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Bionic design modification of non-convex multi-corner thin-walled columns for improving energy absorption through adding bulkheads

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ABSTRACT

Collapse analysis of the non-convex multi-corner thin-walled columns under axial loads illustrates that the non-compact expansion-contraction deformation mode of collapse may occur in some cases, which reduces greatly the energy absorption property of these structures. Inspired from the way by which the bamboo nodes and nodal diaphragms enhance the transverse strength of bamboo, the non-convex multi-corner thin-walled column is modified by adding bulkheads in the column for improving the energy absorption property, and a new excellent energy absorption structure named as the bionic non-convex multi-corner column (BI-NCMC) is proposed in this article, which is a non-convex multi-corner thin-walled column with bulkheads. The energy absorption of BI-NCMC has been investigated numerically. A progressive deformation mode has been achieved and this structure shows a higher energy absorption than a similar column without the bulkheads. The role of the bulkheads is to change the deformation mode from an expansion-contraction mode to a progressive mode, while the bulkheads themselves absorb little energy. The influences of parameters in the energy absorption of BI-NCMC are analyzed. It was found that the column with highest energy absorption efficiency is the one with the smallest number of bulkheads while still maintaining the progressive deformation mode.

1. Introduction

Thin-walled metallic structures and structural members are widely used in transportation vehicles and collision safety protection structures attached to, incorporated within them, or external structures designed to mitigate the direct impact forces of a moving vehicle [1]. When subjected to a collision, metallic thin-walled structure absorbs kinetic energy through irreversible deformation exhibited primarily by crushing; that is, wall collapse. The metal thin-walled column is a common kind of energy absorption structure, and it has an overlapping deformation under axial compression, which is an efficient way of energy absorption. Therefore extensive attention is drawn to this structure. Over the past decades even to the present much research has been done to improve the energy absorption and energy dissipation of thin walled metal columns often by varying the material characteristics, shape and wall thickness [2–5].

Thin-walled columns are important and widely used energy absorber owing to their excellent energy absorption property and manufacturability. Energy absorbing structures can be installed within vehicles or can be incorporated into the primary structure of the vehicle and it must meet two requirements: reduced weight and high energy absorption. Reducing the weight of the vehicle structure is one of the key features in the attempt to reduce vehicle fuel consumption and the corresponding exhaust emissions [6]. Advanced materials with improved energy absorption configurations can both improve the energy absorption and reduce the structure weight whether used as an add-on crash structure or incorporated into the support of the vehicle. It is observed that different deformation modes occur during collations, and much work has been done to predict its performance theoretically [7–11]. The usage of aluminum columns has become predominant in the recent years [12].

The structure of thin-walled columns affects the energy absorption performance enormously. The energy absorption efficiency of these structures is influenced by many factors. Zhang et al. [13] evaluated the energy absorption performance of regular polygonal and rhombic columns under quasi-static axial compression. Foam-filled tubes are often taken into consideration, and studies show that the existence of foam helps alter the collapse mode of the structure, thus could improve the crashworthiness performance [14,15]. Recently, Sun et al. [16,17] presented a novel functionally graded thickness thin-walled structure, which shows its appeal likewise. Cross-section configuration is also one of the

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most important factors. Thus many efforts have been made to improve the property by designing the cross-section configurations to pursue lighter weight structures that have higher energy absorption [18,19]. Thin-walled polygon tube was analyzed that the angle between neighboring flanges should be 90°–120° for the highest energy absorption efficiency [20], researches of multi-cell column [21–23], cylindrical multi-cell column [24] are great explorations. The further study of foam-filled multi-cell thin-walled structures also shows great properties [25].

The non-convex multi-corner thin-walled column (NCMC) is another kind of excellent energy absorption structure based on the improved thin-walled polygon column proposed in [26], which shows great properties. What's more, the structure is simple and easy to manufacture, and this adds to its appeal. If you first consider a thin-walled square column of some fixed perimeter and then uniformly increase the number of sides without increasing the perimeter, the energy absorption of the thin-walled column increases. Because of the nonlinear relationship between the energy absorption and the thickness of a thin-walled column, as the wall becomes thicker the energy absorption also increases while adding stability to the progressive deformation of the column. However, due to the non-convex cross section, as the number of walls increases or the material walls increase in thickness there is a tendency for the column perimeter to expand rather than the column to collapse upon itself. This non-compact overall expansion-contraction deformation mode of the section not only seriously affects the structure of the energy absorption efficiency but also leads to instability of the structure; this should be avoided. Thus, finding a new modification is urgent.

The design of a crashworthy thin-walled structure under an impact load is a very challenging job because it involves geometric nonlinear, elastic-plastic deformation and nonlinear contact deformation. Creatures in nature have experienced a long process of evolution to adapt to the environment, so they tend to have a better design that allows them to adapt to a variety of conditions: their structure often has superior mechanical and multi-functional properties. Bionics or biotical creativity engineering is the application of biological methods which aims the study and design of engineering applications; it has been used successfully in material and structure design [27,28], sensor design [29] and intelligent algorithms [30]. Bamboo is a highly evolved plant with a complex structure and good mechanical properties. It has high strength, high elasticity, stable performance, and high specific strength that can be up to 3–4 times greater than that of steel. At the same time, the slenderness ratio of the bamboo can reach 150–250 [27], indicating an extremely advantageous structure. Bamboo is not only a reasonable macro configuration with internodes, nodes and nodal diaphragm, but its vascular bundle also has gradient distribution along the thickness according to the optimal carrying capacity. The unique structure of bamboo acts as a buffer against external shocks, absorbs energy, while resisting breaking or overall failure. Such excellent materials and structural forms provide very beneficial reference for an energy absorbing structure and device design. Considering that bamboo has a large slenderness ratio and is difficult to be split, it is therefore a structure worth mimicking.

Inspired from the way by which the bamboo nodes and nodal diaphragms enhance the transverse strength of bamboo, the non-convex multi-corner thin-walled column is modified by adding bulkheads in the column for improving the energy absorption property, and a new excellent energy absorption structure named as the bionic non-convex multi-corner column (BI-NCMC) is proposed in this article, which is a non-convex multi-corner thin-walled column with bulkheads.

2. A bamboo-like bionic non-convex thin-walled column

2.1. Non-compact deformation mode of the non-convex multi-corner thin-walled column

Tang, et al. [26] studied the non-convex multi-corner thin-walled column and found that the energy absorption capacity of it was 1–3 times greater than that of traditional square columns under progressive deformation. The more sides and corresponding edges of the transverse section, the greater the energy absorption capacity it has. Appling the super folding element method, an axial folded mechanics model of the non-convex thin-walled square column was modeled. According to this model, the mean crushing force P_m of a thin-walled square column with axial progressive collapse can be written as

$$P_m = 3.26N^{2/3}\sigma_0 L_c^{1/3} t^{5/3} \quad (1)$$

where N is the number of corners in the cross section of the column, t is the thickness of the column wall, L_c is the perimeter of the cross section of the column, and σ_0 is the plastic flow stress of the material. As for the power-law material hardening, $\sigma = \sigma_u(\varepsilon/\varepsilon_u)^n$, the plastic

Fig. 1. The non-compact expansion-contraction deformation mode of non-convex thin-walled column.