Optimisation of a new type of fire-robust beam-to-column connection

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Abstract

In this paper, a new type of beam-to-column connection is analysed, aiming to obtain an optimisation goal defined as the capability of absorbing both very large rotations and axial movements at high temperatures. The novelty of the proposed connection is related to a special connector, that connects the beam to the column. The connector is bolted to the column flange using a face-plate and to the beam web using a fin-plate. The main part of the connector is a hollow tube, which deforms in response to the rotations and axial movements caused firstly by the thermal elongation and subsequently by the extreme weakening of the supported beam when exposed to fire. The connector has been tested at the University of Sheffield both numerically and on scaled prototypes. The goal of this research is to optimize the shape and dimensions of the connector with respect to specific mechanically-based objectives.

Keywords: steel frames, connections, fire, ductility

1. Introduction

Previous studies on this connection resulted in reports of experimental and numerical work related to manufacture (using 3-D printing technology) of the scaled prototypes [1,2] and development of a mathematical model of connector components, to be used later to model the performance of the connection in real assemblies [3]. The outcome of that research was a preliminary design of a beam-to-column connection composed of a special type connector bolted to the column flange using a face-plate and to the beam web using a fin-plate, in which the main part was the circular hollow tube that provides the connection ductility (Fig.1).

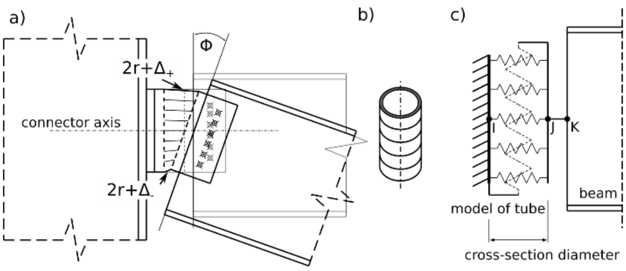

Figure 1: a) connector assembly b) tubular part of connector c) mechanical model of connector

Here, the focus is on the optimisation of dimensions and shape (the previously circular cross-section is generalised as an elliptical shape) of the connector, which is intended to lead to optimal performance of the connection in fire. The goal is to create a robust solution, which in this case implies ductile behaviour and a capability to absorb the very large rotations and axial movements observed in fire.

2. Numerical model

The numerical model needs to reflect the static scheme given in Fig.2. The tubular part of the connector is modelled using shell finite elements, while the beam uses beam elements. Movements and rotations of the left and right edges of the tube are constrained by the rigid-body motions of reference points located at the middle of these edges. The left-hand reference point is fixed, while the right-hand reference point is rigidly linked to the left-hand end node of the beam. The numerical analyses take into account both material and geometrical nonlinearities. Quasi-static implicit solver and material parameters without temperature-rate dependence are used. Because, model is not sensitive to temperature-rate the linear function for temperature increase is chosen. More information about the numerical model is given in [3].

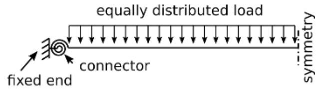

Figure 2: Schematic view of assembled model.

3. Initial findings

The performance of the connection has been studied for panels, composed of pre-tensioned hollow-core slabs supported by steel beams [3]. Findings can be illustrated by the example of an 8.00 m long beam of HEA 340 section which carries a uniformly distributed load of 22.12 kN/m (Fig.2) at the Fire Limit State.

The connector was composed of parallel components which are effectively modelled with non-linear springs, representing the force-displacement relationship of horizontal strips of the tube (Fig.1c). The behaviour of the beam with the proposed connection can be shown at elevated temperatures using graphs such as Fig.3. The shape of the tube at particular stages of thermal exposure can be drawn as Fig.4.

The failure of connections can be postponed by introducing a ductile element which allows both significant axial displacements and large rotations. However, the performance of the proposed connector can be improved further, mainly by increasing its maximum rotation capacity. It can be seen from

Fig.3 that the rotation does not exceed 20°, together with simultaneous large axial displacement. As a result, although the connection has significant ductility, failure may still occur at too early a stage.

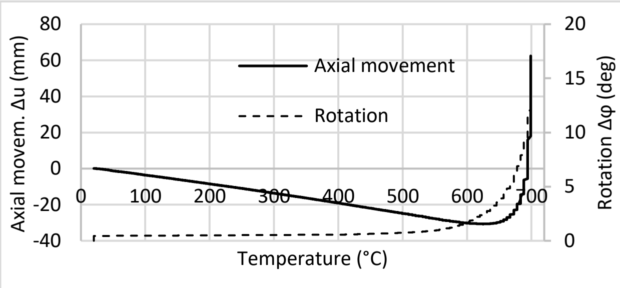

Figure 3: Relationship between axial movement and rotation of the right edge of connection, versus temperature.

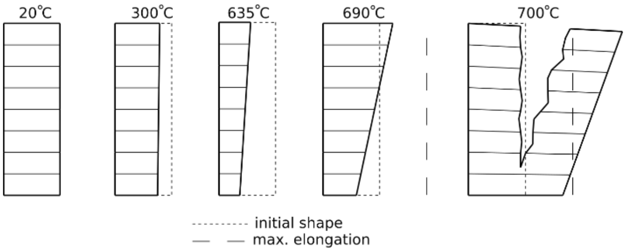

Figure 4: Shape of the tubular part of a connection at particular temperatures.

4. Optimisation function

The structural optimisation problem is defined as finding the best performance of the connection under elevated temperatures. The structural optimisation function ($\mathbb{SO}$) can be defined as follows:

$$(\mathbb{SO})\quad \begin{cases} \text{maximize } \mathcal{F}\big(\boldsymbol{x}, g(\boldsymbol{x})\big) \text{ with respect to } \boldsymbol{x} \\ \text{subject to} \quad \begin{cases} \text{behavioural constraints on } g(\boldsymbol{x}) \\ \text{design constrains on } \boldsymbol{x} \\ \text{equilibrium constrains.} \end{cases} \end{cases} \tag{1}$$

The design parameters are purely geometrical and are stored in vector $\boldsymbol{x}$. A schematic geometry is shown in Fig.5. The $\boldsymbol{x}$ vector has the form:

$$\boldsymbol{x} = [a \quad b \quad t \quad h]^T. \tag{2}$$

Parameters a, b are the diameters of ellipse, t, h are the thickness and height of a tube respectively.
The design constraints are given by:

$$\begin{cases} a, b \le B_f \\ t \le 0.5 t_w \, . \\ h \le 0.9 H_w \end{cases} \tag{3}$$

The objective function $\mathcal{F}\big(\boldsymbol{x}, g(\boldsymbol{x})\big)$ returns the temperature at component failure, determined as fracture of tube's upper fibres. Numerically, this objective function incorporates the function $g(\boldsymbol{x})$ which defines the elongation of these upper fibres, and is constrained by the pre-defined maximum elongation. Thus, behavioural constraints are checked according to the axial deformation Δu and rotation $\Delta\varphi$ of tube, as follows:

$$g(\boldsymbol{x}) := \Delta \mathrm{u} + 0.5\mathrm{h} \sin \Delta\varphi \le (1 + \varepsilon_{max}) \cdot 0.5 \cdot p(a, b), \tag{4}$$

where ε_{max} are the strains at material rupture and $0.5p(a, b)$ is half the ellipse perimeter (Ramanujan's approximation):

$$p(a, b) = 0.5\pi \left[3(a + b) - \sqrt{(3a + b)(a + 3b)}\right]. \tag{5}$$

Equilibrium constraints are incorporated in the numerical model by the differential equations defining static equilibrium.

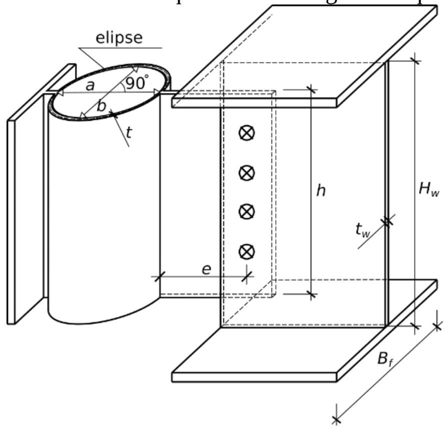

Figure 5: Schematic of design parameters.

5. Optimisation process

A gradient-type "Interior Point Algorithm" is chosen to control the optimisation process. This algorithm uses either a *direct step* (also called *Newton step*) or a *conjugate gradient step* at each iteration. While the analyses are performed in the *Abaqus* FEM solver, the optimisation process is controlled by external scripts written in *Matlab* language. The algorithm is described [4] as robust for smooth nonlinear problem and its implementation does not require an analytical form of gradient. Instead, it can be obtained based on a Hessian, which is approximated using a dense quasi-Newton approximation. Since the cost function defines only the temperature at component failure, the problem is transient. Non-direct form of gradient of the cost function is used.

6. Final remarks

The research already performed has revealed a promising results regarding robustness in fire of this connection. Optimisation studies contribute to a better understanding of connection performance. Sensitivity analyses of robustness of connection in fire, with respect to connector geometrical dimensions, supports selection of optimal connector design.

References

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