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Modeling for CFRP structures subjected to quasi-static crushing

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ABSTRACT

Carbon fiber reinforced plastic (CFRP) composite materials demonstrate significant promise to further improve weight to performance in automotive engineering. Nevertheless, design of CFRP components for crashworthiness criteria remains rather challenging and typically requires laborious trial-and-error processes. This study aims to promote computational design of CFRP structures by establishing effective constitutive model that is implemented in the commercial finite element code Abaqus/Explicit. Two different numerical models (namely, the single layer shell model and the stacked shell model) were developed to simulate experimental crushing tests on the square CFRP tube. The effects of key parameters for these two FE models were analyzed, respectively. The comparisons of numerical results with experimental data indicated that the 9 layers stacked shell model is capable of reproducing experimental results with relatively higher accuracy. Based on the validated modeling approach, crushing behaviors of several CFRP thin-walled structures with different cross sectional geometries and thicknesses were further explored. The failure modes and key indicators in relation to the structural crashworthiness were investigated for identifying a best possible sectional configuration. It is found that the circular tube shows superior specific energy absorption capacity of all different tubal configurations with the same wall thickness, meaning that the tube with circular section is of good potential as a crashworthy CFRP structure.

1. Introduction

Over the past decades, composite materials have been more and more extensively used in industry sectors ranging from aerospace to automobile [1–5]. Compared with the traditional metallic materials, composites exhibited higher specific strength and specific energy absorption capacity to the weight, which provides great opportunity to save vehicular weight and enhance structural performance [6–8].

Recently, carbon fibers reinforced plastics (CFRP), as one class of typical composite materials, have been introduced in vehicular engineering for improving fuel economy and structural safety [9–14]. There have been substantial studies on crashworthiness of various CFRP structures in literature. For example, Mahdi et al. [15] conducted experimental studies on the effect of fiber orientation on the energy absorption characteristics of composite tubes subjected to axial loading. They showed the certain advantages of laying fiber orientations of $15^\circ/-75^\circ$ and $75^\circ/-15^\circ$ for enhancing the load carrying capacity and energy absorption. Israr et al. [16] carried out the quasi-static tests on different configurations of unidirectional fiber and woven fiber composites to investigate the crushing behaviors of one ply under crushing load. Mamalis et al. [6] explored the crushing characteristics of thin-walled square CFRP tubes under static and dynamic axial compressive loads, experimentally; and they found that crushing behaviors of square CFRP tubes are fairly brittle due to the characteristics of the constituent materials. From the previous studies reported in literature, it can be concluded that the crushing behaviors of CFRP structures are generally determined by development of fracture, inter-ply delamination and extensive micro-cracking, which depend on structural and material features, such as fiber orientation, number of stacking layers, properties of each single layer, etc. These factors make the design of CFRP energy-absorbing structures much more sophisticated and challenging than traditional metallic structures.

Typically, the development of crashworthy structures largely relies upon laborious and costly experimental tests. With the fast advances in computational techniques, the ability of numerical simulations for accurately predicting the crushing behaviors has improved remarkably, thereby reducing the development cycle and cost of composite components [17–20]. As the most representative numerical methods, the finite element (FE) simulations have

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played a very important role in the early phase of the crashworthiness design. For metal based energy-absorbing structures, the FE models have been capable to generate excellent prediction thanks to well-established constitutive behaviors [18,21]. For modeling CFRP structures, it is essential to reproduce the complex crushing behaviors precisely by establishing more complex constitutive models. There have been different modeling approaches to the numerical simulation for CFRP structures in literature to date. The first is to develop a micro-mechanical model that simulates the details on the level of fiber/matrix interactions with a focus on fracture analysis and crack growth simulation [22–24]. However, such models could be too expensive to analyze large components with complex microstructures. The second is macro-mechanical model that provides a macroscopic description of the bulk structural behaviors for CFRP. In the macro-mechanical model, the micro-mechanical materials are simplified into the homogeneous anisotropic medium. Currently, it seems that the macro-mechanical model is more extensively used for engineering design of CFRP structure attributable to its high computational efficiency. It is noted that Chiu et al. [25] detailed the theory and implementation of a composite damage model based on macro-mechanical 3D model, addressing intralaminar and interlaminar failure behaviors, for the crushing simulation of unidirectional composite tubes; which showed good agreement with the experimental results [25]. Alternatively, our presented study here aimed to develop a macro-mechanical shell model for simulating crushing behaviors of woven fabric composites, which have different constitutive models of unidirectional composites. This is mainly because most of vehicle body components are made in thin-walled components; and detailed experimental tests of out-of-plane behaviors of CFRP can be complex and time-consuming [9,26].

The macro-mechanical shell model can be classified into the single shell layer model and the stacked shell model. The single shell layer model employs a single layer of shell elements to model the thin-walled structure. Although it cannot be used to properly predict the inter-laminar failure occurred in laminated CFRP subjected to crushing loads, it makes certain sense if only the predictions of overall loading capacity and energy absorption are required. Note that there have been substantial studies on crushing behaviors of various CFRP structures through the single shell layer models. For example, Luo et al. [27] developed a stiffness degraded model by incorporating the extended Hashin failure criterion and damage evolution law from the continuum damage mechanics, allowing predicting progressive failure of CFRP tubes under axial dynamic impact. Their simulation results showed that the proposed single layer shell model can be applied to estimate the energy-absorbing characteristics of CFRP tubes. Boria et al. [28] used the single layer shell elements to investigate the impact behaviour of composite front crash structures. Liu et al. [9] employed the single layer shell model to investigate the structural crashworthiness of CFRP electric vehicle body under the roof crash and pole side impact, respectively. Bussadori et al. [29] numerically investigated crashworthiness characteristics of a CFRP tube by using single shell layer models, and the results demonstrated the advantages of this modeling approach. It can be concluded from these exemplified studies that the single shell layer modeling approach is suitable for engineering applications thanks to its modeling simplicity and computational effectiveness. However, it may be not capable to capture some detailed failure behaviors observed in the experimental tests.

The stacked shell modeling approach, on the other hand, comprises of more than one layer of shell elements by joining them together using specific elements (such as cohesive elements etc.) which allows modeling the CFRP structures more realistically. Such a model is capable to simulate the inter-laminar failure due to the presence of the joining elements between the layers. Not only does it provide better physical representation of the complex failure modes, but also keeps the simplicity inherent of the macro-mechanical modeling approach. In this regard, for example, Sokolinsky et al. [30] presented a stacked shell model of a corrugated CFRP plate subjected to quasi-static crushing, and the numerical results showed very good quantitative and qualitative agreement with the experimental data. Xiao et al. [31] examined the application of a composite damage model (i.e. MAT 58 in LS-DYNA) for crush simulations of braided composite tube by adopting the stacked shell modeling. Joosten et al. [7] described the quasi-static crushing behaviors of CFRP hat-shaped crush components by using a four-layer stacked shell model. The numerical result indicated that this modeling approach is capable to predict the failure modes more accurately and provide better agreement with the load-displacement curves generated from the experiments. In other words, the stacked shell modeling approach can better capture the failure details with a relatively simple constitutive relation for numerical simulation of CFRP structures.

In review of aforementioned studies in literature, it is known that the macro-mechanical model is more applicable for engineering crashing analysis of CFRP structure attributable to its high computational efficiency. In this study, both the abovementioned macro-mechanical modeling approaches, namely the single layer shell modeling and the stacked shell modeling, were adopted to investigate the axial crushing behaviors of square CFRP tubes. The effects of key parameters were examined using these two modeling approaches, respectively. By comparing the numerical results with the experimental data, the overall suitability of these two models was assessed for providing a better prediction accuracy. Further, based on the suitable modeling approach, crushing behaviors of several CFRP thin-walled candidate structures with different cross sectional shapes and wall thickness were then explored. The effects of several key parameters on failure modes and crashing behaviors were investigated in these configurations, thereby providing technical guide for enhancing the crashing performance of CFRP thin-walled structures.

2. Experimental methods

2.1. Crashworthiness metrics

The general goal of designing a crashworthy structure is to reduce occupant injury by having the structure to absorb as much impact energy as possible and lower the peak impact loads [32,33]. The energy absorption during the crushing can be mathematically calculated as:

$$EA = \int_0^d F(x)dx \tag{1}$$

where *EA* is energy absorption; *d* denotes crushing distance and $F(x)$ represents crushing force.

To evaluate weight efficiency of energy absorption of a structure, the specific energy absorption (*SEA*) is often used as:

$$SEA = \frac{EA}{m}, \tag{2}$$

where *m* is the mass of the crash structure. A higher *SEA* indicates a higher energy-absorbing efficiency of the structure.

The peak crushing force (*PCF*) means the maximum impact load during the crashing process, which is often associated with deceleration in dynamic crashing. The crush force efficiency (*CFE*) indicates the ratio of the mean crushing force (F_{mean}) to the *PCF*, defined as:

$$CFE = \frac{F_{mean}}{PCF} \tag{3}$$