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Effect of strain rate on the failure mechanisms and energy absorption in polymer composite elements under axial loading

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ABSTRACT

This paper is concerned with the development of finite element (FE) codes and design tools suitable for detailed fine scale modeling of crush behaviors observed in composite crashworthy structures under dynamic loading regimes. A numerical modeling methodology previously developed to model the quasi-static crush behavior is used here to replicate the dynamic crush behaviors and accurately simulate identified energy absorbing mechanisms determined from experimental work. The methodology undertaken consists of firstly, the numerical modeling of damage development in the FRP composite laminate. To capture the strain rate effects on the crush response, material models were formulated for each loading regime from experimental coupon tests under quasi-static and dynamic loads to retrieve input parameters for the material models. The second feature of the numerical methodology focuses on the implementation of innovative numerical triggers into the numerical models. These numerical triggers were designed to replicate in the numerical model, the initiation, propagation and complex failure mechanisms of the crush responses observed in the experimental crush tests.

1. Introduction

Energy absorbers were first introduced in the automotive field to absorb vehicle kinetic energy and hence increase occupant safety in accidents that are potentially survivable. These absorbers which were traditionally manufactured from metal are being replaced by polymer composite materials that are now gaining acceptance by the automotive industry for lightweight structures, particularly for sports cars and F1 where performance is critical and the higher cost of polymer composites over steels is not considered a disadvantage [1]. In the aerospace field, especially in commercial transport aircraft, the rate of adoption of polymer composites into the structure has been steadily increasing over the last 30 years, since low weight and performance are critical and materials costs are less significant in primary structures. The Boeing 787 Dreamliner [2], features polymer composite materials extensively in the primary structures, such as the wings and fuselage which constitute 50% of the aircraft's structural weight [2]. With the polymer composite fuselage construction in the Boeing 787, energy absorbers had to be added in the aircraft design to meet the airworthiness standards by the FAA that states that the aircraft would have to display similar safety standards (in terms of survivable crashworthiness characteristics) to similar sized aircraft manufactured from metals [3].This introduction of polymer composite energy absorbers in commercial transport aircraft and the limitation of the current airworthiness regulations prompted the formation of the Crashworthiness Working Group of the CMH-17 (Composite Materials Handbook formerly known as MIL-HDBK-17). This working group comprises representatives from the automotive and aerospace industries, academia and government laboratories and operates in parallel with the ASTM Committee D-30 on Composite Materials [4]. The lack of available design guidelines, accurate and inexpensive simulation tools, specialized test methods for the characterization of polymer composite energy absorbers and lastly the accessible and adequate polymer composite material property database was identified by the working group. To understand the energy absorption and failure mechanisms of crashworthy structures, the German Aerospace Center (DLR) has developed a chamfered tube segment specimen [5], which is easy to fabricate and gives reproducible axial crush failures under quasi-static and dynamic loading conditions [6,7]. This may be used for screening of different energy absorbing composite materials and provides design data for crashworthy design studies.

From a previous experimental investigation on the absorption performance characteristics of carbon/epoxy DLR segment specimens under axial crush loads, a particular emphasis was placed

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on the influence of loading rate on the energy absorbed, crush morphology and crush failure mechanisms [6,8]. The experimental methodology consisted of conducting crush tests at loading rates ranging from quasi-static to dynamic regimes (1 mm/s–10 m/s) coupled with a high speed camera capturing the varied crush behaviors. In addition to capturing the crushing behavior of the specimen the analytical methodology composed of High-resolution Computed Tomography (HRCT) scanning of the crushed specimens, was performed to enable detailed analyses of the varied crush front morphologies. The segment specimen under the quasi-static loading condition exhibited the most favorable energy absorption performances in terms of Crush load efficiency (CE), Energy Absorbed (EA) and Specific Energy Absorbed (SEA) compared to the dynamic loading condition. The phenomenon of different crush response modes in quasi-static and dynamic loading conditions, led David et al. [8] to ascertain two independent crush response modes, global splaying failure crush mode (GSF) and local fragmentation failure crush mode (LFF) respectively (see Fig. 1). They attributed these differences to the response of the material system with respect to the time scale of the crush test. In a dynamic loading condition, intermolecular interactions between polymer chains can only occur in the short time that the specimen is loaded causing brittle failure, unlike in a quasi-static loading condition where these interactions are extended to the intramolecular level therefore promoting a ductile behavior. The phenomenon of the two different responses were further investigated in the experimental work [8] on the effect of stacking sequence in the crushing response and energy absorption performances of the carbon-epoxy segment specimens. In this investigation, specimens (ply layup configuration of ± 45°) failed catastrophically when loaded in a quasi-static crush test but achieved stable progressive crushing in the dynamic crush test. Experimental findings from this investigation validate the hypothesis put forth regarding the global response of the specimen in the quasi-static loading condition and a localized response of the specimen in the dynamic loading condition.

A numerical methodology was developed by Johnson & David [6] that utilized an explicit Lagrangian finite element (FE) code PAM-CRASH to replicate the GSF crush mode (quasi-static loading) and accurately simulate identified energy absorbing mechanisms determined from the experimental work. This approach consists of firstly, the numerical modeling of damage development in the composite laminate. From the experimental work [6], the critical influence of both ply damage and delamination in controlling failure mode and energy absorption was acknowledged and hence included in the numerical modeling methodology. As an efficient way of modeling delamination failure in a FRP composite laminate, the meso-scale composite damage model was extended to stacked shells which allow interface delamination failures [9]. In this stacked shell approach, the FRP composite laminate is represented by multi-layered shell elements connected by cohesive interfaces, which are damaged and fail when the prescribed interface fracture energy is reached. The next part of the numerical approach focuses on the implementation of innovative numerical triggers into the numerical models. These numerical triggers were designed to replicate in the numerical model, the initiation, propagation and complex failure mechanisms of the crush responses observed in the experimental crush tests. This numerical methodology achieved considerable qualitative and quantitative improvements in the correlation between experimental and numerical results for the global splaying failure crush mode. The implementation of this methodology to the FE analysis of the local fragmentation failure crush mode is discussed in this paper. In addition, the FE modeling studies presented here include the numerical analysis of the effect of stacking sequence on the crushing response of the DLR segment specimens in both loading regimes and energy absorption characteristics.

2. DLR segment specimen

The geometry of the specimen consists of a half circle segment and two flanges that are each made up of a rectangular and a quarter circle segments. Fig. 1 presents the test specimen affixed in a clamp support and the axially crushed specimens under the two loading regimes (quasi-static (a) and dynamic 10 m/s (b)). A 45° outside chamfer trigger mechanism was machined into the test specimen to initiate the crushing process in the highly stressed region at the tip of the chamfer. These specimens were manufactured from Hexply M18/1/43%/G939/1230 five harness fabric carbon/epoxy pre-preg material system with a ply layup of nine plies in a 0/90 configuration.

In the quasi-static crush test, the specimen exhibits long inner and outer lamina bundles. These outer lamina bundles split into several petal-like portions called fronds that curl up into themselves as seen in Fig. 1(a). This is unlike in the dynamic crush test specimen; see Fig. 1(b) where the inner and outer lamina bundles fragment after the trigger portion is crushed down.

3. Material model characterization

3.1. Meso-scale composite models

Physical phenomena associated with impact damage and progressive collapse of composite structures are complex, and predictive models and simulation tools for design and analysis are being

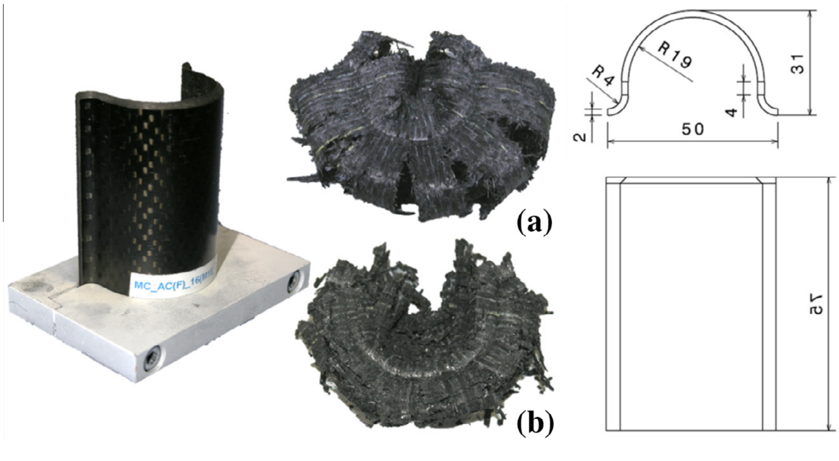

Fig. 1. DLR segment specimen under axial compression.