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Split Hopkinson pressure bar testing of 3D woven composites

M. Pankow [a], A. Salvi [a], A.M. Waas [a,*], C.F. Yen [b], S. Ghiorse [b]

[a] Composite Structures Laboratory, Department of Aerospace Engineering, University of Michigan, 1320 Beal Street, Ann Arbor, MI 48109-2140, USA
[b] Army Research Laboratories, Aberdeen Proving Ground, MD, USA

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ABSTRACT

Results from a series of split Hopkinson pressure bar (SHPB) tests on 3D woven tetxile composites (3DWC) are presented. These tests were done to determine the rate dependent compression response of 3DWC. Three different configurations of the 3DWC, corresponding to compression response in the plane of the material and through-the-thickness direction (out-of-plane) were studied. The rate dependent responses were compared against quasi-static test results and it was found that 3DWC showed an increase in strength in all three directions studied, however, accompanied by a transition in the failure mechanism. The in-plane orientations showed the largest increase in (about 100%) strength at the elevated rates of loading. A follow-on paper provides finite element based results that correspond to the experimental results presented here.

1. Introduction

Early uses of laminated composite materials revealed that delamination was one of the major failure mechanisms of the material [1]. In order to prevent this mode of failure from occurring, different types of through-the-thickness reinforcement have been introduced. One such technique is 3D weaving, where fiber tows are woven together in a complex 3D architecture to create one preform [2]. 3DWC materials are relatively new and investigations to characterize the deformation response of the material, other than simple quasi-static mechanical tests, are ongoing [3].

New applications of the material have lead to considering complex loading scenarios in-service, which include periods of high rates of loading. Historically, the split Hopkinson pressure bar method [4], has been used in conjunction with homogeneous and isotropic materials to obtain information on the effect of strain rate on yield strength, for example in metals. In the present study, the SHPB test is adopted to examine the deformation response of 3DWC when subjected to high strain rates. Since the fiber tows (that consists of fibers and matrix) and the SC15 polymer matrix are the basic constituents of the 3DWC, separate studies have been carried out to obtain the high rate response of these constituent materials [5].

SHPB testing of 2D in-plane woven S-2 glass fiber with SC-15 matrix composites has been shown to exhibit a rate dependency [6]. Additionally, studies of off-axis layered composites have been reported in [7]. SHPB testing of 3DWC has also been done previously [8,9], although in these studies the authors simply assume equilibrium in the specimen, even though a constant strain rate is not achieved during the test duration. Other researchers have examined the tensile rate dependent properties of woven composites showing and explaining the rate-dependent behavior due to the reinforcement [10]. A modified Hopkinson bar has been used to perform high strain rate punch shear tests [11], showing the rate dependency of the 3DWC.

In this paper, results from compression SHPB testing of 3DWC are reported along with quasi-static test results for comparison purposes. High speed Digital image correlation (DIC), a full field strain measurement technique, has been used to determine the strain history on the side surface of the specimens that have a rectangular cross-section. These measurements are used to verify the accuracy of the measurements and to also determine the nature of equilibrium (or lack thereof) during the time period in which data is obtained. The SHPB measurements are also analyzed in a traditional manner to determine the “effective” properties of the 3DWC material. In order to better understand the experimental results presented here, a follow-on paper discusses the results from a finite element model that uses micromechanics to examine the composite response and how it is influenced by the tow architecture and the constituent material properties [12].

2. SHPB method

The SHPB test procedure has been developed and refined over several decades, starting with pioneering work by Kolsky [13].

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* Corresponding author. Tel.: +1 734 764 8227; fax: +1 734 763 0578.
E-mail address: dcw@umich.edu (A.M. Waas).

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Most routine SHPB tests are based on a 1D wave propagation analysis in a solid as described in [5]. The results obtained from such an analysis of the experimental data are used to obtain the effective stress–strain curve of the material as obtained from strain gauge data. These results are also validated using DIC techniques to better understand the full field strain field and interpret the inferred results since, traditionally, SHPB testing is carried out for homogeneous monolithic materials. In the present study, DIC measurements were taken on all of the samples during deformation to determine the effective strain field of the samples. This aspect is very important since it shows the "synthesis" of the strain signal that is recorded through the strain gages in the incident and transmitted bars, due to a highly complex stress and strain field that is present in a non-homogeneous 3DWC sample. Fig. 1 shows the specimen as it would be situated between the two bars. It is necessary that the specimen is perfectly flat between the two bars otherwise there will be poor transmission of the stress waves, at the interfaces between the incident bar, the 3DWC specimen, and the transmission bar. The samples were ground flat using a precision surface grinder.The strain rate was changed in the samples through a combination of changing the length of the pulse shapers and through changing the velocity of the impact bar. Material properties for the bars are provided in Table 1, and bar lengths and dimensions are given in Table 2. To record and capture digital images at high rates, a Photron SA.5 camera was used. A sequence of raw images captured in a SHPB test will be presented in a later section.

3. DIC data interpretation

The DIC data was used to not only synthesize the strain gage measurements, but also for further information on failure mechanisms and strain field non-uniformity. Preliminary tests showed that the spatially averaged strain in the sample agreed well with the strain measured from strain gauges in the bars. When the two measurements are plotted as a function of time, the two results show good agreement, however the results diverge at a certain point, see Fig. 2. The DIC results show that the strain reaches a critical value, however the strain gauges continue to predict "strain". From the DIC images, it is seen that the inferred measurement (from strain gages) often produces more strain than measured in the specimen, therefore the DIC data was used to determine where to truncate the data points that are used to construct an effective stress–strain relation, derived from the strain gauge responses. The reason for "more" strain production in the bars is due to the fact that this is an inferred measurement. The strain recorded in the bars is based on the integral of the reflected signal. Therefore such a measurement is insensitive to failure occurring within the specimen volume. Additionally, when the strain field in the specimen becomes highly localized due to failure, the specimen will soften and continue to compress, however, strain relaxation in other areas of the specimen leads to a net decrease in the DIC data. Strain relaxation cannot occur in the 1D wave analysis since a negative reflected signal would need to occur. The ARAMIS DIC software was used with a facet size of 17 pixels and a step size of 1 pixel for image processing. Additionally, it should be noted that the large variation in strain is due to the matrix and fiber tows within the 3DWC undergoing different strain histories. These differences are related to the different wave speeds within each constituent.

Table 1
Physical properties of incident and transmitted bars.

Material	440C stainless steel
Density	7620 $\frac{Kg}{m^3}$
Young's modulus	220 GPa
Ultimate tensile strength	1965 MPa
Brinell hardness	580

Table 2
Length of bars.

	Small bar	Big bar
Bar diameter	12.7 mm	38.1 mm
Incident bar length	1.83 m	2.438 m
Transmitted bar length	1.22 m	1.527 m
Striker bar length	0.30 m	0.457 m

4. Material

The material studied here is a 6% Z-fiber reinforced architecture. The Z-fiber reinforced architecture consists of a system of warp and weft fibers (in the remainder of this paper, the word fiber and fiber tow are interchangeably used to refer to a fiber tow). Fig. 3a shows

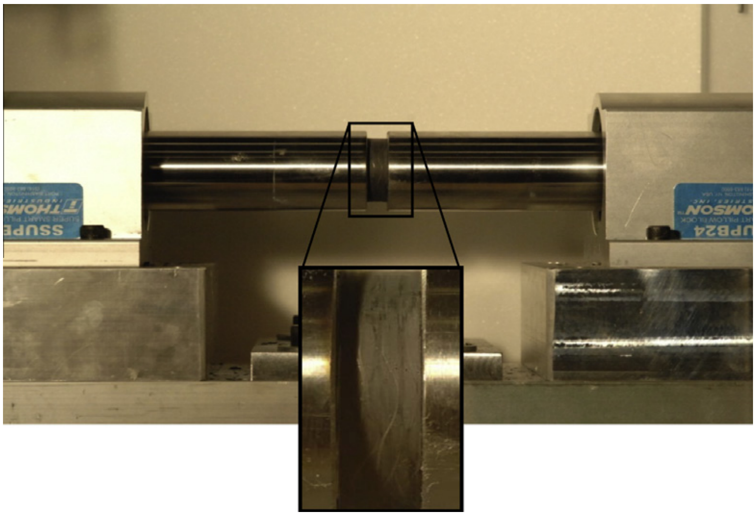

Fig. 1. SHPB setup showing the placement of the specimen in the apparatus. The specimen is held between the two bars. The specimen shown here is not one of the specimens tested as the one shown here is round and the ones tested were square.