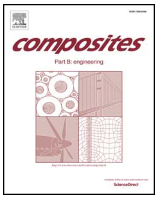
Composites Part B 139 (2018) 24–30

Contents lists available at ScienceDirect

Composites Part B

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



Direct shear stress vs strain relation for fiber reinforced composites

A. Sabik

Department of Mechanics of Materials, Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Narutowicza 11/12, 80-233 Gdańsk, Poland

ARTICLE INFO

Keywords:
Non-linear shear
Laminate mechanics
Constitutive law

ABSTRACT

The majority of fiber reinforced composites exhibit strong non-linear behavior in in-plane shear state. The effect is attributed to the micro-cracks appearing in the matrix and can be modeled on the micro and macro level. In this work the author proposes constitutive laws describing the non-linear in-plane shear response, which can be alternative for the relations commonly considered in the literature. The proposed equations are related to the experimental data.

1. Introduction

Since in long fiber strengthened composites the explicit orientation of reinforcement defines the orthotrophy planes, the response of a layer depends on the loading direction. The same lamina exposed to the tension or compression in the fibers direction behaves significantly different if compared with out of the reinforcement direction loading [1,2]. Basically the material behavior is affected by micro-scale effects arising in the matrix, fibers and their interfaces, like micro-cracks, debonding, rotation of fibers etc. A valuable meso-scale modeling of such effects was presented quite recently in Ref. [3].

In this paper the non-linear in-plane shear response is considered which can influence the laminate behavior in a large extent. In Ref. [4] it is argued that the shear damage mode is usually dominating one, even if it arises after the tensile damage mechanisms. On the other hand, the shear softening can be sometimes a desired effect, if the energy absorption is a design parameter [5]. In view to these facts and taking into account that in practice the laminates are usually subjected to multiaxial stress state and the shear effect appears, it is still reasonable to undertake the attempts to describe the non-linear in-plane shear behavior of these materials.

The reason for this particular nonlinear effect is not obvious. In Ref. [6] an interesting comparison of shear behavior of various composites is presented showing that the deformability of the reinforcement significantly influences the shear response of the resultant composite material. On the other hand the shear nonlinearity is supposed to be caused by the matrix micro cracking following from the fibers and matrix Poisson's ratios difference [7] which finally transform the matrix into the powder form [8]. This leads to the gradual degradation of lamina stiffness parameters depending mostly on resin properties, i.e. transverse and in-plane shear modulus [9]. Worth noticing is the fact that the in-plane shear behavior is significantly influenced by the strain rate value [10].

The corresponding stress-strain behavior can be reproduced with the use of various approaches. In Ref. [11] a spline function with an arbitrary fourth order polynomial in the strongly nonlinear range was adopted, whereas in Refs. [6,12] the shear non-linearity was simulated by bilinear function. On the other hand in Refs. [13–15] the Ramberg-Osgood relations were applied. In Ref. [2] several constitutive models were proposed with anisotropic functions instead of constant material parameters incorporated. In Ref. [16] the in-plane shear nonlinearity was modeled with the use of damage variable being a quadratic function of shear strain. The additional material constant was obtained via virtual fields method. In Refs. [1,17] the loading-unloading process of glass/epoxy laminate was modeled and the corresponding material law was written in terms of the exponentially varying damage variable and the permanent strain, assuming pseudo plastic behavior. Though in Ref. [18] similar model was adopted in progressive failure analysis of notched composites. An original proposal is given in Ref. [19], where the nonlinear in-plane shear behavior is reproduced buy the cubic spline interpolation. In Ref. [20] an advanced approach of matrix damage is adopted to model the shear response of laminates under cyclic loading.

Nevertheless, the nonlinear shear stress-strain behavior is unquestionably most often described by the third order polynomial de-

---

E-mail address: agsa@pg.gda.pl.

https://doi.org/10.1016/j.compositesb.2017.11.057
Received 14 January 2017; Received in revised form 30 August 2017; Accepted 30 November 2017

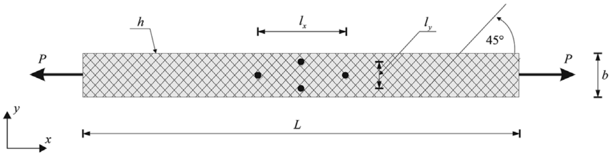


Fig. 1. Shear test conditions.

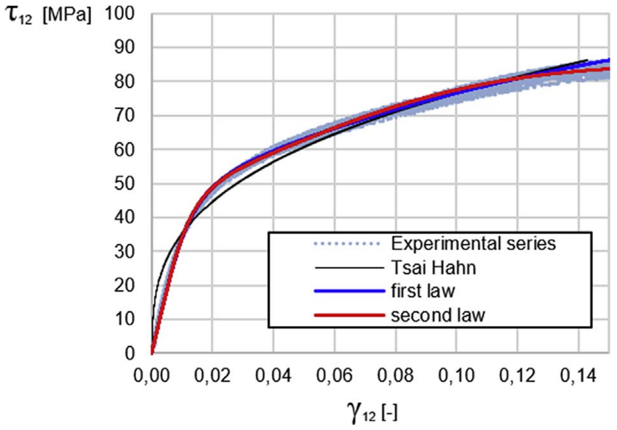


Fig. 2. Comparison of obtained results with experimental data.

rived from complementary energy by Tsai and Hahn [21]. This particular material law includes only one additional material parameter α which has to be obtained through the optimization of the experimental data. In Refs. [22,23] the Tsai-Hahn proposal was used in the analysis of buckling and progressive failure of composite shells. In Ref. [24] the Tsai and Hahn proposal was employed in the postbuckling analysis of sandwich structures. In Ref. [25] it governed the material behavior in the vibration analysis of plates and shells. This relation constitutes also the basis of the Chang's failure criterion, which as the matter of fact is the Hashin hypothesis improved by the in-plane shear nonlinearity constituted by Tsai and Hahn law [26]. In Ref. [27] the third order polynomial was adopted in the estimation of the in situ in-plane shear strength of thick embedded plies. In Ref. [28] the proposal of Tsai and Hahn was also successfully applied in the micromechanical composite material model of woven fabrics, while in Ref. [29] it was introduced into the fiber-matrix failure criterion of braided composite. In all the above mentioned applications and corresponding works the shear nonlinearity parameter α was assumed to be constant and independent on the deformation state. However, as follows from Ref. [13] and the author's experience [30], such an assumption is a strong limitation for the optimal experimental curve fitting. Therefore in Ref. [31] in the composite material damage model the shear nonlinearity parameter varies depending on shear strain values.

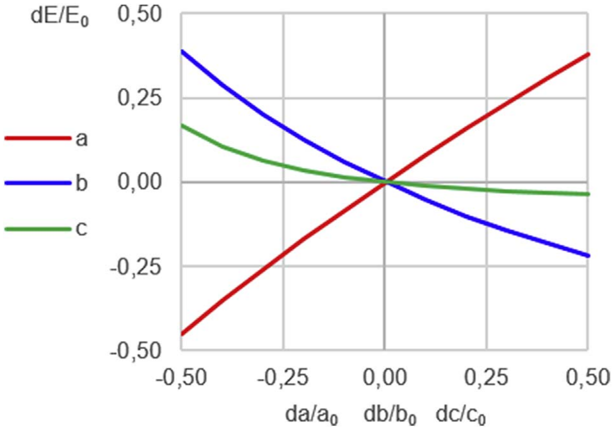


Fig. 4. Sensitivity analysis of energy value (second law).

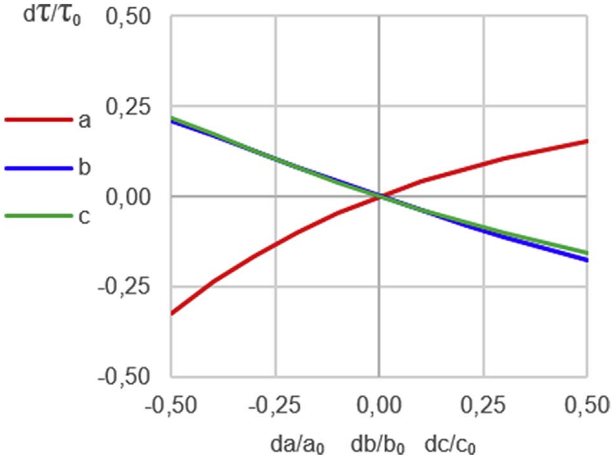


Fig. 5. Sensitivity analysis of stress value corresponding to $\gamma_{12} = 0.015$ (second law).

From the variety of approaches discussed above it is clear, that the relation which commonly serves as this constitutive law including in-plane shear nonlinearity is the function advanced by Tsai and Hahn. It is due to its simplicity, if compared with other approaches, and its strong theoretical background. However, as stated earlier, the constant value of the shear nonlinearity parameter α usually does not provide the optimal approximation of experimental data. An improvement with α being a function of strain is a kind of remedy. However, the law treats the strain as a function of stress. This is very unattractive from the view

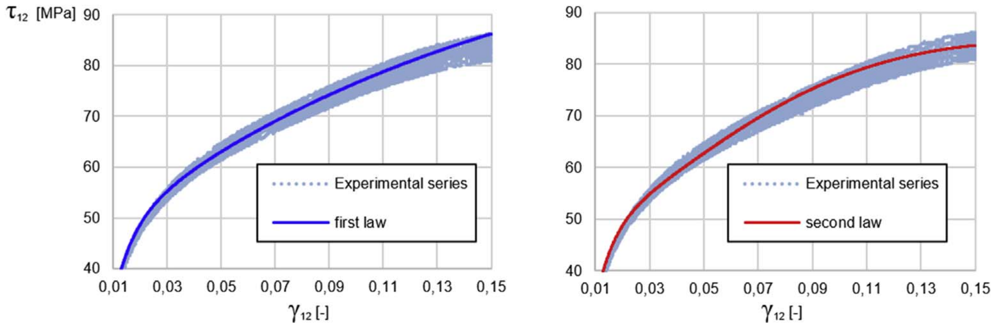


Fig. 3. Comparison of proposed functions efficiency in the non-linear range.