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Crushing analysis of thin-walled beams with various section geometries under lateral impact

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A B S T R A C T

Due to the advantages of light weight and excellent energy absorption capacity, thin-walled beams are widely used as strengthen parts or energy absorbers in vehicle body. Thus, the collapse behaviors and mechanical properties of thin-walled beams under the static and dynamic loadings have drawn great attentions of the researchers. In vehicle side crash accident, the contact parts of the vehicle usually deformed in bending mode. Thus, it is significantly important to investigate the bending collapse behaviors of these parts. In this study, the bending behaviors of several thin-walled beams with simple cross section subjected to lateral impact were investigated using analytical and numerical methods. The crashworthiness parameters such as energy absorption (*EA*), average crash force (F_{avg}), peak crash force (F_{max}) and crash force efficiency (*CFE*) were employed to evaluate the bending resistant property. In order to study how geometry shapes affect the bending performance, the main geometry parameters such as radius/radius ratio of circular/ elliptical section, side length ratio of rectangular section, height and base angle of hat section were chosen as the design parameters. After investigating the beams with simple cross sections, some new beams with complex cross sections were constructed by combing these simple beams or adding reinforce ribs to these simple beams. Then, the bending performance of these new beams was studied by numerical simulation and compared with original section beams. Result shows that the section type b performs better in *SEA* and *CFE* than original simple section beams. It also can be concluded that adding ribs can greatly improve the bending resistant performance for circular, rectangular and hat section beams, and the vertical ribs can achieve the best reinforce effect for the circular and rectangular section beams.

1. Introduction

Due to the advantages of low price, light weight, high strength and stiffness, high reliability and excellent energy absorption capacity, thin-walled beams are widely used in crashworthiness applications such as automobile, train and aeronautical industries to protect passengers from severe injury [1–3]. To better understand the crashing mechanism and find more effective absorbers, a lot of research works on the axial crushing behavior of thin-walled beams have been carried out [4–6]. However, for side impact, the thin-walled beams will collapse in bending mode [7–8]. A study on the real world vehicle crashes presented by Kallina showed that up to 90% involved structural members failed in bending collapse mode [9]. Therefore, the bending behaviors of thin-walled members should be considered when vehicle body is designed.

The first comprehensive study on deep bending collapse of rectangular and square prismatic beams was made by Kecman [10]. In his study, simple failure mechanisms involving stationary and moving plastic hinge lines were proposed, and the moment-rotation characteristic was calculated in the post-failure range. However, the theory is semi-empirical because the rolling radius of moving hinge lines needs to be acquired from tests. A similar approach was developed by Abramowicz [11]. Koteko investigated the yield line mechanism (YLM) of rectangular and trapezoidal box section beams with a high width to depth ratio compared to Kecman's sections [12]. Park developed a solution for the bending collapse of trapezoidal section beams with different folding lengths on the top and bottom flanges and minimization of the total plastic energy rate included to determine the mode parameters [13]. This method however did not consider the mean crumpling moment. Kim and Reid gave a kinematically admissible new model and proposed a more accurate theoretical solution to predict the bending collapse of thin-walled beams based on some existing analytical relationship [14]. Huang and Lu proposed an empirical formula based on dimensional analysis [15]. The

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crushing behavior of circle tube under bending has also been studied analytically and experimentally. Elchalakani conducted a plastic mechanism analysis for thin-walled hollow section tubes deforming in a diamond or multi-lobe collapse mode under large deformation pure bending [16]. The predicted post-bulking moments and slopes of the collapse curves showed very good agreement with those obtained from experiments carried out by the researchers. Based on Elchalakani's research, Soheila applied the YLM technique using the energy method to investigate the collapse behavior and energy absorption capability of circle tubes under large deformation due to lateral impact load [17]. In his study, analytical solutions for the collapse curve and in-plane rotation capacity were also developed and used to model the deformation behavior and energy absorption. Apart from closed form section thin-walled beams, the bending behavior and crushing mechanism of open section beams was also investigated by researchers. Liu and Day studied the bending collapse of the thin-walled channel section beams and derived their approximation moment-rotation characteristics [18].

In order to achieve better bending performance and weight efficiency in energy absorption, ultra-light metal fillers such as aluminum foam, aluminum honeycomb introduced into the thin-walled structures has attracted increasing interest. Chen conducted the study on the crush performance of sheet aluminum foam-filled sections in compression and bending modes [19–20]. A study on the bending collapse of thin-walled beam filled with aluminum foam or honeycomb was also carried out by Chen [21]. In his study, the strengthening effects of ultra-light metal fillers were quantified through numerical and experiment method. The results showed the potential of significant weight saving and volume reduction by utilizing metal filler. It is found that thin-walled foam-filled beams as weight-efficient crash energy absorber have promising future. Santose and Wierzbicki carried out quasi-static three point bending simulations and experiments to study the effect of foam-filling on the bending resistance of a thin-walled beam [22–24]. The results showed that the presence of foam filler retards the inward sectional collapse at the compressive flange and changes the crushing mode from a single stationary fold to a multiple propagating fold which prevents the drop in the loading capacity due to local section collapse. It was shown that filling of metal foam could improve the load-carrying capacity by offering additional support from inside and increase the energy absorption. McGregor conducted experiments for aluminum hat section beams undergoing cantilever bending [25].

In this paper, the bending collapse behaviors of different cross sections thin-walled beams under lateral impact were investigated through theoretical analysis and numerical method. The force-displacement curves were obtained and the crashworthiness indexes such as *EA*, F_{avg}, F_{max}, *CFE* were adopted to analysis the bending resistance performance of thin-walled beams. The effect of geometry parameters of each section on the bending behavior of beam was studied. After that, several cross sections and strengthen schemes were proposed and studied to better understand the effect of topology pattern on the bending behavior of thin-walled beams.

2. Bending theory of thin-walled beams

2.1. Circular section beam

Generally, there are several approaches to determine the mechanical properties of structural members such as finite element analysis, experiments and theoretical analysis, among which experimental approach costs much and finite element method provides relatively accurate results but usually requires extensive time. Thus, the theoretical analysis is an efficient approach for the early step of design.

When circular tube is subjected to bending load, the plastic deformations occur over some folding lines which are called "hinge lines". When hinge lines are completed around the crushing area of the structure, global or local collapse will progress. The internal energy of structure is determined by the summation of plastic energy dissipated in each hinge line. In S. Poonaya's study [26], the collapse mechanism of circular tube subjected to bending is divided into three phases: elastic behavior, ovalisation plateau and structural collapse, and different deformation mode occurs in each phase. Under each phase, the internal energy dissipation rates were calculated for each of the hinge lines which were defined in terms of velocity field. The experiment was conducted with a number of tubes having various diameter to thickness ratios, and the theoretical prediction and experimental results showed great agreement.

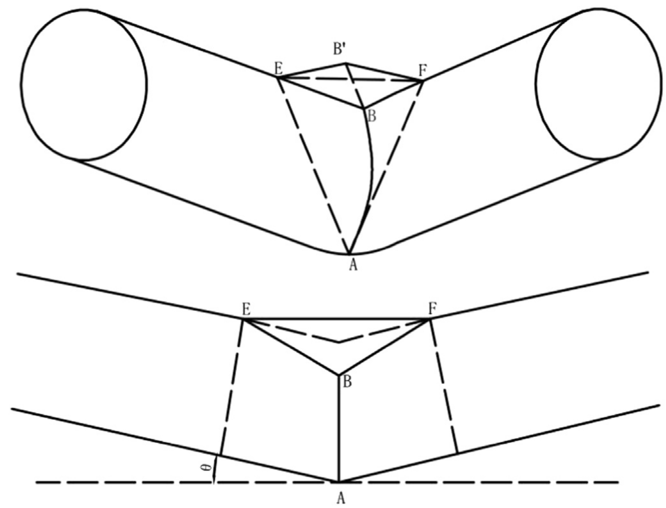

Fig. 1. YLM for circular tubes.

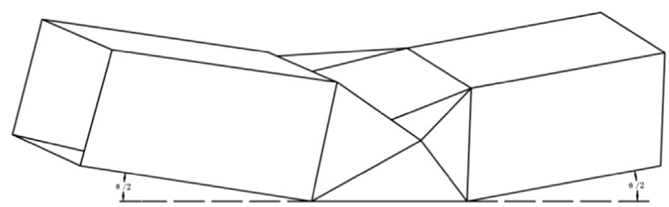

Fig. 2. YLM for rectangular tubes.

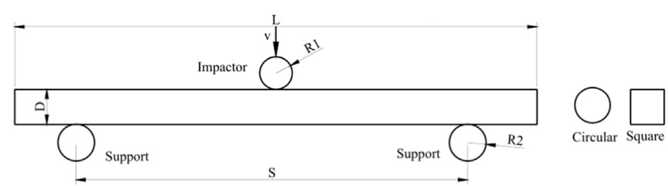

Fig. 3. Scheme of dynamic three-point bending test for circular and square beam.

Table 1
Mechanical properties of material.

Material	Density/kg/m^3	Yield stress, σ_y/MPa	Young's modulus, E/ GPa	Poisson's ratio	Tangent modulus/ MPa
AISI1080	7860	869	205	0.28	5669
AlMg0.5F22	2700	227	68.6	0.29	321