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Lightweight design of carbon twill weave fabric composite body structure for electric vehicle

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ABSTRACT

Design of composite appears more challenging compared with metallic counterparts because of its microstructural heterogeneity and behavioral sophistication. This paper aims to develop a multiscale approach for predicting three-dimensional elastic model of carbon twill weave fabric composite which will be applied to crashworthiness analysis of body structure of electric vehicle. The geometric parameters were obtained by measuring the microstructure of T300 carbon twill weave fabric composite through optical microscopy. The finite element model of representative volume element (RVE) in laminate composite was established to characterize the elastic properties of the materials using the homogenization technique. The numerical results of property were compared with those from uniaxial tensile and three point bending tests. Finally, the constitutive model of such composite was employed to crashworthiness analysis for electric vehicle body structure under the roof crash and side pole impact. The study indicates that the deformation behaviors of laminate calculated by using the elastic properties are in good agreement with tensile and bending experimental results with maximum relative errors of 4.04% and 7.79%, respectively. Meanwhile, a 28% savings of body weight is achieved using the carbon twill weave fabric composite compared to its predecessor made of glass fiber reinforced plastics (GFRP).

1. Introduction

With the growing concerns on energy conservation and environmental protection, development of electric vehicle (EV) has been taking an accelerated pace. At present the range that an EV can travel without recharge is not satisfactory yet due mainly to the limitation of energy storage. In order to minimize energy consumption, lightweight has become a critical issue because, alongside the battery capacity, weight is a key factor limiting the range. The lighter the vehicle, the longer the distance it can travel. Generally, the lightweight design can be addressed from three aspects of applications of novel materials, structural optimization and advanced processing technology, of which novel material application is counted as the most effective approach.

Composites have been increasingly used in automotive industry for their advantages of lightweight, high strength, corrosion resistance and easy manufacturing [1]. As one class of typical composites, glass fiber reinforced plastic (GFRP) has been widely adopted to reduce the weight of vehicle structure. For example, the combus was developed using woven glass/polypropylene composites by Tillotson Pearson Inc., which led to over 30% weight reduction compared with conventional metallic bus [2]. As a matter of fact, GFRP has been extensively adopted in roof door, floor segments, body panel, frame segment, battery access door, and seating systems with a weight saving ranging from 40% to 60%, whilst maintained or even improved the performance compared to conventional metallic components [3–7].

Carbon fiber reinforced plastic (CFRP), as other class of composite materials, gains increasing popularity in numerous advanced applications for crashworthiness over the last decade. In this respect Mamalis et al. [8] conducted a systematical experimental study on crashworthiness for thin-walled CFRP tubes, which found the strong effects of strain rate and layout of fiber reinforcing layers, fiber volume content and thickness of tube wall. Yang et al. [9] explored the energy absorption of square CFPR tubes, in which 3D braided-textile was introduced as a reinforced form of fibers. They recognized a major role played by the composite corners in enhancing energy absorption. Postec et al. [10] identified the influence of the number of inter-ply interfaces on initiation of bearing failure and crashworthiness. Bambach et al. [11] revealed that the steel-CFPR tubes exceed those of steel-only and CFPR only tubes in specific energy absorption (SEA). Ghasemnejad et al. [12] studied the crashworthiness and failure modes of the

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laminated composite boxes made of twill-weave and unidirectional CFRP composite materials. Huang et al. [13] investigated the effects of CFRP parameters on energy absorption characteristics of hat shaped section members. More recently, Obradovic et al. [14] explored energy absorption characteristics of different CFRP structures using numerical and experimental approaches and confirmed the major role played as per failure criteria.

Compared with GFRP, the carbon fiber reinforced plastic is of lower density, higher specific strength and superior impact resistance, and has been used more commonly in high-end sports cars and advanced electric vehicles. The Murcielago presents an entire carbon/epoxy body (bumpers, fenders, hood, etc.), which yields a weight reduction of 75 lb or 34 kg (about 40%) over its predecessor, the Diablo, with an all-aluminum body [15]. BMW continues its innovation for Megacity electric vehicle by developing CFRP passenger cell which reduces additional 100 kg body weight for extra battery [16]. Besides, within the electric vehicle project of SUPERBUS, the body structure is made of CFRP and optimized to achieve the minimum weight [17]. However, most of these abovementioned works about EV are the final profile data, there is lack of detailed reports of CFRP design for EV body structure.

This paper aims to develop a lightweight CFRP structure for electric vehicle, in which carbon twill weave fabric composite is taken into account for its proven impact resistance and excellent formability compared with unidirectional composite. A multiscale approach is proposed to construct the three-dimensional microstructure, predict the material elastic model and verify the crashworthiness for EV body macrostructure.

2. Lightweight design and materials

2.1. Design

Special attentions are placed on making the EV structure accommodate the sizable, heavy battery units and special driving electronic components. Different with automobile structure, the novel electric vehicle architecture can be designed in three independent modules, namely driving module, protection module and body module, as shown in Fig. 1. The main part of driving module comprises the aluminum chassis, battery unit, crash elements, driving and suspension systems. The body module plays a key role in absorbing crashing energy, which is made of sandwich materials. Since the space of electric vehicle is bigger than conventional automobile, these spaces can be divided into several energy absorption blocks. The protection module consists primarily of a high strength, lightweight passenger cell made of CFRP. It is mounted on the load-bearing structure of the driving module and reinforced mutually with the driving module to improve the strength of frame. Since the protection module is essential for the safety of the driver and passengers, it should be sufficiently strong and reliable when a crash occurs. Motivated by lack of experience about the design of the protection module of CFRP, this study will present a multiscale design approach.

A multiscale approach has been employed to the design of EV body structure [18,19]. Fig. 2 shows a methodological framework of vehicle design that involves the material property characterization (microscale), verification (mesoscale) and its applications on crashworthiness analysis (macroscale). In the microscopic level, a three-dimensional (3D) representative unit cell with the detailed architecture of fiber bundles is modeled and material elasticity is characterized. The elastic model is further employed on mesoscale for calculating the laminate deformation; and the calculated results are verified by the uniaxial tensile and three point bending tests. After the validation, the elastic model is applied in crashworthiness analysis on macroscopic level of the EV body structure. As a result, the multiscale approach proposed from microscale to macroscale is expected to improve the accuracy of analysis and design because the fabric architecture greatly influences the mechanical properties, while the mechanical properties affect the strength and failure mechanism of carbon fabric composite structures [20].

2.2. Microstructure of the composite

The T300 carbon twill weave fabric composite is selected for the design of body structure due to its balanced bi-directional properties in the fabric plane, which gives rise to higher specific stiffness, strength, stability and toughness. However, it is by no means easy to determine these mechanical properties due to complex microstructural architecture. In this study, the unit cell finite element analysis (FEA) based homogenization process is implemented to investigate the three-dimensional elasticity tensor.

The specimens are made of T300 carbon twill weave fabric/epoxy resin 618, and the representative unit cell is extracted from the specimen. The selection of unit cell can be important and it

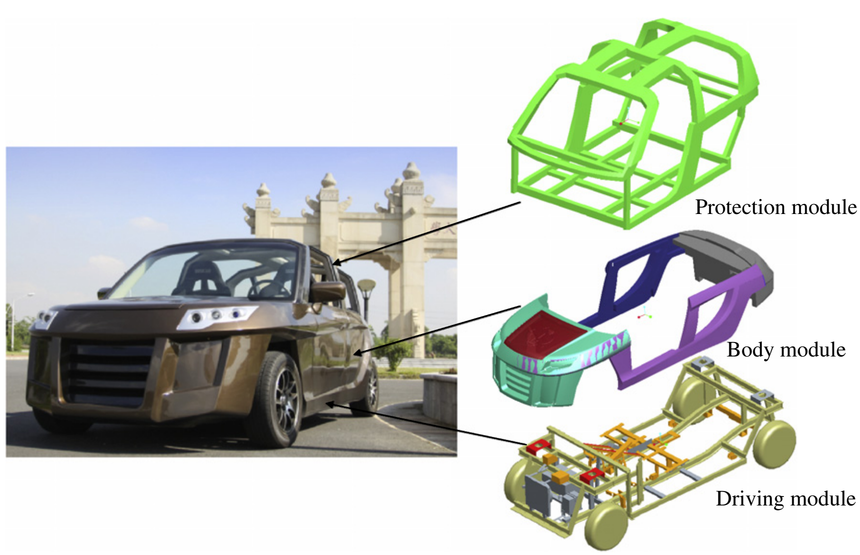

Fig. 1. Novel three module architecture of EV.