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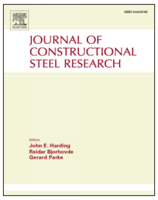

Large deflection behavior of restrained corrugated web steel beams in a fire

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ABSTRACT

Large deflection behaviors of restrained corrugated web steel beams (CWSBs) with both non-uniform temperature distribution (NUTD) and uniform temperature distribution (UTD) across the section in a fire were investigated using finite element model (FEM). The corrugated web adopted a commonly used trapezoidal shape. The applicability of FEM was validated against available test results on restrained flat web steel beams (FWSB) in a fire. Studied parameters included load ratio, axial restraint stiffness ratio, span–depth ratio, thickness of the flange and web and the incline angle of trapezoidal shape. Evolution curves of the vertical deflection, the axial force, the catenary action moment and the axial force provided by the corrugated web of restraint CWSB were presented. Due to the reduced axial stiffness of a CWSB, the axial compressive force in a restrained CWSB was much smaller than that in a FWSB. The vertical deflection of a CWSB with NUTD was larger than that with UTD at first for the bowing caused by temperature gradient across section. And it was smaller in catenary action stage, for the top flange of CWSB with NUTD having much greater yield strength and Young's modulus. At the catenary action stage, the axial tension in the top flange of the restrained CWSB with NUTD was higher than that in the bottom flange, which could cause a negative internal bending moment. Catenary temperature of a restrained CWSB with NUTD was a little higher than with UTD. But failure temperature of a restrained CWSB with NUTD was much lower than that with UTD. For the negligible axial stiffness in corrugated web, variations of web corrugation parameters have little influence on large deflection behaviors of restrained CWSBs with NUTD and UTD. Through including the catenary action of a restrained CWSB in a fire, the critical temperature was increased from the catenary temperature to the failure temperature. And the increase of critical temperature was at least 200 °C, which could greatly reduce the fire protection cost a CWSB.

1. Introduction

Corrugated web steel beams (CWSBs) have been widely used in large span buildings and bridges for their high strength to weight ratio. Compared with a flat web steel beam (FWSB) with the same section height and flange area, the bending stiffness and bend moment capacity of a CWSB is nearly the same [1]. And there is no need to add transverse or longitudinal stiffeners to the web for its local buckling strength is increased through corrugation. However, the axial stiffness of the CWSB is greatly reduced since the corrugated web nearly has no axial stiffness.

The shear buckling failure of corrugated web was the main failure mode of a CWSB. Driver et al. [2] had carried out two full-scale tests to investigate shear buckling behaviors of corrugated web bridge girders. Luo and Edlund [3,4] performed a series of numerical studies to investigate influences of corrugation shape on shear buckling behaviors. Abbas et al. [5] and Elgaaly et al. [6] proposed design equations for calculating the shear buckling strength. The corrugated web should be assumed as an isotropic plate if the shear buckling only occurred in one corrugation wave; and it was assumed as an orthotropic plate with equivalent thickness if the shear buckling occurred overpassing several corrugation waves.

The bending moment capacity and axial tension/compression capacities of a CWSB are different to those of a FWSB. Elgaaly et al. [7] studied the bending moment capacity of a CWSB by model test and proposed that the ultimate bending moment capacity of a CWSB could be calculated based on the flange yielding. The contribution from the corrugated web could be ignored. Luo and Edlund [8] investigated influences of corrugation shape on behaviors of a CWSB with trapezoidal webs under patch load. Failure modes of the CWSB included flange collapse, web crippling or web yielding [9–11].

Under fire conditions, behaviors of a beam in global structure are different to those of an isolated one. The axial restraint provided by adjacent columns allows the beam to develop catenary action at high temperature in a fire. Thus, part of the external bending moment induced by the lateral load on the beam is resisted by the tensile reaction force acting on the vertical deflection, which causes to the load-bearing mechanism changed from a beam to a suspended cable. The failure temperature of a restrained steel beam in a fire can be significantly

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increased. And the fire protection to a restrained steel beam can be reduced or eliminated.

Many experimental and numerical investigations on restrained steel beams in a fire have been carried out. Liu et al. [12] and Liu and Davis [13] carried out a series of fire tests to study the catenary action of restrained steel beams in a fire. Test results showed that the catenary action was more pronounced in cases with lower load levels and higher axial restraint. However, it became obvious only at large deflection. Vácha et al. [14] carried out both isolated element tests and full-scale building tests on composite corrugated web steel beams to investigate their thermal and mechanical responses subjected to standard fire and natural fire, respectively. Uneven temperatures developed along the web height for the protection of concrete slab to the top flange. Single element fire tests showed that web regions in the vicinity of the flange had a lower increase rate compared to the mid-height of the web which would affect the bearing capacity assessment of structural elements. The full-scale building test revealed that the deformation development for both tests was similar and presented in the form of the web loss of resistance due to fast temperature increase. Yin and Wang [15] and Li et al. [16] numerically investigated the behavior of axially restrained steel beams in a fire. And the effects of non-uniform temperature distributions were considered in their investigations.

For the lack of practical design method, structural engineers are reluctant to include the catenary action in the routine fire-resistance design. Some simplified method on catenary action was presented recently. A simplified hand calculation method was proposed by Yin and Wang [17,18] to analyze the catenary action in steel beams under uniform and non-uniform temperature distribution. Li et al. [19,20] proposed a theory model based on restrained steel beams with catenary action under distributed load. Dwaikat and Kodur [21] proposed a performance based design methodology for fire design of restrained steel beams.

Current researches on catenary action of restrained steel beam are mainly focused on a beam with uniform temperature distribution (UTD) across the section. However, the steel beam appears to be exposed to fire from three sides for the protection by the concrete slab which will lead to the non-uniform temperature distribution (NUTD) across the section. The temperature in the top flange will be much lower than that in the bottom and in the web, which will cause additional vertical deflection as well as reducing the fire-induced axial force in the beam. Heidarpour and Bradford [22] 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 [23] proposed a simplified approach for adjusting 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 approximated linear in the thermal analysis results. Catenary actions of CWSBs with UTD had been studied by Wang et al. [24]. However, research results on the catenary behavior of CWSB with NUTD across the section are rarely reported.

This paper investigated large deflection behaviors of restrained CWSBs with both NUTD and UTD across the section in a fire using finite element method. The studied CWSB adopted the commonly used trapezoidal shape web, as shown in Fig. 1. For lack of test results on restrained CWSBs in a fire, the capability of the finite element model (FEM) was verified against available fire test results on restrained FWSBs. The effects of different parameters on large deflection behaviors of restrained CWSB in a fire were presented. Parameters studied in this paper included load ratio, axial restraint stiffness ratio, span–depth ratio, thickness of the flange and web and corrugation shape of the web. The evolutions of the vertical deflection, the axial force and the catenary action moment of the CWSB with elevated temperatures were presented. The difference between the CWSB and FWSB was also presented.

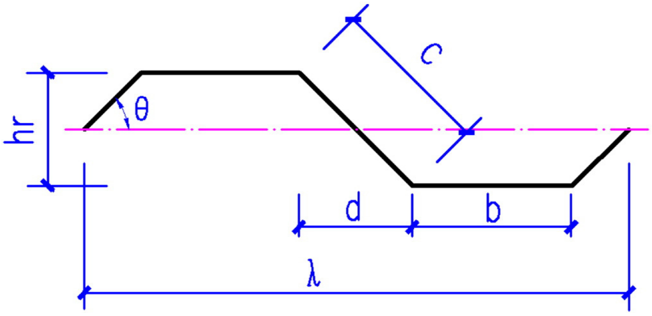


Fig. 1. Trapezoidal shape web.

2. Finite element model and verification

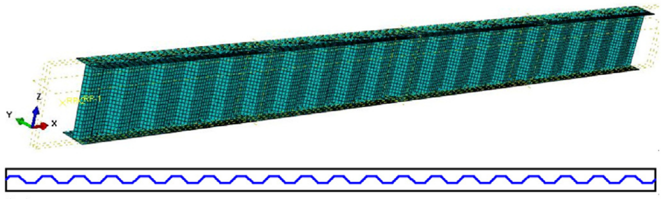
2.1. Finite element model

2.1.1. Model description

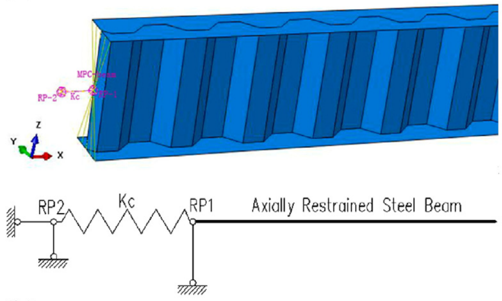
Only half of the axial restrained CWSB was modeled for the beam was symmetry about plane y–z, as shown in Fig. 2(a). The Poisson ratio of steel was 0.3 and the coefficient of thermal expansion was 1.4×10^{-5}. The yield strength and Young's modulus of steel was 345 Mpa and 2.05×10^5 MPa at ambient temperatures, respectively. Reduction factors of yield strength and Young's modulus at high temperatures as well as the stress–strain relationships at different temperatures of steel followed recommendations in EN1993-1-2 [25]. The CWSB was meshed using the shell element S4R in ABAQUS, a four-node reduced integration finite strain shell element, with mesh size of 20 mm as results of mesh sensitivity analysis.

2.1.2. Boundary conditions

Boundary conditions at the left end of the beam were applied through the multi-point constraint (MPC) with beam OPTION in ABAQUS. The u_y, u_z and rot$_z$ degree of freedom of the MPC control point were fixed to simulate the simply supported boundary condition. The x–y–z coordinate system was shown in Fig. 2(b). An elastic spring in the x direction connected the MPC control point to the ground to simulate the elastic axial restraint to the beam, as shown in Fig. 2(b). The



(a) FEM of the CWSB



(b) Boundary conditions of the CWSB

Fig. 2. FEM of axial restrained CWSB.