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# Simplified analysis method for catenary action of restrained cellular steel beams at elevated temperature considering strain reversal

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ABSTRACT

A Simplified Analysis Method (SAM) for predicting catenary action of restrained Cellular Steel Beams (CSB) at elevated temperature, as an alternative of finite element method, was proposed in this paper. A finite element model was developed and validated by existing test results and numerical results first. The temperature distribution along the section height was assumed to be linear based on available research results. Then the simplified analysis method was developed based on equilibrium equations, constitutive equations and geometric equations. The approach considered non-uniform temperature, geometric non-linearity, material non-linearity, as well as strain reversal when calculating section stresses. A series of parametric study using verified numerical model were then carried out to assess the accuracy of the proposed method. It was found that the simplified method yielded results which agreed well with those obtained from Finite Element Analysis (FEA). A lower compressive force and catenary tension were predicted when the web at perforated section was not considered. And the ignorance of strain reversal in the SAM would lead to a larger deflection prediction. The simple approach could also be used to predict the behavior of the beam subjected to non-uniform temperature distribution across the section in the latter stage of a fire, which may not always be obtained from FEA due to convergence problem.

## 1. Introduction

The critical temperature of the restrained beam could be increased greatly considering catenary action in a fire, which makes it possible to limit or eliminate the use of fire protection [1]. Utilizing catenary action is an effective design approach to prevent the structure from progressive collapse [2]. And a sufficient tensile capacity of the connection is required when considering catenary action in the design practice [3]. Many novel fire resistance connections had been presented and their behaviors were investigated through fire tests or numerical simulations [4–6]. Experimental and numerical studies on catenary action of restrained steel beams at elevated temperature have been conducted. Liu et al. [7] and Liu and Davies [8] carried out fire tests to investigate catenary behaviors of axially restrained steel beams in a fire. Test results proved that great tensile axial force was generated in the beam when the beam developed large deflection at high temperature. Li and Guo [9] conducted experiments on restrained steel beams subjected to heating and cooling and found that axial compression was produced in the restrained beams compared with unrestrained beams. Wong [10] presented a simple technique to model the axial restraints imposed on a steel beam by adjacent members and discussed the catenary action due to large deflection effect for beams in a fire. Valipour and Foster [11] formulated a 1D discrete element for the analysis of reinforced concrete frames with catenary action. Comparison with experimental results and available analytical results showed that the formulation was capable to accurately capture the catenary action of the element.

Fire tests are time-consuming and also expensive, while numerical simulation has to do deal with complicated modelling work and possible convergence problems. Researchers have tried to solve this problem through simplified analysis methods recently. Based on equilibrium and compatibility principles, Dwaikat and Kodur [12] developed an approach to assess the fire resistance of restrained steel beams considering catenary action. Linear interpolation between the deflection at the end of the elastic phase and that at the onset of catenary action of the beam was explored to evaluate the elasto-plastic temperature-deflection history of the restrained beam, which led to a conservative result. Li et al. [13] presented a method that employed the axis arc-length and section rotation of the deformed beam as basic variables to analyze the catenary behaviors of axially restrained steel beams at elevated temperature. Yin and Wang [14–16] proposed a simplified hand calculation approach to

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analyze the catenary action of I-sectional steel beams at elevated temperature. It could also be used to cellular beams by modifying the web area in the formulation. This simplified hand calculation method, however, allowed the beam axial load to change in isolation and the beam bending moment was then calculated from the axial load-bending moment interaction equation. This assumption did not comply with stress distribution in the beam, which led to a higher catenary tension prediction. And the large deflection was not considered when calculating the beam curvature at mid-span. Strain reversal of the top flange during the heating stage was also not incorporated.

Cellular Steel Beams (CSBs) have become a widely used structural component in recent years, as shown in Fig. 1. At ambient temperature, the CSB may encounter web-post buckling failure or plastic Vierendeel mechanism failure at the perforated section [17,18]. Bbehaviors of the CSB with novel shape web openings had been studied [19–25]. Investigations on CSBs at elevated temperature had also been conducted [26–28,30].

The character of large spans makes the CSB easier to develop the catenary action at elevated temperature. Compared with Solid Web Steel Beam (SWSB), the reduction in the bending stiffness and bending moment capacity of the CSB can be neglected [29]. However, the axial stiffness and the axial strength of the CSB are greatly reduced due to the web openings, which greatly affected the response of the axially restrained steel beam during the catenary action stage in a fire [30]. Current researches on catenary action of the restrained CSB at elevated temperature were based on the assumption of Uniform Temperature Distribution (UTD) across the section [30]. Due to the protection of the concrete slab in a real fire scenario, the steel beam may be exposed to fire only from three sides, which leads to the Non-Uniform Temperature Distribution (NUTD) across the section. The top flange of the beam has lower temperature comparing with the web as well as the bottom flange and additional deflection will be induced due to thermal bowing. Heidarpour and Bradford [31] presented a generic nonlinear modelling of an isolated steel beam with NUTD at elevated temperatures in a compartment fire. The model was based on a non-discretization semi-analytical formulation of a generic steel cross-section that was subjected to an arbitrary temperature distribution across the section. Dwaikat and Kodur [32] proposed a simplified approach to modify the axial symmetrical P-M curve of a beam section with UTD to account for the shape distortion caused by NUTD across the section. The studied beam was exposed to fire from three sides, and the thermal gradient was approximately linear as indicated by the thermal analysis results.

With advances in finite element technology, the catenary action behavior can be predicted by finite element analysis. However, convergence problem may be encountered when analyzing problems with great geometric nonlinearity and material nonlinearity [33]. On the other hand, the structural fire engineers are more concern the deflection and fire-induced force in the beam in catenary action stage. To introduce the catenary action into routine design action, it was desirable to develop a much less complicated approach. In this paper, a simplified analysis method for catenary action of restrained CSB at elevated temperature was developed. A finite element model was developed and validated firstly. Then the simplified analysis method was proposed based on equilibrium equations, constitutive equations and geometric equations. After that, a parametric study using the verified numerical model was carried out to assess the accuracy of the proposed method.

## 2. Finite element modelling

### 2.1. Finite element model

The finite element software ABAQUS [33] was used to simulate the catenary behaviors of restrained CSB at elevated temperature. Both the two flanges and the web were meshed by S4R, a 4-node reduced integration shell element, with mesh size of 15 mm × 15 mm. The yield strength and elastic modulus of steel at ambient temperature were 345 MPa and $2.05 \times 10^5$ MPa, respectively. The stress-strain relationship and the reduction in yield strength and elastic modulus of steel at high temperatures followed the description in EN1993-1-2 [34]. The Poisson's ratio of steel was 0.3 and the coefficient of thermal expansion was $1.4 \times 10^{-5}$. Only half of the beam was modeled due to symmetry of the beam about the mid-span cross section, as shown in Fig. 2. The beam type Multi-Points Constraint (MPC) was used at the left end of the beam to simulate the roller support. The axial restraint to the beam was simulated using the SPRING element. The out-of-plane displacement at one third and two third span were restrained to prevent the lateral torsional buckling. The automatic stabilization technique in ABAQUS was utilized to ensure convergence of the simulation with a dissipated energy fraction of $1 \times 10^{-5}$ [35]. Effects of local buckling of flanges and web on the catenary action of CSB was not considered in this paper thus no initial imperfection was induced in the finite element model.

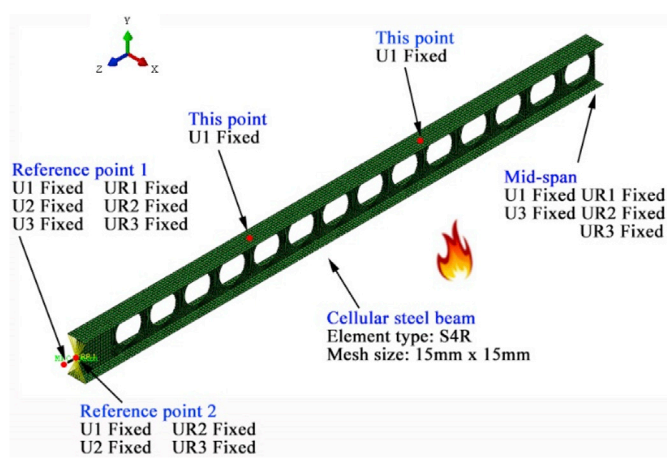


Fig. 2. Finite element model of the CSB at elevated temperature.

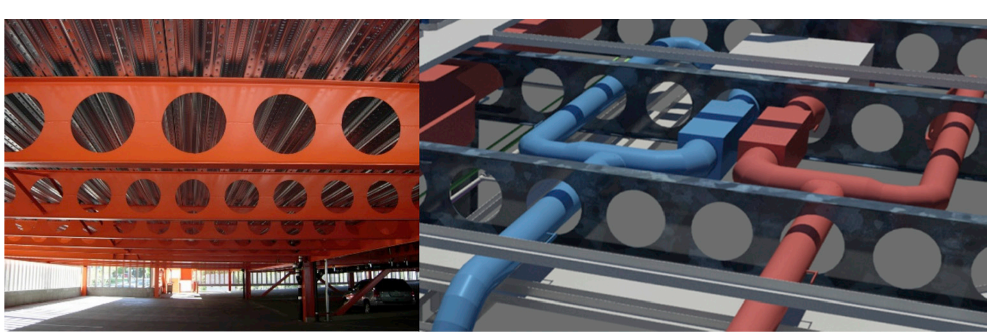

Fig. 1. Application of CSB.