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Numerical studies on large deflection behaviour of axially restrained corrugated web steel beams at elevated temperatures

Peijun Wang*, Changbin Liu, Mei Liu, Xudong Wang

Civil Engineering College of Shandong University, Jinan, Shandong Province 250061, China

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ABSTRACT

The large deflection behaviours of axially restrained corrugated web steel beam (CWSB) at elevated temperatures were investigated using a finite element method. The web of studied CWSB adopted commonly used trapezoidal shape. The applicability of finite element model presented was validated against test results on the restrained flat web steel beam (FWSB) in a fire. Studied parameters of CWSB included the load ratio, the axial restraint stiffness ratio, the span-depth ratio, the corrugation shape of the web, the web thickness and the flange thickness. The evolutions of the vertical deflection, the axial force and the bending moment at mid-span of the CWSB with the elevated temperatures were presented. For the axial stiffness of a CWSB was smaller than that of a FWSB with the same dimension, the compressive force due to the restrained thermal elongation in a CWSB at elevated temperatures was lower than that in a FWSB. In addition, the CWSB went into the catenary action phase at a lower temperature compared with the FWSB with the same load and axial restraint stiffness ratio. The corrugation shape and the thickness of the web had very little influences on the catenary action behaviour of the restrained CWSB at elevated temperatures. Parameters that greatly affected behaviours of CWSB at elevated temperatures were the load ratio, the axial restraint stiffness ratio, and the span-depth ratio. With the increase in load ratio, the temperature at which the restrained CWSB went into catenary action phase decreased. The axial restraint stiffness and the span-depth ratio did not affect the temperature at which the restrained CWSB went into catenary action phase. However, with the increase in the axial restraint stiffness, the maximum axial force that the CWSB experienced increased and the temperature at which the maximum axial force was reached decreased. With the increase in the span-depth ratio, the maximum axial force the CWSB experienced and the temperature at which the maximum axial force was reached decreased.

1. Introduction

The out-of-plane stiffness of a thin plate is greatly increased through corrugating. The height to thickness ratio of the beam web in a Corrugated Web Steel Beam (CWSB) can be as great as 600. It is usually 120 in a flat web steel beam. The corrugation reduces the axial stiffness of the beam web. Its contribution to axial strength and bending moment resistance can be ignored [1]. The bending moment and the axial force are mainly carried by the two flanges of the beam. The transverse shear force is mainly carried by the corrugated web.

The shear buckling of the corrugated web was the main failure mode of a CWSB. Abbas and Elgaaly [2,3] had proposed design equations on shear buckling strength of the corrugated web. Smith and Hamilton [4,5] carried out tests to investigate shear buckling behaviour of the corrugated web subjected to shear. Luo and Edlund [6–8] performed a series of numerical studies to investigate influences of corrugation shape on behaviour of the corrugated web.

The behaviour of a CWSB subjected to the bending moment and axial load is different to that of a Flat Web Steel Beam (FWSB). Results of tests and numerical analysis confirmed that the corrugated web nearly carry no axial stress when the CWSB was in bending. Elgaaly et al. [9] performed bending tests and theoretical analysis to investigate the bending moment strength of the CWSB. The ultimate bending moment capacity of a CWSB can be calculated based on the flange yielding, which neglects the contribution from the corrugated web. Generally, the CWSB fails to bear the load due to a flange collapse, web crippling or web yielding [10–12]. Luo and Edlund [13] used the nonlinear finite element method to investigate the influence of the corrugation shape on the behaviour of the CWSB with trapezoidal webs under patch load.

The lateral torsional buckling is another failure mode of a CWSB. Chan and Khalid [14] had used the finite element method to study effects of the web corrugation shape on the flexural

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

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torsional buckling behaviour of a CWSB under bending. Johnson and Cafolla [15] investigated the interaction of the local flange buckling and the lateral torsional buckling of a CWSB. Lindner [16] studied the lateral torsional buckling behaviour of CWSBs with trapezoidal webs and proposed a simplified equation for calculating the warping constants of the section. Abbas [17] and Abbas et al. [18,19] presented a theoretical design equation for the flexural torsional buckling of a CWSB under in-plane load.

Under fire conditions, the behaviour of the beam in a global structure is different to that of an isolated one. The pulling action from the adjacent structure allows the axially restrained beam to develop large vertical deflection in a fire. The load bearing mechanism will change from a beam to a suspended cable. The survival temperature of a restrained steel beam in a fire was significantly increased if the catenary action was included. 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. [20,21] conducted a series of fire tests to study the large deflection behaviour of restrained steel beams in a fire. Li and Guo [22] carried out fire test to investigate the behaviours of the restrained steel beams subjected to the whole heating and cooling phases of a fire. Yin and Wang [23] presented a numerical study on large deflection behaviours of the restrained steel beam at elevated temperatures. Li et al. [24] investigated the behaviour of axially restrained steel beams in a fire by non-linear finite element analysis.

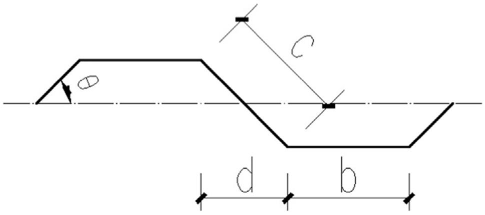

Fig. 1. Trapezoidal shape web.

The robustness of the beam–column connection is the key factor to allow the restrained steel beams to develop catenary action in a fire. Al-Jabri [25] and Al-Jabri et al. [26,27] studied the moment-rotation characteristics of the beam–column connection in a fire. Leston-Jones [28] investigated the influence of semi-rigid connections on the performance of steel framed structures in a fire. Spyrou et al. [29] conducted experimental and analytical investigation on the tension zone component within a steel joint at elevated temperatures.

However, 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. Li et al. [30,31] proposed a theory model based on restrained steel beams with catenary action under distributed load. Yin and Wang [32,33] proposed a simplified hand calculation method to analyze the catenary action in steel beams under uniform and non-uniform temperature distribution. However, there were no research results on large deflection behaviours of restrained CWSB at elevated temperatures yet.

This paper presented numerical studies on large deflection behaviours of axially restrained CWSBs at elevated temperatures. The studied CWSB adopted the commonly used trapezoidal shape web, as shown in Fig. 1. The numerical analyses were conducted by the finite element software ABAQUS. For lack of fire test results on restrained CWSBs, the presented finite element model was verified by test results on restrained FWSBs. Studied parameters included the load ratio, the axial restraint stiffness ratio, the span-depth ratio, the corrugation shape of the web, the web thickness, and the flange thickness. The load ratio was defined as the ratio of the applied maximum bending moment in a simply supported beam to the beam plastic bending moment capacity at ambient temperature. And the axial restraint stiffness ratio was defined as the ratio of the axial

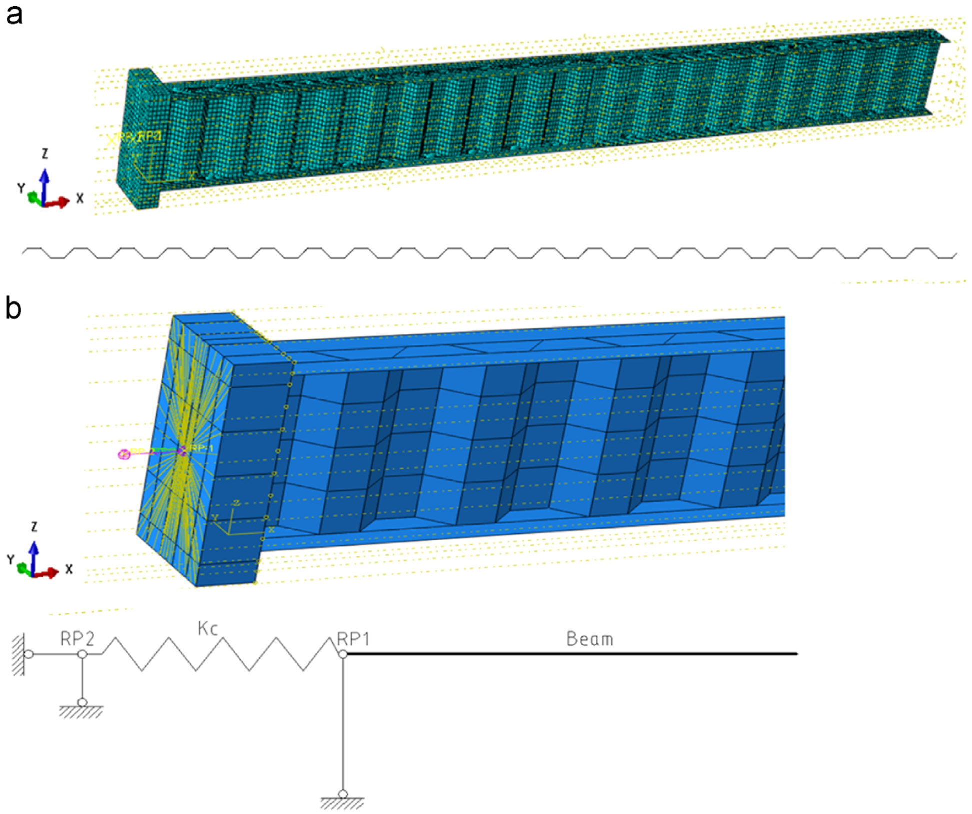

Fig. 2. Finite element model of the corrugated web steel beam. (a) Model of CWSB. (b) Boundary conditions of CWSB.