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Bending collapse theory of thin-walled twelve right-angle section beams filled with aluminum foam

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ABSTRACT

This paper aims at studying the bending collapse behavior of the thin-walled twelve right-angle section (TTRS) beams filled with aluminum foam. This paper presents the theoretical bending characteristics of the TTRS-typed aluminum foam around two axes. Considering the contribution degree of thin-walled beam and aluminum foam in different angle range, the expressions of the bending moments are derived. The accuracy of the theoretical calculations are validated by performing 14 groups finite element simulations respectively including three kinds of aluminum foams with certain scope of plateau stress (1–12.5 MPa) and corresponding density (0.2–0.52 g/cm^3). The results show that the bending collapse theory proposed in this paper can reflect the mechanical properties of the TTRS beams filled with aluminum foam accurately, and the moment–rotation curves calculated by theory are in good agreement with simulation results.

1. Introduction

As one kind of typical energy absorbers, thin-walled structures have been widely used in automotive, aerospace, military equipment and other industries, due to their excellent energy absorption capacity and extraordinary light weight [1]. As one basic deformation and energy absorption pattern of the thin-walled beams, bending deformation occurs when the safety components in vehicle body, which are consist of thin-walled members, are subject to impact loading. Therefore, the study of bending collapse theory of the thin-walled beams is the theoretical basis for the design of the body structure. Recently, the cellular solid is widely used in the energy absorption, thermal insulation and lightweight engineering as the use of the cellular metal filler can increase the energy absorption capacity of the thin-walled beams. In order to acquire higher energy absorption efficiency, hollow thin-walled beams filled with metal filler get more attention, such as aluminum foam which is widely used in the lightweight design of crash box and bumper [2,3].

In general, the bending failure of thin-walled beams occurs at a plastic hinge and the other parts rotate rigidly. The local collapse occurs in the beam and correspondingly the load carrying capacity drops significantly at a relatively small rotation angle, resulting in low energy absorption efficiency. Research results have shown that the interactions between filler and thin wall can change the failure mode and effective deformation space of thin-walled beam, and therefore produce larger bending moment. The mean crushing load of the thin-walled beam filled with aluminum foam is higher than the sum of the single crushing load of aluminum foam and thin-walled beam [4,5].

With the gradually increasing application of aluminum foam in engineering, researchers have begun the study of the bending behavior of the aluminum foam-filled rectangle beam. In 1999, Santosa studied the bending characteristics of foam-filled high-strength beams in the three point bending tests experimentally and numerically, and optimized the filling length of aluminum foam to obtain the maximum energy absorption efficiency [6]. In 2000, Chen quantified the strengthening effects of ultralight metal fillers and the moment–rotation characteristics of the filled section were derived using the fitting method based on the finite element analysis [7]. In 2007, Zarei conducted the three point bending tests, meanwhile, simulated the process with an explicit finite element code LS-DYNA. Using multi-objective optimization approach the density of the aluminum foam and the thickness of thin-walled beam were optimized for the purpose of the maximum energy absorption and the minimum weight [8].

Although the bending collapse theory of the thin-walled beam with rectangular cross-section is quite mature, to meet

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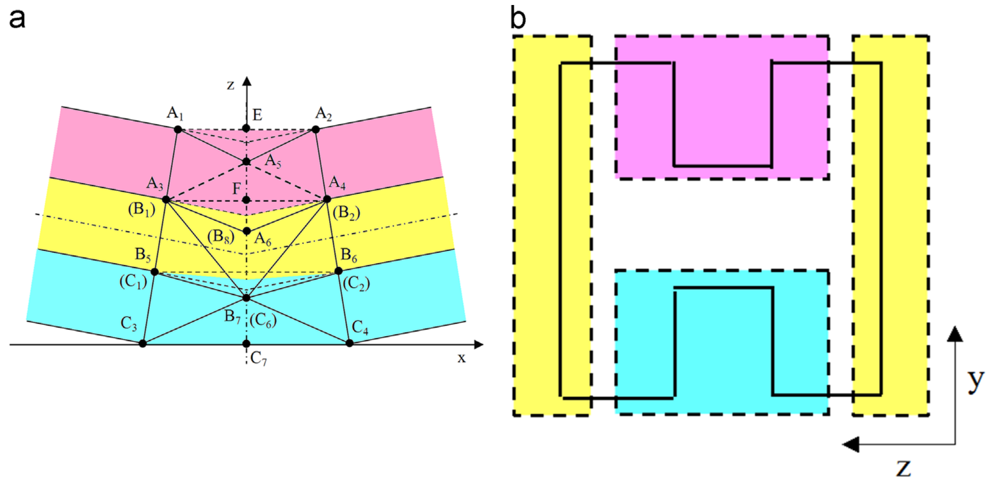

Fig. 1. Theoretical bending collapse mechanism of the TTRS beam around the *y* axis (a) and the *z* axis (b).

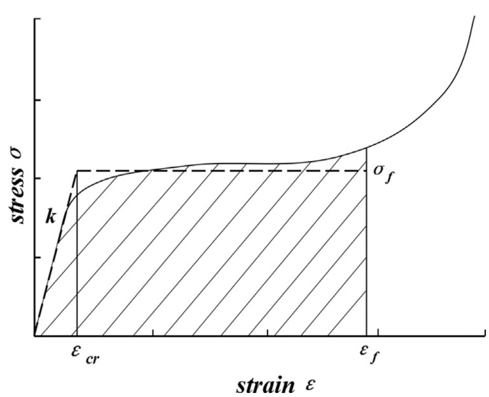

Fig. 2. Simplified stress–strain curve of the aluminum foam.

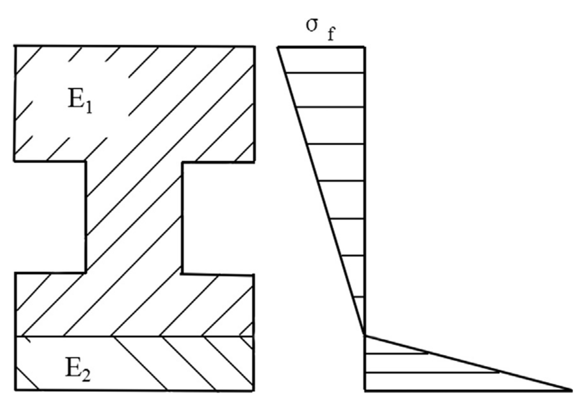

Fig. 4. Stress distribution in critical stress state bending around the *y* axis.

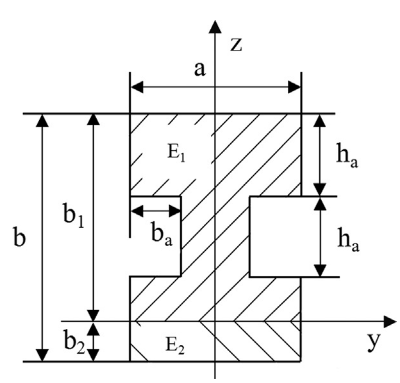

Fig. 3. Location of the neutral surface bending around the *y* axis.

higher requirements of crashworthiness and lightweight, researches for thin-walled multi-right-angle section beam increase gradually in recent years. Related studies have shown that compared with the thin-walled rectangular section beam, the thin-walled multi-right-angle section beam with the same perimeter has higher energy absorption efficiency which means the multi-right-angle section beam have greater lightweight space at the same time [9–11]. In 2014, Zhang et al. derived the bending moment theoretical expressions of the thin-walled twelve right-angle section (TTRS) beams bending around two axes, by extracting the TTRS beam deformation characteristics and simplifying the collapse mechanism [11,12]. Due to the filled aluminum foam, the deformation mode of the thin-walled beam is considerably different with respect to the hollow thin-walled beam. Therefore this paper discusses the bending characteristics of the TTRS-typed aluminum foam with no fracture failure and the hollow TTRS beam respectively, and based on the finite element simulation result, revises the contribution degree of the aluminum foam and the hollow TTRS beam in different angle range, and finally expresses the bending characteristics of TTRS beam filled with aluminum foam by the sum of them adopting weighted correction coefficients. This analysis contributes to a quick design of the section shape, size and material, and provides a prediction of the bending behavior and lightweight effect for the aluminum foam-filled TTRS beams in early design phase.

2. Bending collapse theory of thin-walled twelve right-angle section beams filled with aluminum foam around the *y* axis

2.1. Bending collapse theory of thin-walled twelve right-angle section beams [11]

In 2014, based on the Kecman's bending theory of rectangle section beams, Zhang considered the stretching of the walls and