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Quasi-static axial crushing experiment study of foam-filled CFRP and aluminum alloy thin-walled structures

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ABSTRACT

Thin-walled aluminum alloy (Al alloy) structure, carbon fiber reinforced plastics (CFRP) tube, aluminum foam (Al foam) and polyurethane foam (PU foam) all can be used as good energy absorbers in automobile, aviation and other industries for their light weight and high energy absorption capacity. In order to clarify the advantages of the design modes, this article studies the crushing behaviors of circular, hexagonal and square CFRP and Al alloy tapered tube and their foam-filled structures subjected to quasi-static axial compression, analyzes and compares the collapse modes and force–displacement curves of these investigated structures as well as calculates the energy absorption (EA) and the specific energy absorption (SEA) of these investigated structures. Experimental results show that the CFRP tapered tubes have higher SEA than that of the Al-alloy tapered tubes and the circular CFRP tubes filled with PU foam have better energy absorption capacity than that of the square and hexagonal structures. In addition, the SEA of the CFRP tube filled with PU foam is 30% higher than that of the Al alloy tube filled with Al foam. Therefore this article leads to a conclusion that PU foam-filled CFRP tapered tube is a potential structure for energy absorber and light weight design.

1. Introduction

Light weight, miniaturization and personalized urban electric vehicles will become new favorites for alleviating traffic congestion, energy conservation and environmental protection. At the same time, the crashworthiness requirements and narrow energy absorbing area layout space of this kind of vehicle have brought both opportunities and challenges to the application of new materials and structures such as metal foam and fiber reinforced composite material.

As the most traditional and effective energy absorbing structure, thin-walled metal tube has been widely used in almost all the vehicle collision energy dissipation system. However, thin-walled metal tubes have a weaker ability to withstand the non-axial load and easily generate Euler bucking which leads to inadequate energy absorption [1–4]. Newly emerged metal foam in the late 1990s obtained a rapid development in a short time, especially the aluminum foam, which is suitable for automobile collision, with the features of light alloy, sound-absorbing, heat insulation, vibration reduction, absorption of the impact energy and electromagnetic wave [5–9]. The porosity of the aluminum foam is 75–95%, the strength and density of the material follows the power exponent relation—the strength of the 20% density material is more than twice of the 10% density material [10–12]. Some studies have indicated that if the total external energy is 100%, and the deformation of foam aluminum is 60%, then it can withstand 60% of the total external energy [13].

Al foam-filled structure has been widely used in automotive front bumpers and front beams [6,8,14,15]. This material boasts good overall performance, and its strength and energy absorption ability will vary if any variability happens to the porosity of foam aluminum so that engineers can make the proper foam they need through controlling the processing parameter [8,9,16–18]. This material is now applied in the body of Audi A8, a pioneer car with all aluminum body, whose bottom beam, longitudinal beam, rear beam, roof rack, A column, B column and other parts are all filled with aluminum foam, making it the safest car in its class.

In order to improve the energy absorbing performance of Al foam-filled metal structures, scholars at home and abroad have conducted studies on tube section shapes, foam densities, wall thickness, load types and other parameters through experiment, simulation and optimization. Guillow and Reddy [19,20] studied the deformation mode and mechanical response of the foam filled circular thin-walled metal tube under axial quasi-static and

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Nomenclature

M	mass of tested specimens	PCF	maxpeak crash force
D	length or diameter of top end	MCF	mean crash force
B	length or diameter of bottom end	EA	total energy absorption
H	height of cone	SEA	specific energy absorption
T	thickness of cone wall		

dynamic compressive load. Chen [21] studied the energy absorption performance of single and multi-hole hollow pipe and filled pipe under axial crushing from theoretical and numerical angle. Ahmad et al. [22] studied the dynamic energy absorption properties of Al foam filled tapered tube under oblique impact loading. Duarte et al. [23–25] analyzed the dynamic and static bending performance of thin walled tube filled with aluminum foam. The research results show that the reaction between foam and tube makes the bending ability of the filled-tube greater than that of the pure aluminum alloy tube and foam aluminum combined. Sun, Hou, Yin et al. [26–35], made a comprehensive experimental and numerical study on the crash energy absorption of the Al foam-filled metal tube with quadrilateral, hexagonal, octagonal, round, hat, cylindrical, triangular, tapered shape and with single layer filled, double layer filled, multi-cell filled structure under quasi-static and dynamic axial loading, bending and oblique loading.

Considering the complex production process and high price of functionally graded foam aluminum (FGFA), on the one hand, many scholars study its economic preparation process so as to reduce the cost of the FGFA [36]. On the other hand, other cheaper foam materials are also studied, such as PU foam which is made of polyol, isocyanate and other additive. Rigid PU foam, with the characteristics of light weight, good impact resistance, high specific strength, easy processing and low price, can be used as excellent energy absorption materials. Due to the good energy absorption characteristics of PU foam, soft, semi-hard, hard and other types of PU foam have been widely used in automobiles [37–42]. For instance, the United States Bayer materials company developed a bumper energy absorption system built by PU foam. This kind of bumper with light weight and good energy absorption ability will be broken to absorb energy when impact occurs. It has now been put into use on the Cadillac STS.

In order to have a clearer understanding of the influence factors of energy absorption ability of PU foam and to improve this property, Wang et al. [43] studied the effect of porosity and density on the mechanical properties of PU foam, concluding that both the density and porosity have great influence on the mechanical properties of rigid polyurethane foam and that the high density of rigid PU foam can be used as a structural material. Anindya et al. [44] carried out quasi-static axial compression tests on PU foam with different ratio of polyol and isocyanate, and concluded that PU foam can get the best energy absorption effect when the ratio of two materials is 1:1. Niknejad [45] studied quasi-static crushing performance of empty and polyurethane foam-filled E-glass/vinyl ester composite tubes with different geometrical characteristics to use in sacrificial cladding structures, and the result demonstrates that injection of the polyurethane foam in the tubes causes more regular deformation mode, compared with the empty tubes. Lu et al. [46] studied failure modes and energy absorption characteristic of PU foam-filled glass fiber structure under axial compression condition. Ismail [47] studied thin-walled steel structures filled with different density PU foam, and the result shows that higher density polymeric foam results in higher energy absorption performance.

Metal and metal foam materials have been used in the automotive industry for more than 100 years. Reasonable choosing the type of composite materials, designing the layers, controlling the interface can meet the performance target of optimizing the vehicle structural design. The intensity and modulus ratio of CFRP are much higher than that of metal materials, which means CFRP has the obvious advantages once used in automobiles. Research has shown that the crash energy absorption capacity of CFRP is 4–5 times higher as much as that of steel when the mass of CFRP is half that of steel [48]. With the price of carbon fiber falling and the applied technology in cars becoming more and more sophisticated, CFRP and other composite materials will gradually replace traditional metal materials, becoming the mainstream materials in the automotive industry [48].

Due to the complexity of CFRP mechanical properties, many scholars have carried out experimental and simulation studies about CFRP tubes with different cross-section shapes, wall thickness, taper angles and other parameters [49–54]. As early as 20 years ago, Hull [49] studied the failure modes of CFRP, and analyzed the reason for different failure modes. Mamalis et al. [52] performed experiments of square cross-section carbon fiber tubes under quasi-static compression, and discussed the effects of different height and different layer numbers on the failure mode of CFRP tubes, and analyzed the mechanism of energy absorption in macro and micro scale. Palanivelu et al. [55] compared the energy absorption characteristics of small composite tubes with different cross sections under quasi-static compression, which showed that the square and hexagonal cross section tubes with t/D or t/W aspect ratio of 0.045 crushed catastrophically whereas the circular cross section tubes exhibited uniform and progressive crushing modes. Abdewiet et al. [56] conducted axial compression experiments of radial corrugated composite pipes, cylindrical glass fiber composite tubes and corrugate surrounded cylindrical tubes. The results showed that the composite tubes of corrugation geometry exhibited a kind of effective and stable energy absorption ability. Alkatebet et al. [57] studied the effect of different tapers of elliptical cross-sectioned thin-walled glass fiber tapered pipe under quasi-static compression experiments, and it revealed that the taper could improve the bearing capacity. Hussein et al. [58] studied axial crushing behavior, SEA and EA of hollow CFRP tubes, aluminum honey comb-filled CFRP tubes, and the result shows that SEA of the hollow CFRP square tubes that tested was observed to be greater than the SEA of either aluminum honey comb-filled CFRP tubes.

In this paper, the square, hexagonal and circular section hollow CFRP tapered tubes, and the tubes filled with PU foam under quasi-static uni-axial compression are investigated in order to have a better understanding on the failure mode and energy absorption behaviors of those structures. Besides, these non-metallic structures will be compared with Al alloy metal tubes that have been studied by the research team before. The deformation mode and load–displacement curves of those structures will be analyzed, total energy absorption (EA) and specific energy absorption (SEA) will be treated as the main indicators to evaluate the energy absorption performance.