International Journal of Solids and Structures 000 (2018) 1–17

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

The effect of matrix shear strength on the out-of-plane compressive strength of CFRP cross-ply laminates

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ARTICLE INFO

Article history:
Received 15 September 2017
Revised 28 December 2017
Available online xxx

Keywords:
Composite materials
Laminates
Out-of-plane compression
Failure mechanism
Shear lag
Strain-rate sensitivity
Rate-dependent response
Finite element
Indirect tension

ABSTRACT

The failure mechanism of 'indirect tension' is explored for cross-ply IM7/8552 carbon fibre/epoxy laminates subjected to quasi-static, out-of-plane compressive loading. The sensitivity of compressive response to strain rate and to the state of cure is measured, motivated by the hypothesis that the out-of-plane compressive strength is sensitive to the matrix shear strength. A pressure-sensitive film is placed between specimen and loading platen, and reveals that a shear lag zone of reduced compressive traction exists at the periphery of the specimen, giving rise to a size effect in compressive strength. The width of the shear lag zone reduces with increasing shear strength of the matrix. The laminates fail by the indirect tension mechanism: out-of-plane compressive loading generates tension in the fibre direction for each ply and ultimately induces fibre tensile failure. Finite element (FE) simulations and an analytical model are developed to account for the effect of matrix shear strength, specimen geometry, and strain rate on the out-of-plane compressive strength. Both the FE simulations and the analytical model suggest a recipe for increasing the through-thickness compressive strength.

1. Introduction

Attwood et al. (2014) have recently demonstrated that Dyneema® cross-ply composites fail by the mechanism of 'indirect tension' under out-of-plane compressive loading; this failure mechanism in fibre composites was originally proposed by Parry and Wronski (1990). Unidirectional Dyneema® has an extremely low value of shear strength, and it is unclear whether a low shear strength is required in order to trigger this failure mechanism. Attwood et al. (2014) showed that the indirect tension mechanism in cross-ply laminates is a consequence of the differing lateral expansions of the 0° and 90° plies. The argument is as follows. Consider a stack of alternating 0° and 90° plies and subjected to out-of-plane compressive loading in the *z*-direction by a uniform pressure *p*, see Fig. 1a. A unit cell consists of a single 0° ply (labelled A in Fig. 1a) adhered to an underlying 90° ply (labelled B). If the two plies were allowed to slide freely with respect to each other, then ply B would undergo a much larger Poisson expansion in the *y*-direction than ply A, due to the orientation-dependent Poisson's ratio. This relative motion is prevented by adhesion between the two layers, and the two layers share the same strain in the *y*-direction. Layer A is subjected to a tensile stress σ_{yy}^A, whereas layer B experiences a compressive stress $\sigma_{yy}^B = -\sigma_{yy}^A$, to satisfy no net force in the *y*-direction. Additionally, by a symmetry argument, $\sigma_{xx}^B = \sigma_{yy}^A$ and $\sigma_{xx}^A = \sigma_{yy}^B$. The purpose of the present study is to explore the extent to which indirect tension is an active failure mechanism for carbon fibre/epoxy cross-ply laminates. The sensitivity of the indirect tension mechanism to the matrix shear strength is determined by considering laminates in various states of cure.

The precise relationship between the in-plane stress state in a specimen of finite size and the applied pressure *p* is dependent upon the choice of constitutive law for each ply but, in broad terms, the in-plane stresses are of similar magnitude to the applied pressure *p*. Additionally, interlaminar shear occurs at the interlayer between the alternating 0° and 90° plies in a shear-lag zone near the periphery of the specimen. Within this shear lag zone (of characteristic length l_s), the pressure *p* and in-plane stresses build up from the outer edge of the specimen towards the centre, see Fig. 1c. The pressure *p* remains uniform at a maximum value of $p_{\max}$ within the central region; the magnitude of $p_{\max}$ increases as the compressive strain $-\varepsilon_{zz}$ rises and failure occurs by tensile in-plane fibre rupture. This mechanism has been analysed previously by Attwood et al. (2014) for a rate-independent, elasto–

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https://doi.org/10.1016/j.ijsolstr.2018.01.023
0020-7683/© 2018 Published by Elsevier Ltd.

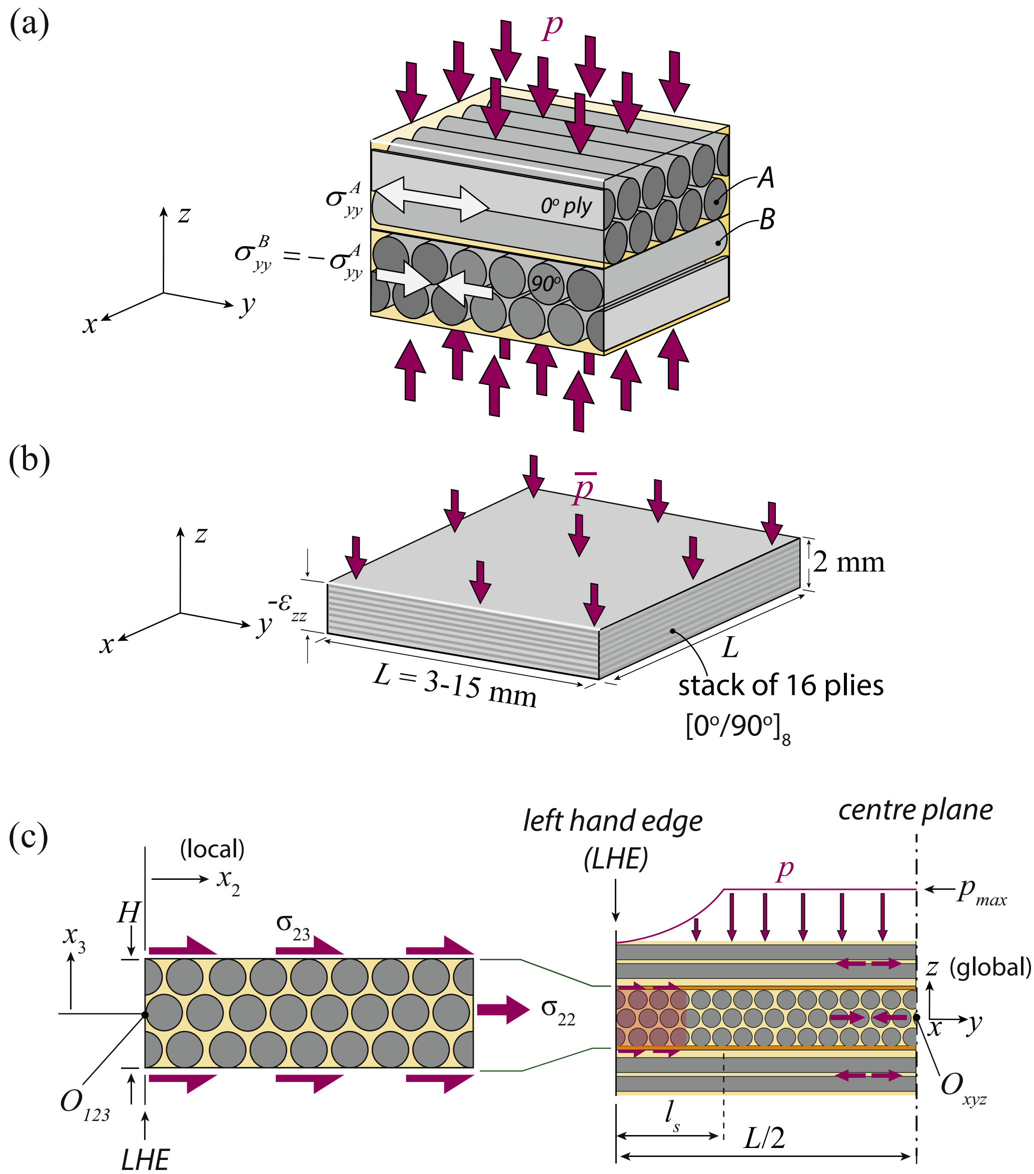

Fig. 1. (a) The indirect tension mechanism in a pair of 0° and 90° plies under out-of-plane pressure; (b) geometry of the quasi-static out-of-plane compression test; and (c) a free-body diagram of a section of the specimen in the $x_2 - x_3$ plane of a 90° ply, within the shear lag zone near the periphery of the specimen.

plastic composite response. In the present study, we shall develop a detailed analysis for the rate-dependent case.

Attwood et al. (2014) found that the out-of-plane compressive strength of the cross-ply laminates scales with the tensile strength of the fibres, thereby suggesting that the ballistic resistance of a composite can be increased by using fibres of higher tensile strength. O'Masta et al. (2015), Karthikeyan et al. (2013) and Attwood et al. (2016) subsequently confirmed that the ballistic resistance of Dyneema® cross-ply composites is dictated by the in-plane tensile failure of plies. The role of matrix shear strength in influencing the ballistic strength is less clear. Preliminary experiments by Karthikeyan et al. (2013) suggest that matrix shear strength does have a significant effect on the ballistic resistance of carbon fibre reinforced plastic (CFRP). We note in passing that the indirect tension mechanism is fundamentally different from the membrane-stretching mode of Phoenix and Porwall (2003).

In the present study, we shall explore in detail the role of matrix cure upon the mechanism of indirect tension for quasi-static out-of-plane compression of IM7/8552 carbon fibre/epoxy cross-ply composites. Particular attention is paid to the effect of rate sensitivity of the matrix upon the out-of-plane strength. In a typical out-of-plane compression test on a cross-ply laminate, the pressure $p_{\max}$ is sufficiently high (on the order of 1 GPa) that the attendant high values of hydrostatic stress leads to a significant change in the shear strength of the matrix and in the tensile strength of the fibres. These interactions are included in our analysis. In summary, a combined experimental, numerical, and analytical study is given in order to address the role of specimen geometry (thickness-to-width ratio) and state of cure upon the observed out-of-plane compressive strength of the CFRP cross-ply laminates.

1.1. Strain rate and pressure sensitivity

The strain rate sensitivity of the matrix flow strength in composites is evident in tests employing dynamic loading or a hot-wet environment, as noted inter alia by Daniel et al. (1981), Gates and Sun (1991), Soutis and Turkmen (1997), Staab and Gilat (1995), and Sun and Chen (1989). Commonly, rate sensitivity of the ma-