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On the initiation and growth of kink bands in fiber composites: Part I. experiments

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Abstract

The initiation and growth of a kink band in a uniaxial composite is investigated experimentally. Experiments on unidirectional plates of AS4/PEEK were conducted using a custom biaxial testing device. A relatively stable post-failure response which occurs for displacement controlled shearing under a compressive preload is exploited to observe quasi-static kink band growth. The band initiates from a stress concentration on one of the free edges and grows across the specimen with a constant inclination of about 12°. Detailed in situ measurements show that the fiber rotation and band width at a point increase as the band goes past it. After traversing the specimen, the band propagates (broadens) with constant fiber rotation. The observed kink band characteristics were similar to those of kink bands which grew dynamically in the same composite tested under pure compression. A difference is that the ends of the bands formed under combined compression and shear are highly bent but not broken.

Keywords: Composites; Compression; Kink band initiation; Extension

1. Introduction

The compressive failure of aligned-fiber composites has received significant attention in recent years because it typically occurs at stress levels 50–60% of the tensile strength. It is now widely accepted that failure is due to plastic microbuckling of the fibers in the inelastic matrix as pointed out by Argon (1972) and later by Budiansky (1983). This premise is in contrast to the earlier work by Rosen (1965) who assumed failure to be due to microbuckling of the fibers in an elastic matrix, which consistently yielded failure loads several times higher than the measured values. Small fiber misalignments present in the composites, lead to shearing of the matrix in misaligned regions. Since commonly used polymeric matrices have relatively low yield stresses, under compression a misalignment of the order of one degree results in matrix yielding. This causes microbuckling and failure due to loss of stiffness (Budiansky and Fleck, 1993).

Kyriakides et al. (1995, 1997) took a deeper look at the problem by idealizing the composite as a two-dimensional solid with alternating layers of elastic fibers and inelastic matrix with an initial waviness. The

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properties of the matrix were selected so that the shear response of the model material matched that of an AS4/PEEK composite, while the axial modulus was also correctly represented. They showed that compression of the model leads to a limit load instability essentially as suggested by Argon and Budiansky. Further, they showed that the limit load is followed by localization of deformation into narrow inclined bands. The fibers inside the bands bend and rotate very much like in kink bands reported from compressive failure experiments. In an extension, Hsu et al. (1998) considered a model with a more realistic microstructure involving circular elastic fibers hexagonally arranged in an elasto-plastic matrix. The model was again calibrated to have the same shear response as the actual composite. Under compression, this model behaved in a manner similar to the two-dimensional model, developing a limit load followed by localized bending in well-defined narrow bands across the microsection.

Thus, these studies confirmed that the formation of kink bands is a post-buckling event. Furthermore, the localization process through which they are formed is highly unstable involving significant load drops and sudden release of energy, which makes failure close to explosive (Fleck and Shu (1995) and Fleck et al. (1995) reached similar conclusions using a couple stress constitutive model for the composite).

An outstanding question is what sets the angle of inclination of kink bands (β). Part of the problem is that, because of the catastrophic nature of the onset of failure, to date it has not been possible to capture the process of the initiation of kink bands (an exception is initiation of kink bands from stress risers such as holes and notches – e.g., Waas et al. (1990), Sutcliffe and Fleck (1994), Sivashanker et al. (1995) and Fleck et al. (1997) – some of these reported propagation of out-of-plane kink bands). Instead, deductions are made from post-failure analysis of specimens in which kink bands formed dynamically. At the same time, kink bands formed under more controlled conditions, where the extent of deformation is limited to some degree by confinement, are consistently within well-defined ranges. For example, for the AS4/PEEK composite tested in several different types of experiments (Kyriakides et al., 1995; Kyriakides and Ruff, 1997; Vogler and Kyriakides, 1997, 1999a), the band inclination was consistently between 13° and 16°.

Several attempts to predict the value of β have been made using a variety of explanations of the phenomenon. Budiansky (1983), associated β with characteristics emanating from an imperfection on a free surface of a compressed composite. The predicted β depends on the elastic properties of the composite as well as the wavelength of the assumed initial imperfection, both of which are questioned in this work. The great majority of other attempts are based on the assumption that the band inclination is inherent to the unloaded material (Schapery, 1995; Christensen and DeTeresa, 1997; Jensen and Christoffersen, 1997). This is at variance with the conclusion from the numerical models mentioned above that the band is formed after the onset of failure through a process of localization of deformation.

Part I of this two-part series, presents recent experimental results showing in detail the quasi-static growth of kink bands across composite plates. This was accomplished using a custom biaxial testing facility, where unidirectional plates are loaded under combined compression and shear. The results include detailed views of the tip of a kink band during its growth across the specimen. In Part II, modified versions of 2-D and 3-D FE models, used previously to model compressive failure, are used to simulate the initiation of inclined kink bands and their growth across initially intact material. The sensitivity of the models to various input parameters is assessed, and their ability to capture the characteristics of the phenomenon is discussed.

2. Experiments

2.1. Experimental setup

The kink band initiation and growth experiments were conducted in the custom biaxial loading device developed for testing composite plates under combined axial compression and shear shown in Fig. 1

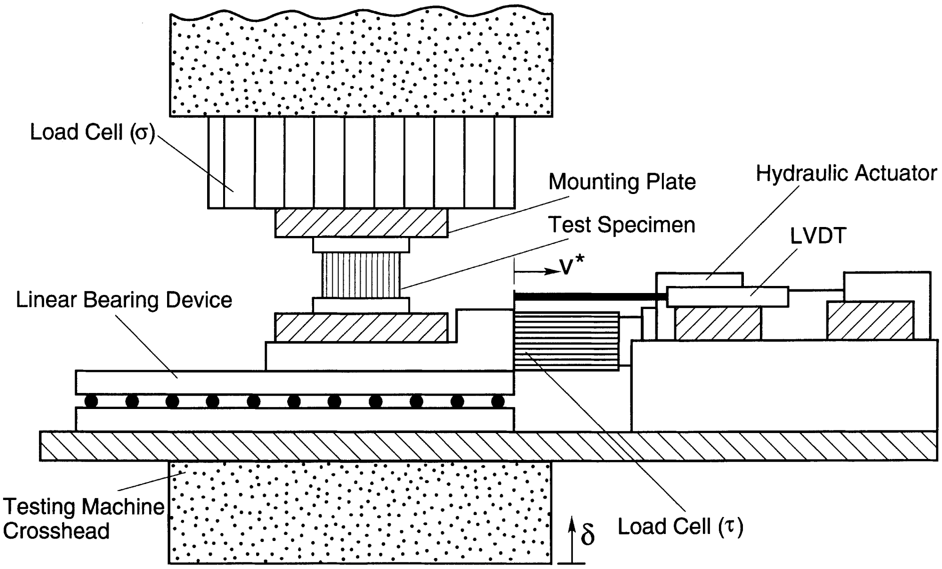

Fig. 1. Side view of custom biaxial testing device used for combined compression–shear loading of composite plates.

(Vogler and Kyriakides, 1999b; Vogler et al., 2000). The device is mounted onto a universal testing machine which applies compression. Shear is applied by a 1 in. stroke, 10 kip (44 kN) capacity hydraulic actuator mounted onto a stiff carrier plate which in turn is attached to the crosshead of the testing machine.

The specimen, in the form of a unidirectional composite plate, is attached via a special end plate to the load cell of the axial testing machine which is very stiff under a side load. A similar mounting plate at the bottom of the specimen is attached to a linear bearing connected to the horizontal actuator as shown in the figure. The bearing allows horizontal motion of the bottom of the specimen with minimal friction even at high axial loads, effectively decoupling the two loading types. The horizontal load is monitored by a load cell connected between the actuator and the bearing; the horizontal displacement (v^*) is monitored by a displacement transducer (LVDT). Both axes of loading can be operated in either load or displacement control. The independence of control for the shear and axial loads allows arbitrary choice of path in the biaxial stress (τ–σ) or strain (γ–ε) spaces.

The material tested was the same AS4/PEEK composite used in our previous studies in order to exploit the existing material characterization data essential for the analyses that follow in Part II. Specimens were square plates with dimensions of $2 \times 2 \times 0.125$ in.^{3} ($51 \times 51 \times 3.18$ mm^3). The top and bottom ends of specimens were bonded with a high strength adhesive to steel plates as shown in Fig. 2. A special aligning jig was used to assemble the specimen and the end plates. Assembled, the specimen had a test section of $1.2 \times 2 \times 0.125$ in. ($30 \times 50 \times 3.18$ mm). As in our previous experiments (Vogler and Kyriakides, 1997, 1999a; Vogler et al., 2000), out-of-plane buckling and displacement were prevented by laterally confining the test plate with 0.4 in. thick, hardened steel plates clamped to the sides. These plates were well lubricated and the applied clamping force was relatively small to keep friction to a minimum.

For certain experiments, a 0.5 in. (13 mm) thick, transparent synthetic sapphire (Al_2O_3) plate was used in place of one of the hardened steel plates (Vogler and Kyriakides, 1999a) to allow observation of the growth of the inclined kink band across the plate. A digital video camera (Kodak ES 1.0 SC) connected to a Macintosh computer running MAXX Grab software from Precision Digital Images was used to acquire images during such tests. Images 1024×1022 pixels in size were obtained, and Adobe Photoshop software

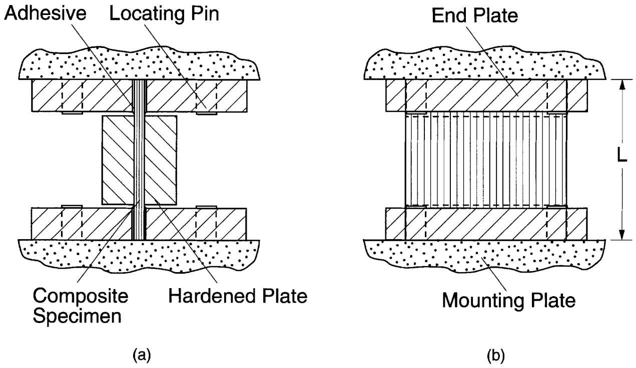

Fig. 2. Details of mounting for shear–compression plate specimen.

was used to enhance the images. Measurements of kink band characteristics were made using the NIH Image software.

2.2. Experimental results

The failure of aligned fiber composites under pure compression is sudden and catastrophic. The initiation of resultant kink bands involves high loads, is almost always dynamic and, as a result, is difficult to capture. Numerical results (Kyriakides et al., 1995; Hsu et al., 1998) have shown that this catastrophic behavior is due to a cusp-like post-failure response associated with localization of deformation resulting in the development of inclined kink bands. In the biaxial experiments conducted by Vogler et al. (2000), it was found that for certain loading paths, the post-failure response was less catastrophic and could be followed to a certain extent. This is the case for a specimen which is first compressed to a relatively low load and then sheared in displacement control, while the axial load is held constant. Results from such an experiment, including in situ observations of the progression of an inclined kink band across a specimen, are described next.

The specimen was first compressed to a stress (σ) of 60.9 ksi (420 MPa–$\boxed{\text{I}}$ to $\boxed{\text{II}}$). The recorded axial stress–displacement (σ–δ/L) response is shown in Fig. 3a (referred to as "first loading"). This initial response is nearly linear, but with a slope lower than E_{11} because the displacement measured by the testing machine (δ) includes the deformation of various parts of the setup. At $\boxed{\text{II}}$, the value of σ was fixed and the specimen was sheared in displacement control at a rate ($\dot{v}^*/L$) of 3×10^{-5} s^{-1}. The recorded shear stress–displacement response (τ–v^*/L) is shown in Fig. 3b (first loading). It is seen to be quite nonlinear while, at the same time, the specimen is seen to shorten as δ grows between $\boxed{\text{II}}$ and $\boxed{\text{III}}$. (Note that in this setup shearing of the plate results in somewhat non-uniform stress distribution – see Vogler et al., 2000 for extent). As the shear stress increased, the shear stiffness decreased and a limit load was reached at $\tau_{12} = 8.70$ ksi (60.0 MPa). The shear stress then began to drop, an indication that a kink band had been initiated. The shear load was removed soon thereafter and the specimen unloaded. Examination of the specimen confirmed that a single kink band had initiated from the corner of the gage section and grown about one-third of the way across the plate as shown schematically in Fig. 4a. The band was found to have an inclination, β, of 12° (Fig. 5).

For the second part of the test, one of the hardened steel plates was replaced with a sapphire plate as described above. The digital camera was used to monitor a 0.15×0.11 in.^{2} (3.75×2.90 mm^2) region just ahead of the partial kink band as shown in Fig. 4a. The resolution of the camera permits measurements accurate to approximately 10 μm. Measurements of kink band inclinations are estimated to be accurate to

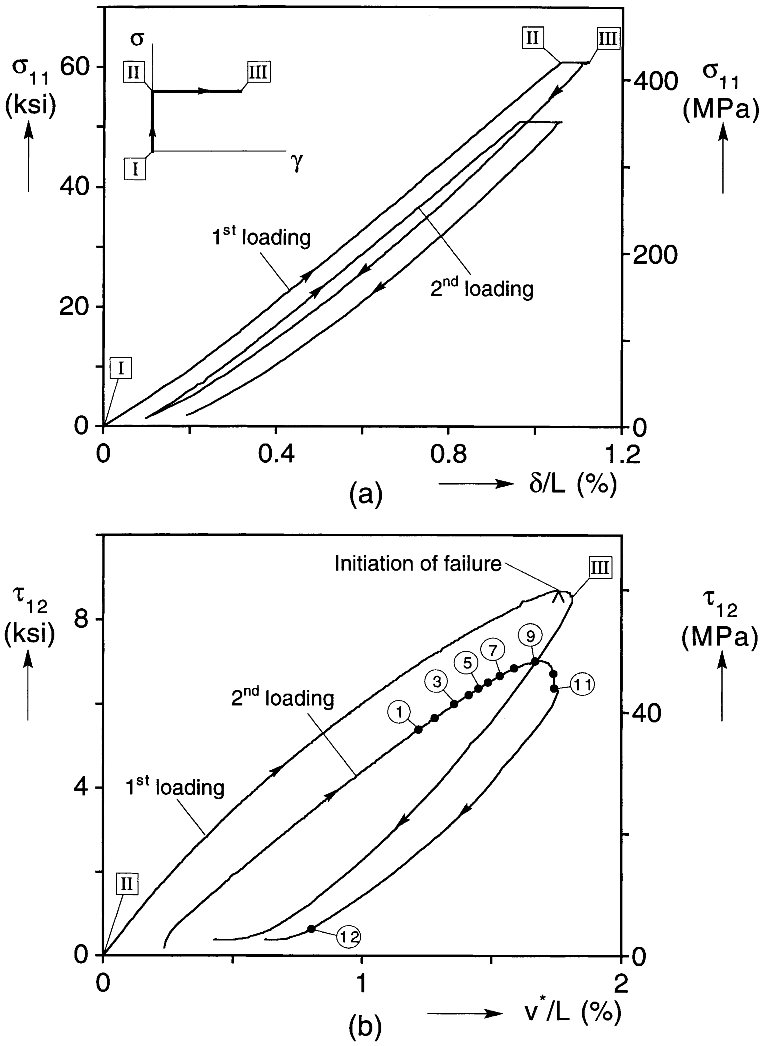

Fig. 3. Experimental results for biaxial specimen: (a) axial stress-end shortening and (b) shear–stress-horizontal displacement responses.

$\pm 0.5°$. Kink band widths and fiber rotations are measured somewhat less accurately due to the small width and the difficulty in determining where the edge of the kink band is when the fibers are not broken.

The test was continued by reloading to a compressive stress somewhat below the level applied initially (50.9 ksi to 351 MPa) and the resultant σ–δ/L response is shown in Fig. 3a (second loading). The slope of this response is nearly the same as in the first loading. With the compressive stress held constant, the specimen was once more sheared in displacement control, while the progression of the kink band was monitored with the digital camera. The recorded τ–v^*/L response is shown in Fig. 3b. The limit load is now lower at 7.02 ksi (48.4 MPa), but the response is followed well past the limit load. The inclined kink band grew quasi-statically across the specimen. The growth could be terminated by stopping the motion of the horizontal actuator. A sequence of 10 images taken with the digital camera at points along the response, denoted by ● in Fig. 3b, are shown in Fig. 6.

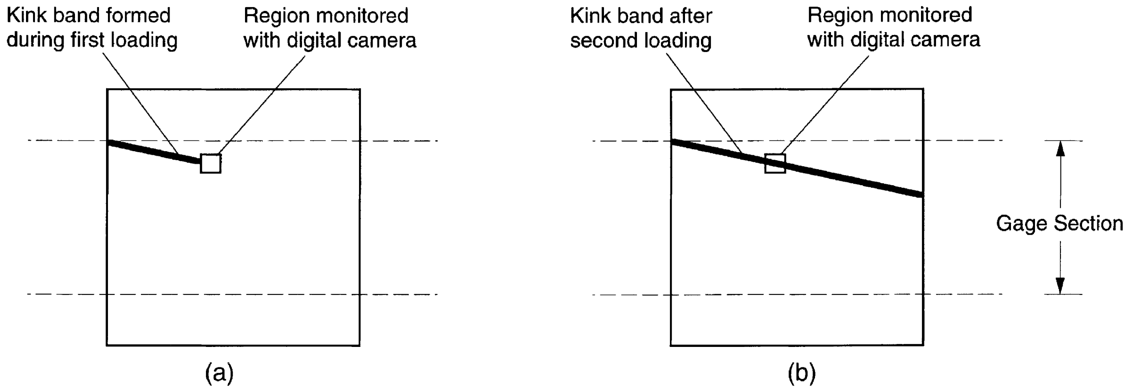

Fig. 4. Schematic of kink band from the specimen shown in Fig. 3. (a) after 1st loading and (b) after 2nd loading.

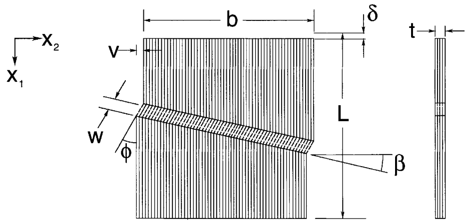

Fig. 5. Definitions of geometric variables of a kink band.

In image ①, the tip of the kink band is just to the left of the region monitored, though a slight distortion can be seen on the very left edge of the picture. By ②, the band has entered the field of view and is seen as a dark zone approximately 1 mm long. From ④ to ⑦, the band continues to grow to the right, eventually traversing the 3.75 mm wide field of view. The band has an inclination β of 12° which remains essentially constant throughout the loading. No curving of the kink band tip such as that reported by Moran and Shih (1995, 1998) was observed. (It is believed that the curving they observed was due to stress gradients caused by bending induced by the relatively large notch cut into the column-like tall specimen they compressed.) The band width w as well as the fiber rotation ϕ inside the kink band (Fig. 5) for the twelve points identified on the response (Fig. 3b) are shown in Fig. 7a and b, respectively. In the fully developed part of the band behind the tip (②–⑦), the width w is around 25 fiber diameters (h); this remains constant until the band has reached the right edge of the specimen. This width is consistent with values measured for simple kink bands in pure compression experiments on rods by Kyriakides et al. (1995); Kyriakides and Ruff (1997) (Fig. 9a). The fiber rotation ϕ is seen in Fig. 7b to have a gradient inside the growing kink band, with ϕ increasing upstream (to the left) of the tip of the band until a value of approximately 26° is reached. This is illustrated schematically in Fig. 8. The gradient of fiber rotation causes a continuous increase in ϕ at a fixed point on the specimen from images ④ to ⑨ as the kink band grows across the field of view.

The kink band reaches the right edge of the specimen in the neighborhood of image ⑨, which happens to also be close to the maximum shear stress of 7.03 ksi (48.5 MPa) as shown in Fig. 3b. This point corresponds to the schematic shown in Fig. 4b. Once the kink band has fully traversed the specimen, its width begins to increase significantly. The width is seen to nearly double from ⑨ to ⑫ as the kink band propagates axially (Vogler and Kyriakides, 1997, 1999a). By contrast, the fiber rotation ϕ remains essentially constant

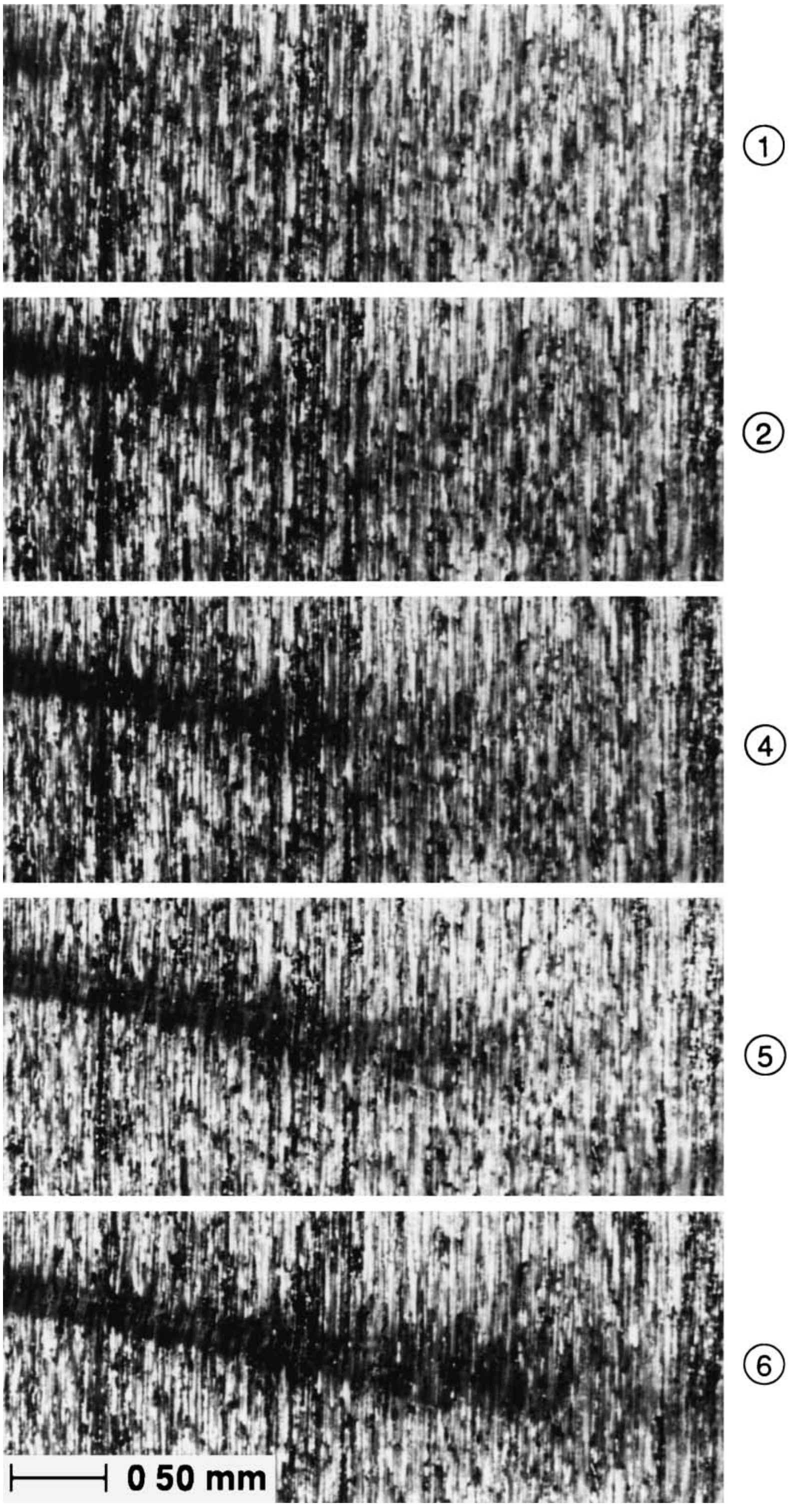

Fig. 6. Sequence of digital images of a kink band growing across a specimen. Images correspond to the points marked on the response in Fig. 3b.

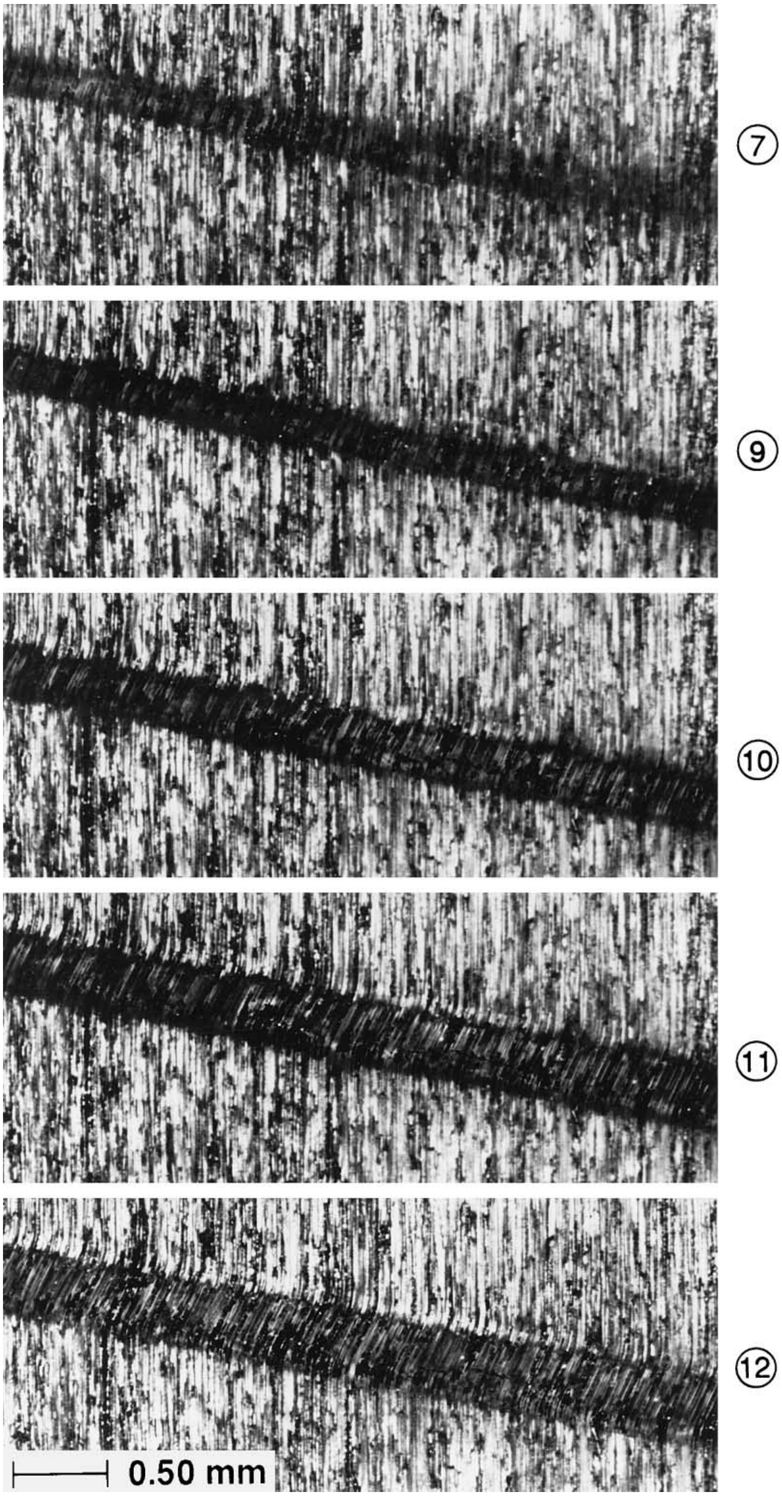

Fig. 6. (*continued*)

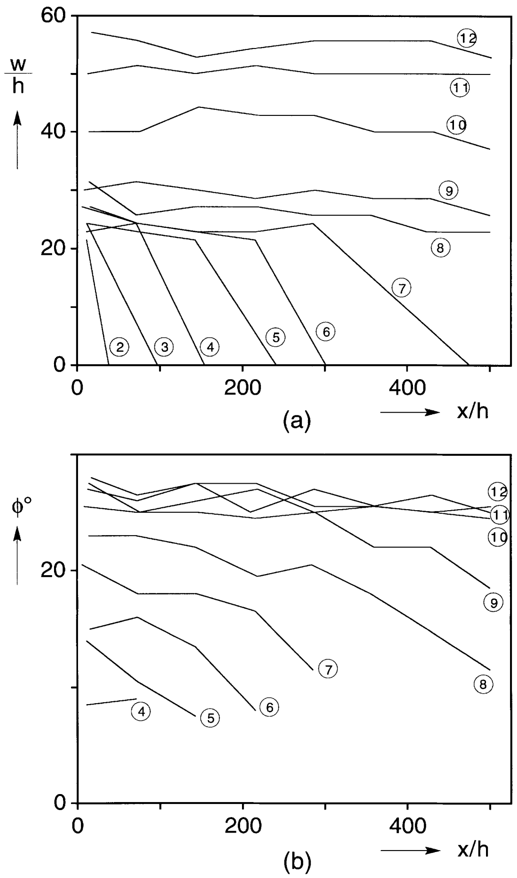

Fig. 7. Evolution of (a) kink band width and (b) fiber rotation during band growth.

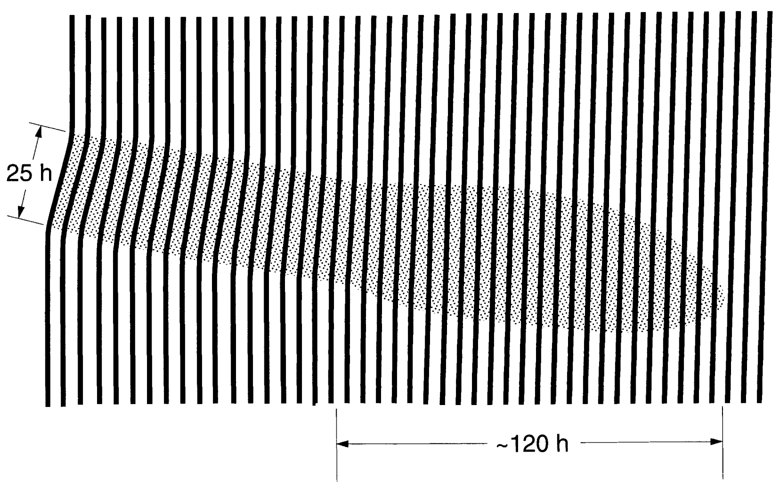

Fig. 8. Sketch of the tip of a kink band as it grows across a unidirectional composite.

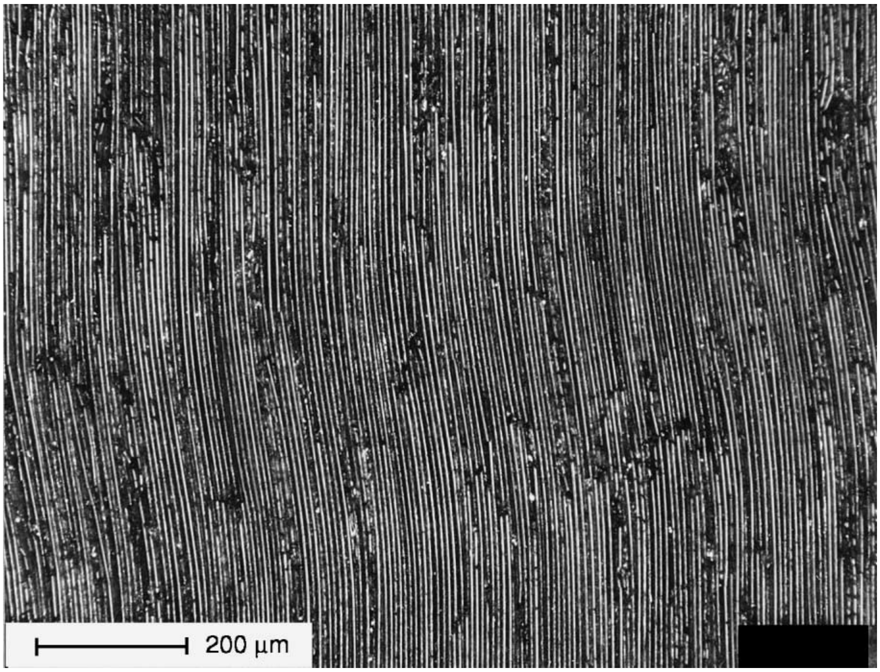

Fig. 9. Micrograph showing fiber bending and rotation inside the kink band grown quasi-statically by shearing under constant compression (unloaded state).

at about 26°. From ⑪ to ⑫, the shear stress is gradually removed. The final width of the band is approximately $55h$, and the fiber rotation is about 27° (i.e. somewhat greater than 2β).

Examination of the specimen following the test revealed that very few of the fibers inside the kink band were broken, which is contrary to kink bands formed dynamically under pure compression. This is illustrated in the micrograph shown in Fig. 9 taken from this specimen (consistent with the findings of Vogler et al., 2000). Two factors contribute to this, first the fiber curvature here is less (smaller ϕ), and second the band forms quasi-statically without sudden release of energy from the surrounding intact material.

The lower axial stress and the displacement controlled shearing used in the experiment described has enabled the growth of the kink band to occur quasi-statically which in turn made it traceable. In such experiments, the location of initiation of a kink band in a specimen cannot be guaranteed without providing some initial stress riser (e.g., indentation of one of the sides). In the present tests, the kink band initiated at one of two of the corners of the specimen at which stress concentrations existed. Irrespective of the initiation site all other events including the band characteristics were repeatable. As pointed out earlier, tracking of such a kink band has not been achieved to date for pure compression because of the dynamic and catastrophic nature of the corresponding events. We do, however, suspect that the sequence of events described above carries over to pure compression to a large extent. In fact, for one of the thicker plate specimens tested in the band propagation experiments of Vogler and Kyriakides (1999a), a kink band initiated dynamically from the side indentation damage and grew only halfway across the specimen (due to nearly simultaneous end-failure and splitting). Two micrographs of this band are shown in Fig. 10. In Fig. 10a, the kink band is distinct with the fibers broken at the upper and lower edges. The fiber rotation is approximately 13°. The micrograph in Fig. 10b shows a region of the specimen approximately 7 mm to the right of the first. This is close to the tip of the kink band and the deformation is much less pronounced.

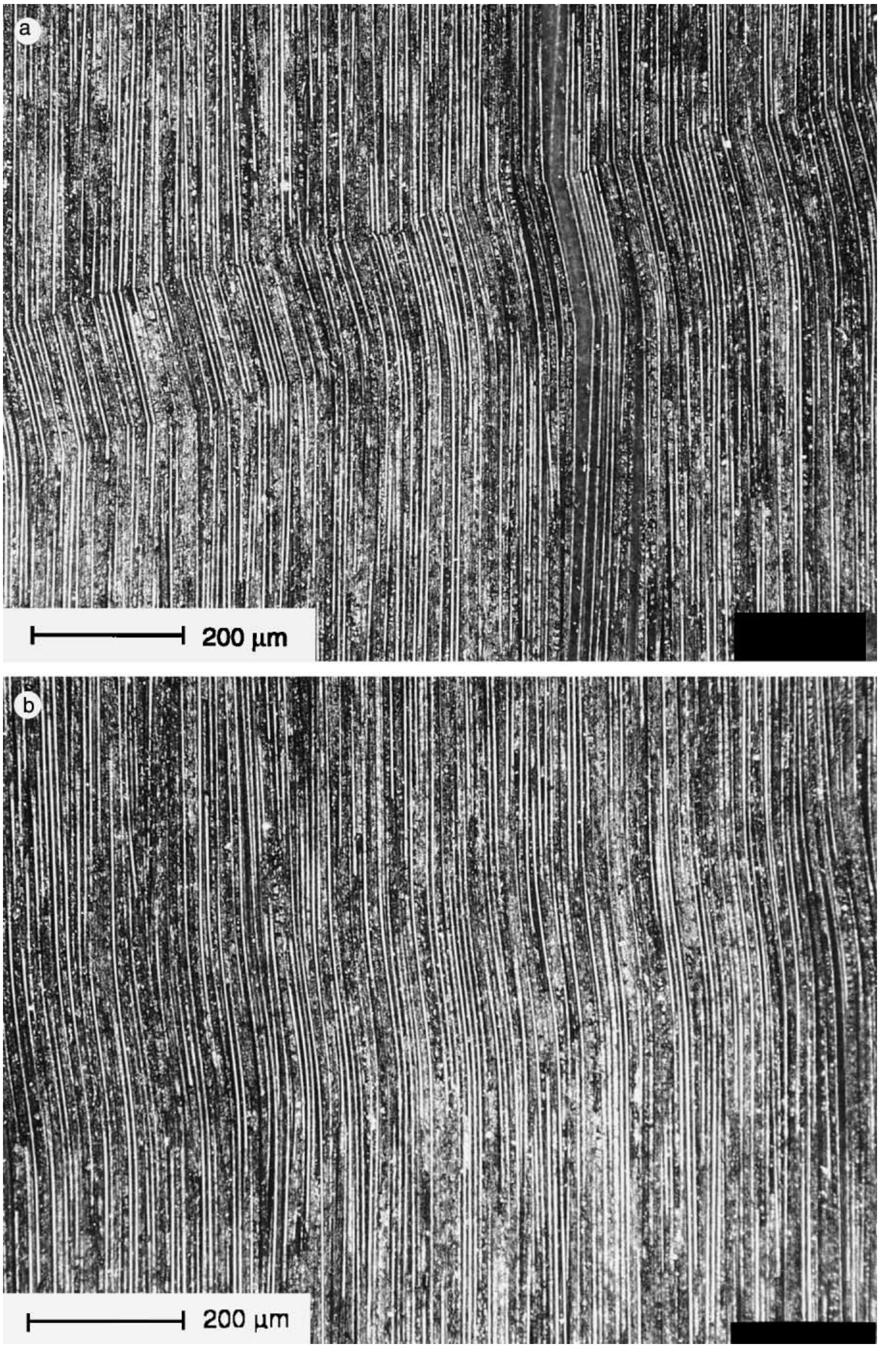

Fig. 10. Micrographs of a kink band which propagated dynamically and partially traversed a plate loaded by pure compression: (a) fully developed band and (b) zone closer to tip of band.

None of the fibers are broken yet, and the fiber rotation is only 7°. The band inclination in both is approximately 14°, and the fully developed width is 25*h*. Further to the right of the second region, the deformation decreases further and eventually it becomes impossible to discern the boundaries of the band. The geometric characteristics of this dynamically formed band are similar to those of the band in Fig. 6.

In summary, the displacement controlled shearing of a composite plate while it was simultaneously loaded by a constant axial load made kink band initiation and propagation across the plate a quasi-static, controlled event. The tip of the kink band is a zone of bent and rotated fibers on the order of 120 fiber diameters long. Both fiber curvature and rotation decrease to zero at the front edge of the tip (Fig. 8). The axial stress that was applied was not sufficient to fail the intact material. The shear deformation associated with the fiber rotation in the tip of the band plasticizes the matrix and reduces the local shear stiffness sufficiently for the axial stress to buckle the fibers. In this manner, as more transverse displacement is provided, the kink band grows. The inclination of the band was 12°, somewhat lower than the 15° average inclination of kink bands formed under pure compression.

Inside the tip, the band of increasingly bent fibers is a bit wider than the fully formed band behind the tip which was approximately $25h$ wide (Fig. 8). The gradient in bending of fibers inside the transition zone causes a corresponding gradient in fiber rotation. However, fiber rotation was found to continue even outside the tip. Once the kink band traversed the whole plate the band broadened uniformly in the axial direction. The broadening stress and fiber rotation angle are both lower than the values reported for the corresponding event under pure compression. The first is due to the presence of the shear stress and the second is due to the fact that the side support limits the extent of rotation of the fibers in the broadening band. In contrast to kink bands formed under pure compression, in this test the fibers did not break at the edges of the band either during its initial formation or subsequently during its uniform broadening.

Acknowledgements

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