On multiple transverse cracking in glass fibre epoxy cross-ply laminates

A. PARVIZI, J. E. BAILEY
Department of Metallurgy and Materials Technology, University of Surrey, Guildford, UK

An investigation has been made of multiple transverse cracking in glass fibre epoxy cross-ply laminates. Four laminates of differing transverse ply thicknesses were investigated. Transverse crack spacing was found to decrease with increasing applied stress and decreasing transverse ply thickness. Very close agreement has been found between the experimental results and a multiple cracking theory based on shear lag analysis in which the plies remain essentially elastically bonded. In these composites a small modulus change is observed at a strain lower than that at which cracking initiated. This phenomenon is associated with a visual, under some circumstances reversible, whitening effect.

1. Introduction

In a recent paper, Garrett and Bailey [1] described the occurrence of systematic multiple cracking in glass fibre reinforced polyester 90° cross-ply laminates. The crack spacing in the transverse plies was found to decrease with increasing applied stress and in general was not accompanied by delamination between the plies. A simple multiple cracking theory based on shear lag analysis in which the plies remained elastically bonded could explain the general trend of the experimental results. However, there was an apparent underestimate of the crack spacing values for a given applied stress in their work.

In this paper, more detailed studies of the nature of the cracking behaviour are reported for a glass fibre reinforced epoxy composite. The aim of these experiments is to explain the apparent discrepancy between theory and experiment mentioned above. The experiments formed part of a wider investigation into cracking mechanisms in these systems; the effect of ply geometry on initial transverse cracking behaviour has been reported, Parvizi et al. [2].

2. Experimental procedure

0, 90, 0 cross-ply and unidirectional laminates were made from epoxy resin (Shell Epikote 828 cured with 80 PHR Epikure NMA and 0.5 PHR BDMA) reinforced with “E” glass fibre rovings (Silenka 1200 TEX). The glass rovings were wound onto open metallic frames of about 2 mm thickness and then the laminate was built up over an aluminium sheet by stacking up a sufficient number of frames in each direction. Fibres were wetted thoroughly by the liquid resin after each frame was laid down and the air entrapped was expelled by using a hot air blower. The laminate was eventually covered with a glass sheet to ensure a smooth surface and the excess resin squeezed out by applying sufficient pressure onto the laminate. Curing took place at 100°C for 3 to 4 hours followed by three hours of post curing at 150°C.

Cross-ply laminates were made, as illustrated in Fig. 1, with a transverse ply thickness 2d ranging from 0.4 mm to 4 mm whilst the longitudinal ply thickness, b, remained constant at about 0.5 mm on either side of the laminate. The fibre volume fraction of laminates was also kept constant at an average value of 0.55. Parallel sided specimens of dimensions 220 mm × 20 mm were cut from each cross-ply laminate so that their length was parallel to the fibre direction in the longitudinal outer plies, i.e. y-direction in Fig. 1. The specimen ends were reinforced with GRP tabs to prevent their premature failure at the grips.
Specimens were tensile tested to differing strain levels on a TTD model Instron machine at a cross-head speed of 0.5 mm min\(^{-1}\) (0.5 \(\times 10^{-4}\) sec\(^{-1}\) strain rate). The strain was recorded by electrical resistance strain gauges attached to the specimen and connected to the Instron recorder via a suitable bridge circuit. An acoustic emission transducer was also fixed to each specimen to give additional information during failure.

Tensile tests were also carried out on the unidirectional laminates, parallel and perpendicular to the fibre axis. Specimen preparation and test procedure were similar to those for the cross-ply laminates.

Transverse crack spacing in the inner ply was measured using a travelling microscope. The initial crack is clearly detectable both visually and acoustically and thus the transverse failure stress \(\varepsilon_{tu}\) is easily measurable.

### 3. Experimental results

The stress/strain curve of a typical laminate is shown in Fig. 2. The first “knee” observed at approximately 0.3% strain is associated with an apparent whitening effect. This whitening effect partially disappears when the specimen is unloaded and can be completely removed by a thermal treatment of a few minutes at 100° C. While the whitening phenomenon is observed in all samples, the magnitude of the departure from linearity at the “knee” is dependent upon the thickness of the inner ply, the greater the thickness the larger the change of modulus.

The second “knee” occurs at a strain of approximately 0.55% and is associated with the appearance of the first crack in the inner ply and acoustic emission; with increasing stress the crack spacing progressively reduces. Examples of the crack spacing are shown in Fig. 3.

In general, cracks formed span the inner ply (Fig. 4a) without causing debonding at the interface between the plies. At comparatively thick inner ply spacings, approximately 3 mm, a limited amount of debonding occurs, together with...