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Finite element analysis of thermal residual stresses in castellated beams

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ABSTRACT

The objective of the study is to numerically investigate the residual stresses in castellated beams. The fabrication processes with cutting and welding will significantly change the residual stresses of the castellated beam compared to its parent I-beam (or H-beam). These residual stresses have a significant impact on the lateral-torsional buckling resistance of castellated beams. However, due to the complexity of the problem, the investigations are far from complete. In this study, three-dimensional finite element models are developed to simulate the thermal residual stresses in the castellated beams due to the cutting and welding fabrication processes. The temperature fields and the cutting-induced and welding-induced residual stresses are numerically investigated. In addition, the predicted thermal residual stresses are then validated with experimental results in the literature. With the validated model, a parametric study is conducted to investigate the effects of the sectional parameters on the thermal residual stresses, including the flange thickness (t_f), the flange width (b_f), and the thickness of the web (t_w), etc. Then, the influences of t_f, b_f, and t_w, etc. on the thermal residual stresses at the flange tips are compared. Finally, the potential development of residual stress distributions in castellated beams is discussed.

1. Introduction

Compared to conventional I-section beams, castellated beams possess great advantages in terms of lighter weight, greater flexural stiffness, better aesthetic architectural appearance, and substantial material efficiency, etc. Therefore, castellated beams are widely used in stadiums, bridges, plants, and multi-storey buildings, which demand a large span. As shown in Fig. 1, a castellated beam is commonly produced by flame cutting the web of an I-beam (or H-beam) along with a predefined line and then welding the halves following certain pattern. During the production of the castellated beam, the intense localized heating in the cutting and welding processes causes severe thermal gradients, which result in thermal residual stresses due to the uneven cooling. Typically, the tensile residual stresses (up to the material's yield stress) are generated at the locally heated zone and balanced by the compressive stresses in the remaining portion of the beam. It is expected that this production process will significantly change the initial residual stresses in the conventional I-beam (or H-beam).

A large number of studies related to the residual stress patterns of the castellated beam are available in the literature including a limited size of experimental investigations. Experimentally, Sonck [1, 2] measured the variations of longitudinal residual stresses of castellated beams produced from a standard fabrication procedure as illustrated in Fig. 1 and investigated their impacts on the lateral-torsional buckling resistance of the castellated beams both experimentally and numerically. Jia et al. [3] also reported an experimental investigation on the residual stress distributions in the web of seven castellated beams fabricated from welded H-beams, using standard procedure, and non-standard procedure by cutting openings in the web directly. The influences of the opening shape and vertical opening ratio on the residual stresses were then investigated. It was worth noting that they considered that the openings had a negligible effect on the residual stresses in the flange and thus the residual stresses were not measured in the flange, instead it was assumed to be the same as those in the parent H-beams.

Meanwhile, the buckling behaviors of castellated (and cellular) beams taking into account the effect of residual stresses were investigated by a variety of studies, such as the investigation on the lateral-torsional buckling behavior of castellated beams by Sonck [2] aforementioned. In addition, Ellobody [4] studied the impact of residual stresses on the behavior of the cellular beams numerically by assuming the same residual stress pattern as that in the conventional I-section beams [5] and revealed that the Australian specification [6] would overestimate the load-bearing capacity of the cellular beams failing by a combined web distortional and web-post buckling. Moreover, Chen et al. [7] numerically investigated the lateral-torsional buckling behavior of castellated beams by taking in account the residual stresses in [1]

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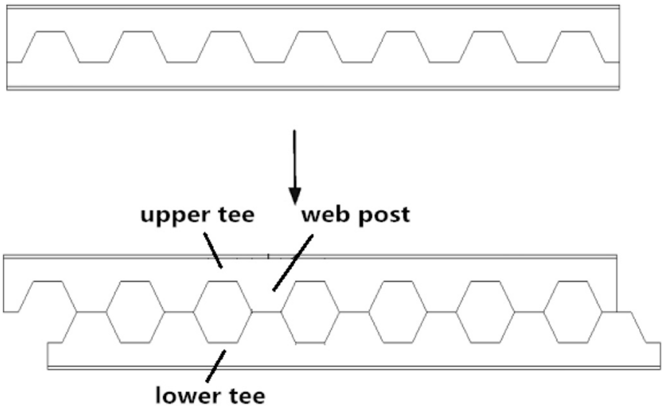

Fig. 1. Fabrication of a castellated beam.

and revealed the significant influence of the residual stresses at the tips of the flanges. Other studies on the buckling resistance of the cellular and castellated beams considering the residual stress impact can be found in [8–10]. These studies showed that the longitudinal compressive residual stresses at the tips of flanges facilitated the onset of yielding and had a detrimental effect on the lateral-torsional buckling resistances of castellated or cellular beams.

However, with the limited investigations on the residual stress distributions in castellated beams, the conclusions are far from complete or even conflicting with each other in certain aspect due to the complexity of the problem. In order to facilitate a wider application of castellated beams, it is necessary to clarify that to what extent the fabrication process influences the initial residual stresses of castellated beams, especially the residual stress distribution in the flange. Hence, further numerical and experimental studies are necessary.

Thus, this paper numerically investigates the effect of the fabrication on the longitudinal residual stress distribution in castellated beams. Simulations of the cutting and welding processes are carried out using the commercial finite element package ANSYS on the CS1 test member in [1, 2]. Because the parent beam, I section, is symmetric about the centroid of the web, with the welding along the centroid line and the openings of the castellated beam along the length evenly spaced, the resulted section is still symmetric about the centroid of web and the openings are periodic along the length. Hence with these symmetric conditions, only the upper half of a short section between the center-line of adjacent openings has been modeled. The thermal induced residual stresses predicted from the numerical investigations are then compared with those in the published experimental results. Additionally, a parametric analysis is performed to investigate the effect of sectional properties, such as the flange thickness, the flange width, and the thickness of the web, on the thermal induced residual stresses in the production process. Finally, as a demonstration, an exercise of the potential development of the residual stress distributions in castellated beams is presented.

2. Finite element analysis

2.1. Finite element model

In this section, the commercial finite element package ANSYS was used to build the thermo-mechanical finite element models to simulate the real cutting and welding processes in experiments. In Refs. [1, 2], castellated beams with hexagonal web openings were produced by cutting the web of a rolled I-beam in a zigzag pattern along its center-line and then the two halves were shifted and welded as shown in Fig. 2. The openings in the web along the beams were evenly spaced. According to symmetry, only the upper half of a short section between the center-line of adjacent openings was modeled in the study as shown in Fig. 3.

The mesh sensitivity was investigated using mesh convergence studies. For the balance between the accuracy and computational cost, a fine mesh was used in the regions including the kerfs, the weld, and the heat-affected zones. These regions experience dramatic local temperature variations during cutting and welding. Accordingly, the thermal induced stresses are large at these regions. Relatively coarse mesh could still provide adequate accuracy for the other parts far away from the location of the kerfs and the weld, as shown in Fig. 4. This mesh scheme was consistent with that in [11, 12]. The model contained a total of 7224 elements and 10,084 nodes.

The ANSYS package provides direct and indirect methods for the thermal stress analysis. The direct method simulates the thermal and mechanical analyses simultaneously by using the coupling element with temperature and displacement freedom. However, the convergence is usually difficult. Given the structural deformation has little impact on the thermal analysis, this study employed the indirect method in which a thermal analysis was performed first and then the mechanical analysis was implemented based on the thermal results. Specifically, the thermal analysis was implemented by adopting the 8-node thermal solid element of SOLID70 to acquire the temperature history in the cutting and welding processes. Later, the SOLID70 element was converted to the SOLID185 element for the mechanical analysis with the thermal load acquired in the thermal analysis.

2.2. Temperature field analysis

2.2.1. Temperature-dependent material properties

In the fabrication of castellated beams, the steel members undergo intense temperature change. Because the material properties vary with temperature, the simulation model needs to properly account for the temperature-dependent material properties. In this study, the material properties of steel at room temperature and at high temperature were referenced from [2] and [12–14] respectively, as listed in Table 1.

2.2.2. Selection of heat sources

The heat source models generally used for numerical simulation include the Gaussian heat source [15], the double ellipsoidal heat source [16], and the birth-death element body heat source [17]. According to the experiment in Refs. [1, 2], the web was cut using an oxygen-

Fig. 2. Fabrication of the test members [2].