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Practical method for calculating the buckling temperature of the web-post in a cellular steel beam in fire

Peijun Wang*, Xudong Wang, Mei Liu

Civil Engineering Department, Shandong University, Jinan 250061, Shandong Province, China

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ABSTRACT

Buckling behaviors of web-posts in a cellular steel beam at elevated temperatures in a fire were studied using the Finite Element Method (FEM) analysis and available analytical models. The buckling temperatures obtained by the analytical models differed greatly to those obtained from the FEM simulation. Among these analytical models, the buckling temperature obtained through the strut model based on BS5950-1 agreed with the FEM result the best. It is more reasonable to take the width of the compression stress band in the web-post as the effective width of the strut. Numerical parametric studies showed that the width of the compression stress band varied with the opening diameter, the opening distance and the web thickness. A simplified method was proposed to calculate the effective width of the strut. The accuracy of the strut model integrating the new effective width was validated against the FEM simulations. The obtained buckling temperature of the web-post using the modified strut model agreed well with the FEM simulation result.

1. Introduction

The cellular steel beam (CSB) can be made through cutting an H-section steel beam in a zigzag pattern along the web and then re-welding the web-post together or through cutting circular holes in the web directly. The obtained CSB has a higher strength to weight ratio and allows service integration to be installed within the beam depth, as shown in Fig. 1. For the discontinuous in the web, local failures modes, such as the web-post buckling and the Vierendeel bending failure at the perforated section, may happen in a CSB [1]. In the fire situation, the design of a CSB is getting more complex for the degrading of steel at high temperatures and the non-uniform thermal strain across the section [2–4].

For a CSB with a high web height to thickness ratio, the web-post buckling failure was the main concern. Web-post buckling behaviors in CSBs had been investigated experimentally and numerically recently. At ambient temperature, the buckling of the web-post is defined as when the out-of-plan displacement in a web-post suddenly increases [5,6]. The web opening shape may also affect the buckling strength of the web-post. Wang et al. [7] had studied the web-post buckling strength of a CSB with fillet corner hexagonal web openings. Analytical models have also been developed to simply estimate the buckling load of the web-post in a CSB [8–13].

For the Young's modulus of steel degrades faster than the yield strength with the elevating temperature, the CSB is more vulnerable to the web-post buckling failure in the fire situation. A CSB was failed by Vierendeel mechanism failure at ambient could be failed by web-post buckling in the fire situation. Though modifying the degrading function of the yield strength of steel at high temperatures, Bihina et al. [10] calculated the critical temperature of a composite cellular beam in a fire. Bitar et al. [11] proposed an empirical model to calculate the buckling strength of a composite cellular beam based on the method presented in SCI publication 100 [12]. Lawson et al. [13] proposed a method to determine the maximum compressive stress in the web-post. Instead of checking the critical section in the web-post, the strut model treated the web-post as a compression strut and checked its stability based on the column buckling curves in BS5950-1 [14].

In this paper, three analytical models for assessing the web-post buckling behaviors at ambient temperature were used to find the buckling strength and buckling temperature of the web-post in the fire condition. A simplified method through modifying the current strut model was proposed to calculate the buckling temperature of a web-post in the CSB. The new effective width in the modified strut model took the width of the compression band in the web-post which was obtained through FEM analysis. And a simplified method was presented to calculate the new effective width. The buckling temperature of the web-post predicted by the proposed strut model was validated by FEM analysis.

2. Finite element model

The finite element software ABAQUS was used to simulate buckling behaviors of the web-post in a CSB at the ambient

* Corresponding author. Tel./fax: +86 531 88392843.
E-mail address: Pjwang@sdu.edu.cn (P. Wang).

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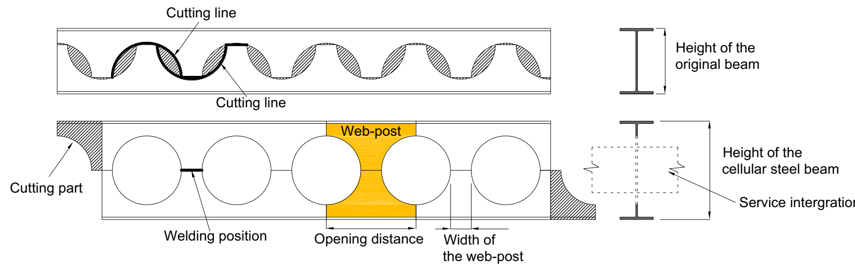

Fig. 1. Cellular steel beam.

temperature and in the fire situation. The numerical simulation included three steps:

(1) Obtaining the load bearing capacity of a CSB under the concentrated load at middle span at ambient temperature through utilizing the Riks method in ABAQUS;
(2) Obtaining the temperature fields in the unprotected CSB or the unprotected composite cellular beam exposed to standard fire using the thermal analysis;
(3) Obtaining the buckling temperature of the web-post in CSB at a given load ratio in the fire situation. The load ratio is the ratio of the applied load to the load bearing capacity at ambient temperature obtained in step (1). The load ratio takes 0.5 here for illustration.

2.1. Mechanical model at ambient temperature

The studied CSB was made through cutting circular holes in the web of a steel beam with section of UB457 × 152 × 52. In order to prevent the flexural torsional buckling failure of the CSB, the lateral displacement of the flange at the middle span was fixed. Web stiffeners were placed at the supports and the mid-span where the concentrated force was applied to prevent the buckling of the web under the local concentrated force. Initial out-of-plane imperfection of the web-post took the first buckling mode obtained from the buckling analysis of ABAQUS. The magnitude of the initial-out-of-plane imperfection was 1 mm. The CSB was meshed by the S4R element in ABAQUS, a 4-node reduced integration shell element, as shown in Fig. 2. The steel was grade S355 steel with Young's modulus of 200 GPa and the Poisson's ratio of 0.3. Geometrical and mechanical properties of the studied beams were listed in Table 1 [6].

The FEM model was calibrated against experimental results reported by Tsavdaridis and D'Mello [6]. Mesh convergence studies showed that the S4R shell element with the mesh size of 10 mm could give accurate results, as shown in Fig. 3. Comparison of load-deflection curves and failure modes of the web-post obtained from the proposed FEM model and the test were shown in Fig. 4(a) and (b).

The ultimate load obtained from the FEM simulation was greater than that from the test [6], which might be caused by the assumption in the magnitude of initial out-of-plan imperfection of the web-post. In the test carried out by Tsavdaridis and D'mello [6], no measured initial imperfection was reported. Redwood and Demirdjian [5] recorded a measured maximum imperfection of the web in their tests which was about 1 mm (26.3 times of $t_w/200$). Undoubtedly, the web-post with a greater initial geometric imperfection has a smaller ultimate load. However, at present there were no researches that presented a larger initial imperfection than 1 mm. In the following parametric study, the initial imperfection was taken as 1 mm. FEM simulation results reported by Tsavdaridis and D'Mello [6] were also presented in Fig. 4(a). The simulated ultimate load presented by Tsavdaridis and D'mello [6] was greater than that obtained from the FEM model presented here, for a much smaller imperfection of $t_w/200$ (0.038 mm) was introduced in their model.

In the FEM simulation, the CSB was failed by the web-post buckling, which agreed well with the test result, as shown in Fig. 4(b). The out-of-plane displacements in the upper and lower part of the web-post were in the opposite direction and the web-post buckled in an S-shape mode along the section height.

2.2. Thermal-mechanical coupled model in the fire situation

2.2.1. Thermal-mechanical coupled model

Heat transfer analysis was carried out first to obtain the temperature field in a CSB and a composite cellular beam exposed to the ISO834 standard fire. Points where the temperatures were reported for verification were shown in Figs. 2 and 5.

In the thermal analysis model, the CSB was meshed using the 4-node heat transfer quadrilateral shell element DS4. The concrete slab in the composite cellular beam was meshed using the 8-node linear heat transfer brick element DC3D8. Both the radiation and convection heat transfer between the fire and the structural component were included in the model, as shown in Fig. 6. The CSB exposed to fire from four sides and the composite cellular steel beam exposed to fire from three sides. The emissivity of the surfaces and the convective heat transfer coefficient were taken as 0.8 and 25 $W/m^2 K^{-1}$, respectively. The convective heat transfer coefficient was taken as 4 $W/m^2 K^{-1}$ for the unexposed side of the concrete slab in the composite cellular beam. Thermal properties of steel and concrete varied with temperatures and took those described in ENV1993-1-2 [15] and ENV1994-1-2 [16].

In the mechanical model, the DS4 element to mesh the CSB was replaced by S4R structural shell element and the DC3D8 element to mesh the concrete slab was replaced by C3D8R structural brick element. The temperature field in the CSB and the concrete slab were defined by reading the result file generated during the thermal analysis. Mechanical properties of steel and concrete at elevated temperatures followed the descriptions in EN 1993-1-2 [15] and ENV1994-1-2 [16]. The ABAQUS/Explicit was used in the simulation to avoid convergence problems which were often encountered when doing the geometric and material non-linear numerical analysis. The buckling temperature was defined at which the lateral displacement of the web-post suddenly increased.

2.2.2. Model verification

2.2.2.1. Verification of the thermal model. EN1993-1-2 [15] provided equations to calculate the temperature elevation of an unprotected steel structural component exposed to fire.

$$\Delta\theta_{a,t} = k_{sh}\frac{A_m/V}{c_\alpha \rho_\alpha}\dot{h}_{\text{net}}\Delta t \tag{1}$$

where k_{sh} was the correction factor for the shadow effect; A_m/V was the section factor for unprotected steel members [1/m]; A_m was the surface area of the member per unit length [m^2/m]; V was the volume of the member per unit length [m^3/m]; c_a was the