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Property Modelling

Numerical and experimental studies of damage generation in a polymer composite material at high strain rates

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Abstract

Samples of S2-glass/epoxy composites have been subjected to microstructural investigation after testing in compression at quasi-static and high strain rates using the split Hopkinson pressure bar. A numerical model was developed that accurately describes the high strain rate mechanical response of the samples. Moreover, in contrast with earlier phenomenological or constitutive models, the model can also predict a variety of failure modes such as delamination, matrix cracking or fiber crushing. High-speed photography was used to check the model results. Interrupted tests, followed by metallographic examination, have revealed that the sequence of damage events differs between quasi-static and high strain rate regimes. The effect of sample size on measured mechanical properties is noted and is confirmed via numerical modeling.

Keywords: S2-glass; Numerical simulation; LS-DYNA; Mechanical properties; High strain rate; Stress wave propagation

1. Introduction

A variety of studies have addressed failure modeling of composite materials under impact loading, e.g., [1–6]. Some of these have used the split Hopkinson pressure bar (SHPB) to study the dynamic properties of composites under compressive, tensile and shear loading conditions while others have used other techniques such as drop weight testing. Research efforts utilizing various versions of the SHPB to characterize dynamic properties of composites at high strain rates have mainly been focused on specimen geometry effects, through thickness stitching effects, fiber orientation effects, and strain rate effects. The present work focused instead upon using the SHPB as a means to validate a numerical model as well as generating reliable mechanical property data and investigating specimen size effects.

Song et al. [7] compared the quasi-static and high strain rate properties of an S2-glass/SC-15 composite as a function of orientation in a recent study and found the strain rate sensitivity to be more pronounced in the through thickness direction than the in-plane direction. They also presented a constitutive model that satisfactorily described the mechanical response of this composite in both testing directions and as a function of strain rate

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although, in common with other currently used models, it was not able to account specifically for different fracture modes. Indeed, few experimentally supported studies have been reported concerning the fractographic details of the sequence of events involved in progressive failure in composites during Hopkinson pressure bar testing. In this paper, in addition to making such observations with the aid of interrupted tests, a rate-dependent progressive failure model was developed to account for the nonlinear and rate-dependent behavior commonly observed for fiber reinforced composite materials under high strain rate conditions and to investigate the sequence of deformation and fracture events leading to ultimate failure.

2. Experiments and modeling

S2-glass fiber woven fabric (0.81 kg/m^2)/SC-15 epoxy (toughened resin) composite plates, 11.3 mm in thickness, were produced using the vacuum assisted resin transfer molding process. Cylindrical composite samples 11.0 mm in diameter were core-drilled from the plate in the through-thickness direction and samples were compression tested (a) quasi-statically at $1.1 \times 10^{-1}\,s^{-1}$ and (b) at various nominal strain rates between 595 and 1500 s^{-1} using the SHPB. All tests were conducted with the compression axis normal to fiber plane. The particular SHPB apparatus used consists of Inconel 718 bars, a 356 mm long striker bar, 3450 mm incident and 1850 mm transmitter bars, all with a diameter of 19.05 mm. Multiple loading of the sample in SHPB was avoided by use of a transmitter bar shorter than the incident bar: this is crucial for identification of the microstructural damage progression during the loading period.

Briefly, in an SHPB test the striker bar generates a compressive elastic wave in the incident bar; this wave travels to the end of the bar where a portion of it enters the specimen and the rest is reflected back as a tensile wave. Of the portion of the wave entering the sample, some is reflected back at the sample/transmitter bar interface and the rest enters the transmitter bar, still as a compressive wave. Strain gages on the incident and transmitter bars record the passage of the wave and the data presented below are generally shown in this form, i.e. as the tensile or compressive waveforms recorded after the initial wave has interacted with the sample. The strain gage data were used for conventional data reduction using the 3-wave method and a dispersion correction was applied for all the data sets. Further details of the specific experimental set-up [8] and SHPB testing in general [9,10] are available elsewhere.

Several interrupted quasi-static and high strain rate compression tests were also conducted to allow evaluation of deformed microstructures as a function of increasing strain: a series of maraging steel collars were used to limit the maximum strain during the SHPB tests. Following testing, interrupted and fully loaded test samples were longitudinally sectioned and examined by optical and scanning electron microscopy. To study damage evolution in the samples in real time, a high-speed Ultra 8 camera was used to record the SHPB tests. The progression of damage was observed by photographing the specimen at predetermined intervals of the order of a few microseconds. With this high-speed camera, a maximum of eight frames could be recorded with an inter-frame time that could be varied between 10 ns and 1 ms.

The commercial explicit finite element code LS-DYNA 970 was used for three-dimensional SHPB finite element modeling. Numerical simulations were also carried out using a newly developed damage model, namely MAT 162, which has recently been incorporated into LS-DYNA. This model uses damage mechanics principles for progressive damage and material degradation. In the damage analysis of a composite specimen, a full-symmetric numerical model was used with appropriate boundary conditions. The model has three components in contact; the incident and transmitter bars each of length 1524 mm, and the specimen. A rectangular stress pulse is taken as the input to the impact face of the incident bar and all other boundaries are traction free and can move in any direction. In order to reduce computation time, the simulation uses bars 1524 mm in length instead of full-length bars and, although this decreases the transit time between successive waves and shortens the wave duration slightly, it does not affect the basic wave-shapes or amplitudes. Trial computations were carried out using full-length bars but, apart from the slightly smaller time window, no significant differences were found and the shorter bars were used in all calculations henceforth. The mesh includes a total of 292 800 elements, 52 800 elements for the specimen and 120 000 elements for each of the incident and transmitter bars. The composite specimen was modeled with 44 layers of elements in the thickness direction. Eroding single