International Journal of Solids and Structures 51 (2014) 1263–1273

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Nonlinear shear behavior and interlaminar shear strength of unidirectional polymer matrix composites: A numerical study

Yihong He, Andrew Makeev *

Department of Mechanical and Aerospace Engineering, The University of Texas at Arlington, Arlington, TX 76019, USA

ARTICLE INFO

Article history:
Received 3 May 2013
Received in revised form 14 November 2013
Available online 15 December 2013

Keywords:
Polymer matrix composites
Short-beam shear test
Interlaminar shear strength
Finite element analysis
Constitutive modeling
Digital image correlation

ABSTRACT

Detailed finite element implementation is presented for a recently developed technique (He et al., 2012) to characterize nonlinear shear stress–strain response and interlaminar shear strength based on short-beam shear test of unidirectional polymeric composites. The material characterization couples iterative three-dimensional finite element modeling for stress calculation with digital image correlation for strain evaluation. Extensive numerical experiments were conducted to examine the dependence of the measured shear behavior on specimen and test configurations. The numerical results demonstrate that consistent results can be achieved for specimens with various span-to-thickness ratios, supporting the accurate material properties for the carbon/epoxy composite under study.

1. Introduction

Interlaminar shear failure is one of the major failure modes for laminated composites. The resistance against shear delamination is characterized by the interlaminar shear strength (ILSS). American Society for Testing and Materials (ASTM) standards D5379 for V-notched (Iosipescu) shear test (ASTM International, 2005), and D2344 for short beam shear test (ASTM International, 2006), are commonly used to measure the ILSS of laminated polymeric composites. Compared to the V-notched specimen, the short-beam specimen is simpler to manufacture and consumes a much smaller amount of material. However, due to several challenges discussed in the remainder of this section, the test method is traditionally limited to materials screening and quality control instead of generating design allowables (Adams et al., 2003).

A typical test configuration and specimen geometry for a short-beam specimen subjected to three-point bending are illustrated in Fig. 1. In a short-beam test, the low span-to-thickness ratio (typically, $L/h = 4$ or 5) minimizes bending stresses, allowing through-thickness shear stresses to dominate, and promoting interlaminar shear failure at the neutral plane. Classical (mechanics of materials) beam theory (Timoshenko, 1972) is usually used to interpret the experimental result, despite the fact that the actual stress state of the short-beam specimen is complex due to the low span-to-thickness ratio and the stress concentration induced at the loading and support locations. It is assumed that the axial normal stress in the unidirectional SBS specimens varies linearly thorough the beam thickness, and the shear stress in the plane of loading varies parabolically and reaches its maximum on the neutral plane. For a beam with a rectangular cross-section, the maximum shear stress is

$$\sigma_{13}^{\max} = \frac{3}{4}\frac{P}{A} \quad (1)$$

where A is the cross-sectional area ($A = bh$) and P is the load applied at the loading nose. Eq. (1) is used in ASTM D2344 (ASTM International, 2006) to calculate the short-beam strength (F^{sbs}) by substituting the maximum load ($P_{\max}$) observed during the test.

The accuracy of the closed-form approximation (1) has been a major concern since the test method was introduced to composite materials community four decades ago. Rigorous studies, using elasticity solutions (Whitney, 1985; Sullivan and Van Oene, 1986) or finite element (FE) simulations (Berg et al., 1972; Cui and Wisnom, 1992; Cui et al., 1992; Adams and Lewis, 1984; Xie and Adams, 1994, 1995; He, 2010), have been conducted to determine the validity of the test for the measurement of ILSS. These studies have all demonstrated inadequacies in the classical beam theory in defining the stress state in the short-beam configuration (ASTM International, 2006). Furthermore, the accuracy of Eq. (1) was found depending on various parameters such as specimen size, loading conditions, and most importantly, through-thickness shear behavior. For this reason, the term “apparent” interlaminar shear strength is often used to define the ILSS calculated using Eq. (1).

Highly nonlinear behavior of the test specimen is often observed in shear testing of unidirectional polymeric composites,

---

* Corresponding author. Tel.: +1 404 840 2378.
E-mail address: makeev@uta.edu (A. Makeev).

0020-7683/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijsolstr.2013.12.014

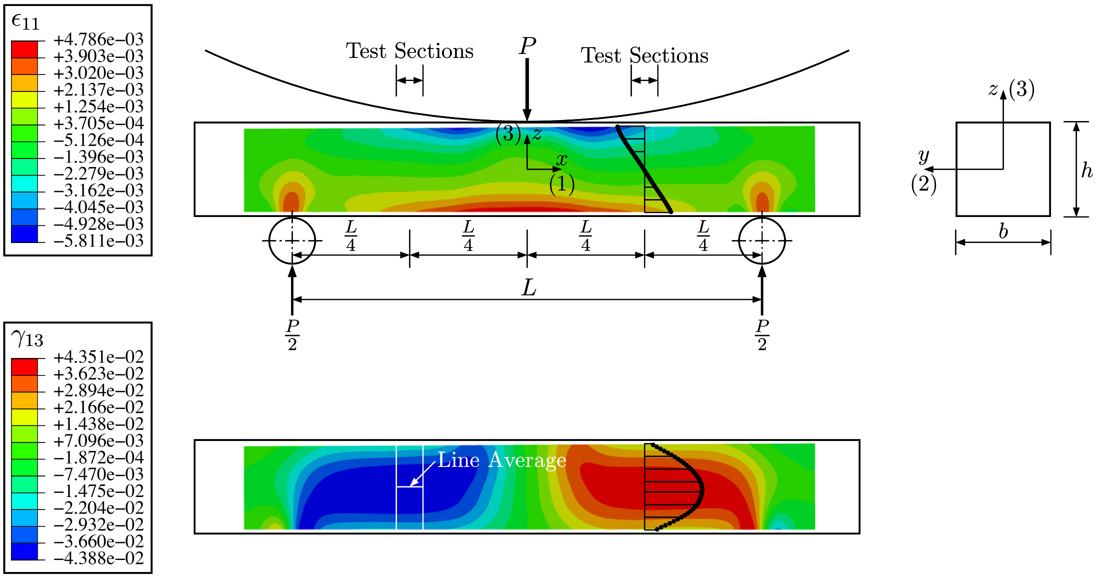

Fig. 1. Experimental setup of a SBS specimen and strain contour plots based on a DIC measurement taken right before failure.

since shear response of unidirectional composite is matrix dominant and polymer matrix is usually highly nonlinear material. The finite element analyses with shear nonlinearity taken into account (Cui and Wisnom, 1992; Cui et al., 1992; Xie and Adams, 1994, 1995; He, 2010) revealed that the shear softening significantly affects the classical beam theory assumptions, and consequently the accuracy of Eq. (1). For example, in a finite element analysis conducted by Cui and Wisnom (1992) for a glass/epoxy composite, the maximum shear stress away from the loading and support locations at the failure load is about 15% lower than the maximum value given by the classical beam theory.

In the presence of shear nonlinearity, it was also found that the discrepancy varies with the specimen configurations, in particular, the span-to-thickness ratio. Typical numerical results are shown in Fig. 2 for a unidirectional IM7/8552 carbon/epoxy prepreg tape (Hexcel, 2013). The simulations were conducted using a finite element model (FEM) developed in this study; and the material properties are listed in Table 1. The figure shows the comparison between closed-form and FE-based stresses over the entire loading history till failure for typical specimens with various spans. In each case, the discrepancy is negligible at low load levels where linear elastic material response can be assumed, the discrepancy increases at high load levels where significant shear nonlinearity exists, and reaches its maximum at failure load. Significant discrepancy of the closed-form approximation can be clearly observed in the typical short-beam configuration, i.e., $L/h = 5$, where the shear stress at the failure load is reduced by as much as 16% compared to the closed-form approximation. For the comparison purpose, a simulation was also conducted with linear shear response assumed. As shown in Fig. 2, the discrepancy is much smaller than its counterpart: the shear stress at the failure load is only reduced by 2.6% from the closed-form approximation. Fig. 2 also demonstrates the accuracy of the closed-form based approximation (1) is dependent on the specimen configuration and the discrepancy alleviates at higher span-to-thickness ratios. This explains the inconsistency of the apparent interlaminar shear strength observed in the experiments with various spans (Kedward, 1972; Christiansen et al., 1974; Lewis and Adamas, 1991).

Recognizing direct application of the classical beam theory for calculating the ILSS is significantly in error when the material response is nonlinear, FE-based correction was suggested by Cui and Wisnom (1992) to take into account the influence of shear nonlinearity. However, the FE-based calculation is dependent on the knowledge of the entire shear stress–strain response till failure, which is not available from the same test using conventional strain gage measurement, due to the strong-gradient strain distributions and the small span-to-thickness ratio. It is worth noting that the shear properties used in the early finite element analyses (Cui and Wisnom, 1992; Cui et al., 1992; Xie and Adams, 1994, 1995) were obtained from other shear test methods or micromechanical analyses. This challenge was overcome (Makeev et al., 2012) by using digital image correlation (DIC) to measure strain components on the specimen surface during the entire loading history. Digital image correlation is a full-field, non-contact measurement technique which allows to measure arbitrary complex (heterogeneous) deformations (Sutton et al., 2009). Fig. 1 shows contour plots for axial normal and shear strains on the specimen lateral surface obtained from a DIC measurement taken right before failure.

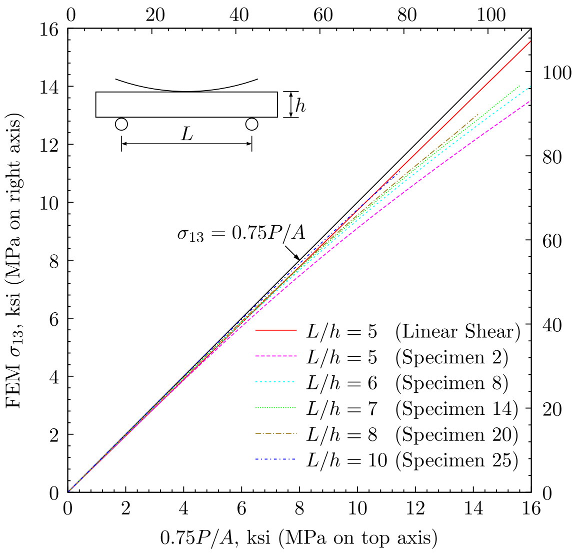

Fig. 2. Comparison of closed-form stress approximation and finite element stress calculations for SBS specimens with various spans.