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Crush responses of composite cylinder under quasi-static and dynamic loading

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ABSTRACT

Despite the abundance of studies investigating the performance of composite structures under crush loading, disagreement remains in the literature regarding the effect of increased strain rate on the crush response. This study reports an experimental investigation of the behaviour of a carbon–epoxy composite energy absorber under static and dynamic loading with a strain rate of up to 100 s^{-1}. Consistent damage modes and measured force responses were obtained in samples tested under the same strain rate. The energy absorption was found to be independent of strain rate as the total energy absorption appeared to be largely associated with fibre-dominated fracture, which is independent of strain rate within the studied range. The results from this study are beneficial for the design of energy absorbing structures.

1. Introduction

Interest in energy absorbing structures for crashworthiness applications has been growing due to the increasingly safety-conscious environment in which the aviation industry operates. Design guidelines [1] and standards [2] impose a maximum allowable acceleration envelope experienced by the occupant in a crash. Composite materials have been gaining popularity in aircraft structures due to their superior specific strength and stiffness, corrosion and fatigue resistance. Their complex failure modes [3–5] facilitate a high level of energy dissipation making them suitable for use in energy absorbing structures to meet crash protection requirements. Jackson et al. [6] showed that composite energy absorbing structures can significantly reduce the acceleration experienced by the occupants in a crash environment which would reduce risks and severity of injuries. Hence, the performance of composite structures under crush loading is of great interest.

Performance of energy absorbing structures can be measured through their specific energy absorption (*SEA*), peak force (F_{peak}), steady-state force (F_{SS}) and crush efficiency (*CE*). The energy absorption is area under the force (F) – displacement (x) curve, and is directly related to protective capability. *SEA* is defined as the energy absorption of unit mass (m) of structure (Eq. (1)). Hence, for weight-conscious applications such as aviation, *SEA* is a critical measure of performance.

$$SEA = \frac{energy\ absorbed}{mass\ of\ structure\ consumed} = \frac{\int_{x_{start}}^{x_{end}} F\,dx}{m} \tag{1}$$

F_{peak} is the highest force (hence highest acceleration) experienced during the crush event and is directly related to the potential for injury suffered by the occupants in a crash situation. One of the purposes of the energy absorber is to keep acceleration levels within human tolerance limits. F_{SS} is the mean force during steady-state crushing of the specimen after the consumption of the trigger and the passing of peak force, and is a good indicator of the overall energy absorption capability of the structure. *CE* [7] (Eq. (2)) is the ratio between F_{SS} and F_{peak} (Eq. (2)) and is indicative of the nature of the crush response.

$$CE = \frac{F_{SS}}{F_{peak}} \tag{2}$$

A catastrophic failure is characterised by a high peak force as well as a low steady-state crushing force, and hence a low crush efficiency.

A wide variety of composite energy absorber configurations have been reported in the literature since the pioneering work by Thornton [8] and Farley [9]. Simple geometries such as circular

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tubes [9–12], rectangular tubes [13–15] and flat plates [13,16] have been studied extensively. More complex geometries have also been investigated, including C sections [17,18] and I sections [15]. Triggering has been shown to be an important aspect of energy absorbent structure design, with chamfering on the loading surface being most common [19]. Other trigger mechanisms studied include the tulip [12,20] and ply drop [21]. Some authors have designed the structures so that they are self-triggering, for example, using corrugated [22] or hourglass profiles [20]. Others have evaluated different types of material systems and layup configuration [19,23]. However, most of these experimental data were based on quasi-static testing, despite crushing being a dynamic event. Consequently, the effectiveness of energy absorbers can only be reliably determined once an assessment of possible rate dependence is made.

Currently, there is disagreement in the literature [24] over the effect of intermediate nominal loading rate between 0.1 and 100 s^{-1} on the response of composite structures. Initial tests completed by Thornton [8] suggested rate independence for glass and graphite–epoxy cylindrical tubes. Farley [10] noted that for chamfered cylinders, $[0/\pm\theta]_2$ graphite–epoxy specimens were rate insensitive, but Kevlar–epoxy and $[\pm\theta]_3$ graphite–epoxy specimens displayed increased specific energy absorption (SEA) as the testing speed increased. Palanivelu et al. [7] found the SEA of specimens with a circular cross-section were rate insensitive, whereas those with a square cross-section increased slightly with crush speed. Work done on rectangular tubes by Mamalis et al. [25] has found that both the SEA and peak force of square tubes increased with respect to increasing strain rate. On the other hand, crush testing conducted by Jackson et al. [17] on chamfered C-section found an approximately 10% reduction in SEA for specimens impacted at 8.5 m/s when compared, with those crushed at 20 mm/s. This was confirmed by David et al. [18] who also observed a reduced SEA on dynamically tested C-section specimens with a $[(0/90)_2/0/(90/0)_2]$ layup. Brighton et al. [26] reported a decrease in SEA for chamfered carbon–epoxy tubes with a $[0/90]_4$ layup when the test speed was increased whereas the rate effect for a chamfered 4 ply glass-polypropylene fabric tubes were inconclusive.

A sufficiently large sample size is often required to measure the scatter in the experimental data. Brighton et al. [26] noted that the lack of manufacturing control has a significant effect on the specimen response which leads to possible strain rate effect being hidden within the noise. Unstable collapse of specimens [25] also presented challenges in their measurement due to the presence of high force spikes in the resulting force response. Furthermore, unstable crushing response is also more dependent on any microscopic defects or weak points within the structure, which are random in nature. In order for a conclusion to be drawn with confidence, the observed trend must be compared with the size of the scatter inherent in the experimental results.

This study presents a comparison between the response and damage mechanisms of a tulip triggered composite cylinder subjected to quasi-static and dynamic crush loading with strain rates of up to 100 s^{-1}. Qualitative analysis of the specimens was conducted to identify the damage modes and their propagation through the structure. Quantitative analysis of the force response for each test condition was also completed. The reliability of the results was assessed through analysing the scatter of the measured data.

2. Experimental method

2.1. Specimen design

The specimen is a cylindrical tube with a series of tulip triggers cut into the top surface. The tubes were manufactured using a unidirectional Hexcel HexPly T700/M21 carbon–epoxy prepreg with a $[0/90/0/90]_s$ layup. The tubes were autoclave cured as per manufacturer's specifications. The effect of seams is minimised by placing seams of adjacent plies on opposing sides of the cylinder. After curing, the composite tubes were machined to the geometry specified in Fig. 1.

A tubular geometry was selected to facilitate their testing as free-standing energy absorbers. A circular cross-section also avoids stress concentrations, which leads to a more steady and localised damage progression [19], resulting in a higher energy absorption in comparison with a square or rectangular cross-section. The triangular tulip trigger can achieve a higher steady-state crush load [19] in contrast to hourglass [20], crown and chamfer [27] triggers, leading to increased energy absorption. The increased length of the trigger region helps to spread the force spike in the initial stage of impact and reduce the peak transmitted force. A balanced $[0/90/0/90]_s$ layup was chosen to ensure lateral confinement and support within the orthogonal plies. Jacob et al. [24] noted increased overall energy absorption when fibres parallel to the loading direction were laterally supported, leading to increased fracture of these fibres. Commercially available filament wound tubes were not considered due to a lack of fibres parallel to the loading direction.

2.2. Test method

MIL-STD-1290A [2] sets out that airframes should be designed for at least an 8 m/s vertical speed at impact. NASA [28] conducted drop tests on representative fuselage sections with attached energy absorbers at impact speeds between 7.3 to 11.6 m/s, which correspond to nominal strain rates of between 15 and 23 s^{-1} in these absorbers. These are the likely strain rates experienced in a survivable crash scenario. Hence, the chosen strain rates for this study were 2.1×10^{-4}, 0.2, 30, 60 and 100 s^{-1} to encompass likely strain rates that an energy absorber would be exposed to in the event of a crash. The chosen specimens were tested at a range of different strain rates, as detailed in Table 1, along with the number of specimens associated with each test configuration.

The specimens for the low rate tests (2.1×10^{-4} and 0.2 s^{-1}) rested freely on the lower steel platen while the top steel platen descended on the specimen at the designated speed. The force measurement was recorded directly from the load cell attached to the top platen and the displacement was obtained from the moving crosshead. In contrast, the Instron 8800 VHS machine used for high strain rate tests has a fixed upper platen with an attached load cell. The bottom platen was then driven upwards using a hydraulic ram to crush the specimen in between. The specimen was fixed on the bottom platen with a small amount of adhesive to prevent it from detaching during its acceleration to the desired test speed. The crush stroke was nominally set to 40 mm. The platen then progressed approximately another 20 mm for the hydraulic system to bring the piston and attached platen to a complete stop at the end of the test. This deceleration phase significantly contributed to the variation in the actual test speed.

3. Results and analysis

3.1. Comparison of damage modes

The typical crush progression of a low rate test is shown in Fig. 2. The eight tulip peaks provided trigger points for damage initiation. The sharp tips of the tulip triggers were easily damaged by the loading surface, which created points of initiation where the damage then spread progressively throughout the entire structure. This process maximised the amount of material damaged and