degrees of freedom, and are suitable for thick or thin shell applications (9). A mesh convergence study has been performed to identify an appropriate mesh density to achieve suitably accurate results whilst maintaining computational efficiency. Models with a range of mesh sizes from five to fifteen elements across the cross-section depth yielded very similar results. Therefore, ten identical elements are employed across the each flange width with an aspect ratio of close to unity.

The end conditions adopted in the model replicate those in the test, which were simply supported boundary conditions, by restraining the appropriate displacement and rotation degrees of freedom. The finite element analysis is performed in two stages. Firstly, the beam is loaded mechanically under two point loads of 58 kN each. Then, the load is maintained at a constant level whilst the elevated temperature extracted from the test is applied at various locations such as top flange, bottom flange and web. The temperature gradient through the cross-section is applied uniformly along the length of the beam. In the following sub-sections, the model is first validated using a published set of experimental data from a carbon steel cellular beam that was subjected to fire loading. Thereafter, the details of the numerical modelling relating to the stainless steel cellular beam are presented and discussed.

2.1 Validation of the model

The model is first validated using the test data published on a simply supported carbon steel cellular beam (8). The cellular beam is based on the geometry of a 457×152×60 UB (universal beam) in grade S275 structural steel and has a span of 8 m. It has multiple rectangular web openings as shown in Fig. 1. A uniformly distributed load of 35 kN/m, giving a load ratio of 0.7 based on the ambient temperature capacity of the beams, is applied to the upper surface of the member. The analysis is conducted in two steps. In the first step the static load is applied and in the second step, a uniform temperature distribution in the cross-section is applied until failure occurs.

Fig. 2 shows the temperature versus midspan deflection behaviour for this steel cellular beam, from both the FE model and the experiments. It is clear that a very good agreement is obtained. The shapes of the responses are identical and the real and simulated responses almost perfectly match. There are two stages in the fire behaviour of simply supported steel cellular beams. In the first stage, up to about 250°C, there is very little deflection in the beam due to the absence of thermal gradient in the section as well as the absence of any horizontal resistance to the development of thermal expansion. Later, as the temperature increases, there is a significant decrease in the strength properties of the material, causing the top tee-section of the cellular beam to buckle under high compressive forces and deflections to increase rapidly until a runaway failure occurs.

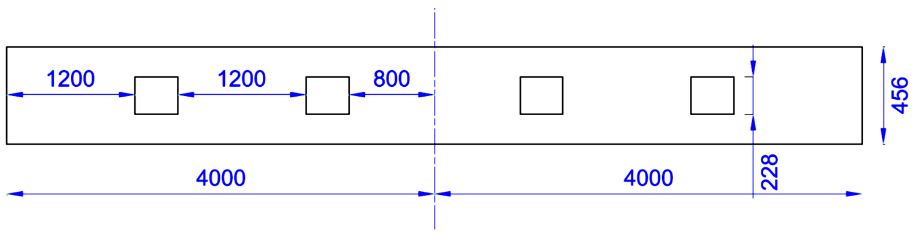


Fig. 1 Opening layout for the simulated beam (all dimensions are in mm)

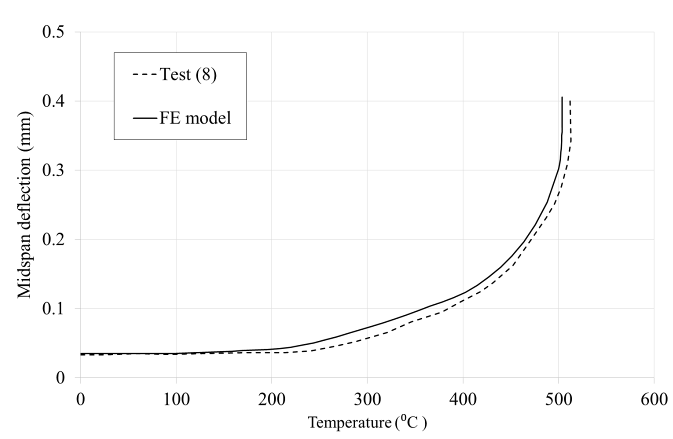


Fig. 2 Time versus midspan deflection behaviour

2.2 Stainless steel material properties

The stainless steel grade employed in the current analysis is austenitic grade 1.4301. In the numerical model, the mechanical properties of stainless steel at room temperature and at elevated temperature are the key parameters in the analysis model. The material model for the stress-strain response of stainless steel that is adopted in the finite model is the modified Ramberg-Osgood model (10-12) as given in Eqs. 1 and 2, and included in the SCI design manual for structural stainless steel (5).

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \text{ for } \sigma \leq \sigma_{0.2} \tag{1}$$

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} \text{ for } \sigma_{0.2} < \sigma \leq \sigma_u \tag{2}$$

In these expressions, ε and σ are the engineering strain and stress, respectively; $\sigma_{0.2}$ and $\varepsilon_{0.2}$ are the 0.2% proof stress and corresponding strain values, respectively; E_0 is the initial Young's modulus; $E_{0.2}$ is the tangent modulus at $\sigma_{0.2}$; σ_u and ε_u are the ultimate stress and corresponding strain, respectively; and n and m are model constants related to strain hardening. In order to convert the nominal stress-strain (σ_{nom}-ε_{nom}) values obtained from Eqs. 1 and 2 into the true stress-true logarithmic plastic strain terms required in the ABAQUS model, the following expressions are employed:

$$\sigma_{true} = \sigma_{nom}\,(1 + \varepsilon_{nom}) \tag{3}$$

$$\varepsilon_{true}^{p} = \ln(1 + \varepsilon_{nom}) - {}^{\sigma_{true}}/_{E_0} \tag{4}$$

At elevated temperature, the stainless steel mechanical properties are defined according to the equations given in Eqs. 5 and 6, as given in the SCI design manual for structural stainless steel (5):

$$\varepsilon_\theta = \frac{\sigma_\theta}{E_\theta} + 0.002\left(\frac{\sigma_\theta}{\sigma_{0.2,\theta}}\right)^{n_\theta} \text{ for } \sigma_\theta \leq \sigma_{0.2,\theta} \tag{5}$$

$$\varepsilon_\theta = \frac{\sigma_\theta - \sigma_{0.2,\theta}}{E_{0.2,\theta}} + \varepsilon_{u,\theta}\left(\frac{\sigma_\theta - \sigma_{0.2,\theta}}{\sigma_{u,\theta} - \sigma_{0.2,\theta}}\right)^{m_\theta} + \varepsilon_{0.2,\theta} \text{ for } \sigma_{0.2,\theta} < \sigma \leq \sigma_{u,\theta} \tag{6}$$

In these expressions, σ_θ and ε_θ are the stress and strain of stainless steel at temperature θ, respectively; $\sigma_{0.2,\theta}$ and $\varepsilon_{0.2,\theta}$ are the yield strength and corresponding strain at temperature θ; E_θ and $E_{0.2,\theta}$ are the initial elastic modulus and tangent modulus corresponding to $\sigma_{0.2,\theta}$ at temperature θ, respectively; $\varepsilon_{u,\theta}$ is the ultimate strain at temperature θ; and n_θ and m_θ are the strain hardening constants at temperature θ for stainless steel.

2.3 Boundary and loading conditions

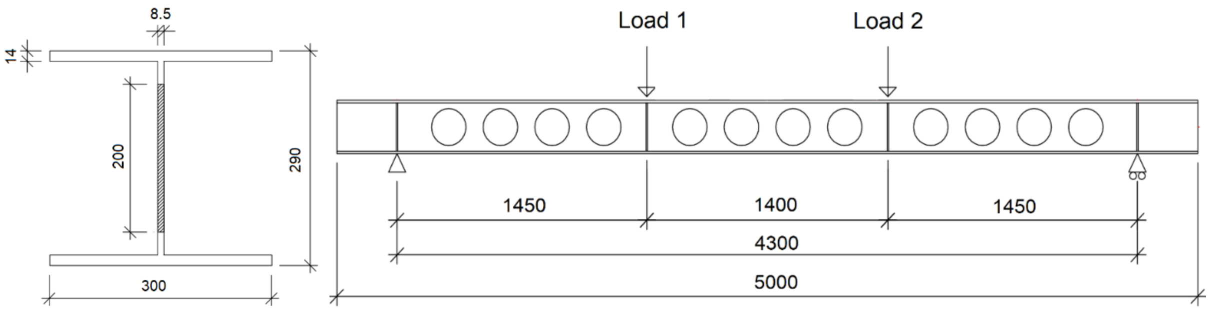
The geometry and loading conditions of the beam are symmetrical about the mid-span. The end sections have simply supported boundary conditions meaning that the vertical and lateral displacements of all nodes along the longitudinal axis are restrained against movement and therefore assigned values equal to zero. The loading is applied to the top surface of the beam in displacement control through two concentrated loads along the full length of the beam.

2.4 Geometric imperfections and residual stresses

All structural members contain geometric imperfections which are introduced during production, fabrication and handling. Initial imperfections in the form of the lowest local and global buckling mode, obtained from a linear elastic eigenvalue buckling analysis, with the amplitudes as those measured in the test specimens, are included in the numerical model. Residual stresses, likewise introduced to during manufacturing (e.g. cold-forming) or welding, are not explicitly incorporated into the models due to their low measured amplitudes and minimal influence on the member behaviour in similar studies (13).

2.5 Stainless steel validation

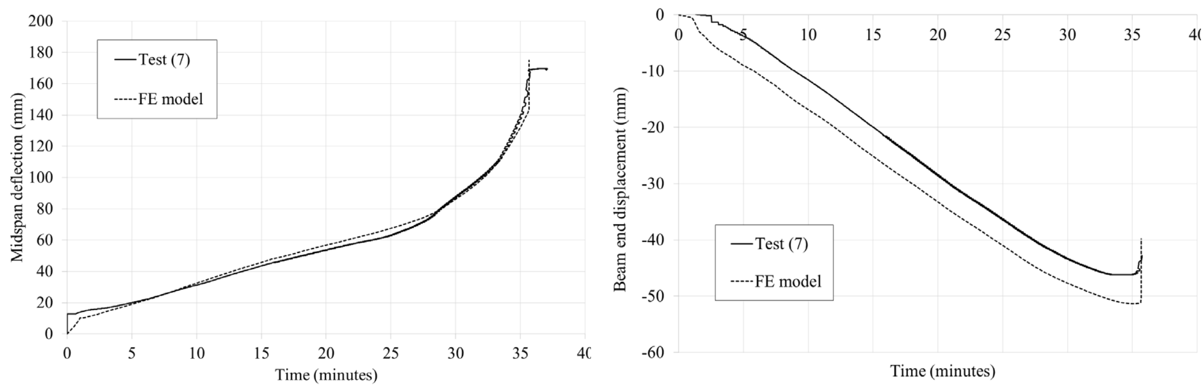
A stainless steel cellular beam has been tested at Tampere University, Finland, and this is described in detail in a companion paper (7). The beam was fabricated from grade 1.4301 stainless steel plates, and a schematic view is presented in Fig. 3, including the arrangement of the openings. The span of the tested beam was 4.3 m and it had 12 circular openings of 200 mm diameter at 300 mm centre/centre spacings. The beam was tested in two stages. In the first stage, the beam was loaded mechanically under two point loads of 58 kN each. Then, the beam was heated using a furnace which was programmed to heat up in accordance with the ISO 834 standard fire curve (14). The misspent vertical deflections and horizontal displacements at the supports were recorded in the test and then plotted against time.



(a) (b)

Fig. 3 Schematic of the stainless steel cellular beam (all dimensions are in mm) including (a) the cross-section and (b) an elevation view.

In the current analysis, the previously described and validated numerical model is employed to assess the tested beam. The simulation of the tested beam is also carried out in two stages. In the first stage, the mechanical load is applied and in the second stage, the thermal load is applied. The temperature history obtained during the test is applied at various locations of the beam i.e. top flange, web and bottom flange as the thermal load. The time versus misspent vertical deflection and time versus beam end displacements are plotted and compared with the test results, and these are presented in Fig. 4. Clearly, an excellent agreement has been obtained between the simulation and the test results. The model depicts all of the major behavioural phenomena, particularly the large increase in deflections that occurs in the later stages of the analysis. There are some minor discrepancies in the early stages of the test, and these are most likely due to some initial movement in the test specimen upon the application of loading.



(a) (b)

Fig. 4 Comparison between the experimental results (7) and FE simulations for (a) mid-span deflection versus time and (b) end displacements versus time

3 CONCLUSIONS AND FUTURE WORK

This paper has presented an initial overview of the development of a finite element model which is capable of representing the behaviour of a stainless steel cellular beam under elevated temperature loading conditions. The model is developed in the ABAQUS software and is first validated against previously published experimental data on a carbon steel cellular beam. Then, the model is extended to account for the stainless steel material properties at elevated temperature, using available data. The model is shown to provide an excellent depiction of the behaviour. The work presented in this paper is an initial step in a wider study, which will aim to use the developed model to gain a greater understanding of the overall behaviour for a wide range of variables. Parameters which are expected to affect the behaviour include boundary conditions, opening layout, grade of stainless steel which is being used, and type of fire which is applied. Each of these will be studied in detail in the future, and the information obtained will be used to develop useful design guidance for these types of structural members.

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