Experimental study of microbuckle initiation in a model composite system

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Abstract

Model composites comprised of alternate layers of steel plates and epoxy adhesive have been tested in compression. The early stages of microbuckle growth were captured on video, confirming the mechanisms of initiation and growth assumed by theoretical models of plastic microbuckling for compressive failure of long-fibre engineering composites. © 2001 Published by Elsevier Science Ltd. on behalf of Acta Materialia Inc.

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Introduction

Fibre reinforced polymer matrix composites are attractive materials in structural applications where strength and stiffness to weight ratios are the important factors. One of the main design problems with these materials is in estimating the compressive strength. A number of theories for compressive strength of unidirectional composites have been proposed. These and associated experimental findings are reviewed in [1,2]. For normal engineering composites the governing failure mechanism is plastic microbuckling, leading to the formation of kink bands. Argon [3] considered kinking of an infinite band of inextensible fibres with initial small fibre misalignment angle $\phi_0$. For the case where the normal to the band forms an angle $\beta = 0$ with the fibres, he derived a simple expression for the compressive strength $\sigma_c$ of unnotched material as

$$\sigma_c = k / \phi_0$$

(1)

where $k$ is the shear yield stress of the composite. The collapse stress $\sigma$ decreases with additional small fibre rotation $\phi$ in the band according to

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\[ \sigma = k/ (\phi_0 + \phi) \]  

This result is extended by Budiansky [4] for the case of an elastic-perfectly plastic composite with composite shear modulus \( G \) and shear yield strain \( \gamma_Y = k/G \) (again for \( \beta = 0 \)), to give the collapse response before yielding of the composite (i.e. \( \phi < \gamma_Y \)) as

\[ \sigma = \phi G/ (\phi_0 + \phi) \]

while after yielding Eq. (2) still applies. These models have been shown to have good agreement with measured values of compressive strength for bundles of fibres with large amplitude waviness, as for example in woven composites [5]. For material with small amplitude misalignment, e.g. laminates made from unidirectional pre-preg, good agreement is found using a reasonable value of fibre waviness of the order 1–3° [1]. However, the unstable nature of microbuckle initiation in unnotched composites means that, although theoretical models can track the collapse response, experimental studies have been restricted to measurements of the peak compressive load.

Laminates made from pre-preg do not contain waviness in the form of an infinite band; rather they contain finite regions of higher misalignment [6]. To explore this effect Fleck and Shu [7] have developed a finite element code which includes couple-stresses to model the bending stiffness of the fibres. For sufficiently large regions of misaligned fibres (typically larger than about 200 times the fibre diameter), the predictions tend to the infinite band results. This work has been extended to consider large amplitude fibre waviness [8] and initiation from a hole [9]. Recently there has been considerable interest in propagation of microbuckles; the key finding is that the propagation stress is generally much below the initiation strength [10,11].

Numerous authors have observed microbuckling in engineering fibre reinforced systems or in model composites (see the reviews of [1,2]). It is generally supposed that microbuckles initiate from resin-rich regions, free edges or regions of fibre misalignment. However, the unstable nature of microbuckle initiation for unnotched compression means that observations of the failure mode in this case have only been made after the microbuckle has propagated across the specimen (for example Ref. [12] gives a typical set of observations). The exact sequence of events as the microbuckle initiates in unnotched composites has not, to the authors’ knowledge, been verified experimentally. Several authors have observed microbuckle initiation or propagation from holes or notches [13–15], but these observations can shed rather limited light on microbuckle initiation from unnotched specimens. Model composite systems have been widely used to study microbuckling in fibre reinforced plastics (reviewed in Ref. [2]), but again the focus has been on measuring the peak load rather than the microbuckling initiation details.

This paper investigates microbuckle initiation for unnotched specimens made from a model composite system. By using specimens which are small compared with the size of the region of misalignment, stable collapse is observed. In the first specimen, which contains a uniform band of waviness, the collapse response is compared with theoretical predictions. The second specimen contains a non-uniform region of waviness, more typical of the fibre misorientation found in engineering composites [6]. For this speci-
men, observations of the microbuckle initiation event are presented. The aim of these measurements is to provide confidence in theoretical models of microbuckle initiation in engineering fibre composite systems.

Experimental setup

Model composite specimens containing either a uniform band or a limited region of misalignment were manufactured using steel plates (‘fibres’) and epoxy matrix. Details of the manufacture method, specimen geometry and testing procedure are given in this section.

Specimen preparation

The ‘fibres’ of the composite model with a uniform band of waviness were made of 28 mild steel plates with a thickness of 0.9 mm, width 9 mm and length 110 mm. The plates were bent to produce an initial waviness, cleaned with abrasive paper, degreased and inserted into an aluminium mould. This had slots in its ends to hold the plates an even distance apart, giving a ‘fibre’ volume fraction \( v_f = 0.64 \). Epoxy matrix (Araldite 2011) was then poured into the mould, the specimen was placed in a vacuum chamber to eliminate any air bubbles and then cured. Fig. 2(a) shows a side view of central section of the specimen. (Although this figure is for the specimen at peak load, it has essentially the same geometry as the initial specimen.) The steel plates, which are light in this video image, have a uniform band of waviness of width 39 mm, with an initial misalignment angle \( \phi_0 = 16.3^\circ \) and a band inclination angle \( \beta \) equal to zero.

A specimen with a patch of waviness was manufactured to examine the effect of a limited region of fibre waviness on microbuckle initiation. To produce a specimen containing a significant number of ‘fibres’ while still failing below the load capacity of the testing machine (100 kN), thinner steel sheets of thickness 0.1 mm, width 7.5 mm and length of 30 mm were used. To ensure a consistent spacing between the sheets and to reduce manufacturing time, Redux 312L epoxy matrix in film form was used as the matrix. Alternate layers of metal and epoxy were laid up in a mould and the assembly was then cured, under a dead-weight pressure. After curing, the specimen was machined to give final dimensions of 7 mm deep, 21 mm wide and 30 mm high. A non-uniform waviness was induced in the specimen by adding straight plates at the top and bottom of the mould and increasingly misaligned plates towards the middle of the specimen. The misaligned plates were bent by hand prior to laying up the specimen. The initial specimen geometry is essentially that observed at peak load, Fig. 3(a). Further details of the specimen preparation methods are given by Yuwono [16].

Matrix material

A small block of the neat Araldite epoxy resin was manufactured and tested in uniaxial compression at a nominal strain rate \( 10^{-1} \text{s}^{-1} \) to derive its stress–strain behaviour. The matrix can be well approximated as elastic-perfectly plastic with modulus \( E_m = 1.14 \text{GPa} \) and compressive yield stress \( \sigma_{mY} = 75 \text{MPa} \). Using the elasticity relation
\( G_m = 0.5E_m/(1 + v_m) \), where \( v_m \) is the Poisson ratio of the matrix (taking a typical value for this of 0.4), the shear modulus of the matrix \( G_m \) is estimated as 0.41 GPa, consistent with manufacturer’s data. The shear response of the composite can be inferred from the compressive behaviour of the matrix, making the assumption that the steel plates are rigid. The matrix shear yield stress, which in this approximation is equal to the composite shear yield stress \( k \), is taken equal to \( \sigma_{mY}/\sqrt{3} \), giving a value of \( k = 43 \) MPa. The matrix and composite shear moduli \( G_m \) and \( G \) are related by \( G = G_m/(1 - v_f) \) to give a value of \( G \) equal to 1.13 GPa.

**Testing procedure**

The specimens were tested under compression loading using a screw-driven Instron machine. The crosshead velocity was held fixed during loading at 1 and 0.5 mm/min for the specimens with a band and a patch of waviness, respectively. These rates were chosen to be able to follow the failure effectively on video. To suppress Euler buckling, an anti-buckling guide of transparent Perspex was used. The top and bottom of the specimen were lubricated with PTFE. A video camera and recorder were used to observe the side of the specimens during loading.

**Results**

**Specimen with a band of fibre misalignment**

This section describes the results for the model composite with a band of fibre misalignment. Video images were used to estimate the fibre rotation \( \phi \) in the microbuckle during deformation, taking the fibre orientation at the point of inflection in the fibre. Some fibre rotation was observed at very low loads as the specimens deformed during the bedding-in process. This behaviour is not related to microbuckling and has been subtracted from the fibre rotations presented here. Fig. 1 shows the collapse response in the form of variation in the applied stress with fibre rotation within the band. The peak load is reached after an additional fibre rotation of 3.5°. Due to the relatively

![Fig. 1. Collapse response for the specimen with a band of waviness.](image-url)
small dimensions of the specimen, the collapse response was stable under displacement control. Fig. 2 shows the sequence of collapse. At peak load, Fig. 2(a), the specimen looks essentially the same as the initial geometry, though there has in fact been a slight fibre rotation. As the fibres continue to rotate, Fig. 2(b), the inclination angle $\beta$ of the microbuckle band increases from its initial value of $\beta = 0$.

Theoretical predictions of the collapse response using an infinite band kinking model of microbuckling are compared in Fig. 1 with experimental measurements. Predictions for the rigid-perfectly plastic and elastic-perfectly plastic models are taken directly from Eqs. (2) and (3), with the matrix material properties given above. There is little difference in the predicted peak stresses with or without elastic behaviour and both models are in good agreement with the measurements. However the form of the collapse curve up to peak load is not well modelled using the rigid-perfectly plastic model. The shape of the collapse curve is captured much better when elasticity in the matrix is included. The relatively large fibre rotations measured early in the loading history suggest that the discrepancy in fibre rotation at peak load may be associated with errors arising from specimen rotation introduced during bedding-in.

**Specimen with a patch of fibre misalignment**

Fig. 3 shows images of the specimen with a non-uniform patch of waviness at peak load, soon after this peak and after the microbuckle has propagated across the specimen. The specimen looks essentially the same at peak load, Fig. 3(a), as before loading, although in fact measurements show that there is a maximum additional fibre rotation of about 4°. Just after the maximum load, Fig. 3(b), an initiating microbuckle is visible in the middle and towards the left of the specimen, at the edge of a resin-rich region. It has a width of $\approx 10$ fibre ‘diameters’, and at this stage a length of about 2 or 3 times its width and an inclination angle $\beta \approx 20°$. Fig. 3(d) shows an enlarged view of the initiating microbuckle just after peak load. As loading continued, the microbuckle propagated rapidly across the specimen, at an angle of between 15 and 20°, until it was
arrested by a split on the far side of the specimen, Fig. 3(c). These observations confirm the notion that the unnotched strength of the composite is determined by microbuckle initiation at regions of high misalignment. In this case initiation did not occur at the region of maximum misalignment in the specimen. Presumably the stress raiser at the resin-rich region was a contributory factor. It is interesting to note that the angle of propagation of the microbuckle is established at a very early stage, adopting inclination angles similar to those observed in engineering composites. Because of the variation in fibre waviness across the width, infinite band models cannot be used effectively to predict the collapse response for this specimen; a two-dimensional analysis (e.g. [7]) would be needed.

Conclusions

Model composites comprised of alternate layers of steel plates and epoxy adhesive have been tested in compression to investigate the initiation of plastic microbuckling. By using specimens which were relatively short compared with the microbuckle width, collapse proceeded in a stable manner, allowed the initiation event to be followed. Specimens containing ‘fibre’ misalignment in the form of a kink band running across the specimen were constructed with a ‘fibre’ volume fraction of 0.64. An elastic-perfectly plastic kinking model for the composite material is able to predict the collapse
response well. A specimen containing a patch of waviness was used to investigate microbuckle initiation from a finite region of imperfection. The early stages of microbuckle growth were captured on video, confirming the mechanism of initiation and growth assumed by theoretical models. It was interesting to see that the microbuckle propagation direction was locked in at an early stage, adopting inclination angles similar to those observed in engineering composites.

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