Chapter 58
Characterization of Deformation Localization Mechanisms in Polymer Matrix Composites: A Digital Image Correlation Study

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Abstract Polymer matrix composites (PMCs) are attractive structural materials due to their high strength to low weight ratios. However, due to their low shear strength, failure can occur due to kink bands that develop on compression via plastic microbuckling. This phenomenon has been modeled extensively; however, experimental measurements of the strain fields leading to and developing inside these bands are scarce, as the sample preparation for digital image correlation (DIC) requires a microscale speckle pattern, which is hard to obtain using inks as PMCs they absorb them. In this study, two dimensional DIC is used to measure strains inside kink bands during 3-point bending of Dyneema HB80 samples. A novel micro-scale speckle pattern along with precision optics have been used to measure strains within the kink band, which had a width of approximately 600 micrometers. The speckle pattern was created by dropping copper particles through fine mesh sifters on a thin adhesive film that was applied and cured on the side surface of beam samples. This led to speckle dots that have a minimum of 15–20 µm mean diameter along with an inter-spacing ≤10 µm through the kinkband width. Images were captured during sample loading and processedusing ARAMIS™ software. Measurements indicate a mixture of large shear and normal strains (∼30%) in Dyneema HB80 inside the kink band.

Keywords Polymer matrix composites • Plastic microbuckling • Digital image correlation • Micro-scale speckle pattern • Kink band • Deformation localization

58.1 Introduction

Polymer Matrix Composites (PMCs) are attractive materials due to their high strength-weight ratio and controlled anisotropy. The use of PMCs in demanding applications in aerospace and defense industries makes it essential to understand their complex failure mechanisms under compression and bending. Many researchers [1, 2] have studied these failure mechanisms, including plastic microbuckling, and significant insight has been gained into PMC behavior. However, the same literature has not shed light on understanding kink band evolution under stress-gradients, such as those present during bending. This can be achieved, experimentally, by using high-resolution DIC to quantify the evolution of displacement and strain fields inside the kink band in the presence of stress-gradients. This investigation is focused on Dyneema HB80—Trademark of DSM Dyneema, NL. This is a cross-ply laminate [0/90] made of ultra-high molecular weight polyethylene (UHMWPE) fibers and polyurethane (PU) matrix. The traditional method of creating a speckle pattern by airbrush and water based inks does not work on these materials as they absorb them leading to smearing; hence, a new technique was developed to create a micro-scale speckle. Details on the procedures used during the experiments are described next.

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Table 58.1 Sample dimensions
(in mm) for 3 point bending tests
(aspect ratio used followed [3])

Total beam length	203.2
Supported beam length	152.4
Beam width	12.38
Beam thickness	10.57

58.2 Methodology

58.2.1 Three Point Bending Test and DIC

Samples of Dyneema HB80 and Spectrashield were cut from plates using a water-jet to conduct 3-point bend tests to study the kink band characteristics. Sample dimensions are shown in Table 58.1, which result in a 1–20 thickness to span ratio, which is acceptable as per ASTM standards [4].

A micro-scale speckle pattern was created on these samples to match the length scale of the kink band, which was expected to be 600 μm [1, 2]. In this method, a thin adhesive film, 3M™ Adhesive Transfer Tape 9485PC, with 100 μm thickness was applied with on the side surface of beam samples. For better adherence, the film was cured for 24 h at room temperature. After curing the film, Cu particles were applied on top of the film by dropping them from a fine mesh sifter. As a result, the fine particles adhered to the film and formed a micro-scale speckle pattern size of dots that had a minimum of 15–20 μm mean size diameter along with an inter-spacing ≤10 μm through the kink band width.

Understanding the sequential events of kink band formation and evolution can be difficult, since the process can be sudden; hence, all tests were conducted under displacement control to insure stability. An appropriate ASTM standard [3] was followed as closely as possible. Tests were performed at room temperature using a computer-controlled, screw-driven, electro-mechanical load frame with a constant displacement rate of 2 mm/min. Samples were rested on knife-edge roller supports), a radius of 5 mm, as accepted by the standard [3] and load was applied through a roller of 5 mm radius [3] in the middle of the span. Load vs. displacement data were captured digitally during the tests.

58.2.2 Data Acquisition for DIC

A 5 megapixel monochrome CCD camera with a ½ inch CMOS sensor equipped with a Rodenstock™ 35 mm lens was used, along illumination from 1400 lumen fluorescent CFL light bulbs. The manipulation of the focal length and aperture of the camera-lens assembly was a key factor to resolve the speckle through the band width. An aperture stop of $f/4$ was found appropriate and when the system was in focus resulted in 15 × 15 mm field of view, large enough to capture enough speckle dots. The picture had 2560 pixels horizontally across the 15 mm, i.e., about 100 pixels across the expected kink band width of 600 μm. Figure 58.1a shows the resulting speckle pattern. The band was expected to develop on either side of the load point application, so the large field of view helped with this issue. However, a translation stage to move the camera along 3 axes was also built to allow studying kink band formation and propagation during loading. This entire assembly was placed in front of the load frame, and photographs of the sample were taken at different values of load during testing. At some instances, the test was paused to reposition the camera-lens assembly to follow the kink band. All these pictures were taken before the test was paused and after the load-displacement curve returned to its original path after the loading was resumed. The ARAMIS™ software used these pictures to calculate the strains within and around the kink bands.

58.3 Results and Discussion

Load-displacement curves were found to have load oscillations, which were associated to the formation of kink bands. Tests were carried out along with DIC to find the strains inside the kink band during its evolution up to two subsequent peaks (pointed out with two red circles) using the stages shown in Fig. 58.1b for Dyneema HB80. The drops in Fig. 58.1b correspond to the point of the pause of the test as the camera-lens assembly was moved to follow the propagating band. After re-starting the test, the data acquisition continued recording the corresponding loads and displacements. Images were captured at zero load and also as load increased, with particular emphasis at the first two subsequent peak loads to visualize the development of the kink band from the compression side of the beam.
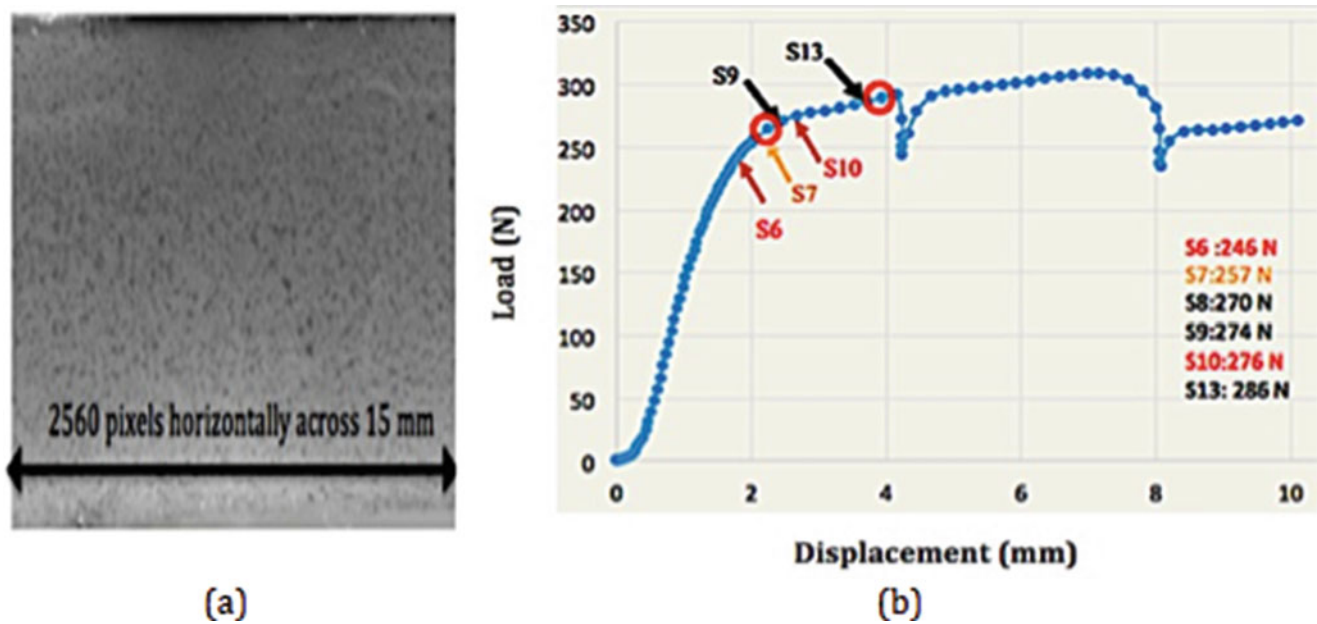
Fig. 58.1 (**a**) Speckle pattern used here (**b**) Load-displacement curve for Dyneema HB80. Different stages of the DIC measurement are marked with arrows and were done at the loads shown in the inset

58.3.1 DIC Results

The series of images captured during testing of the samples were processed using DIC software to determine the displacements and strains within and around the kink band. Variables of interest extracted from the DIC results include shear strains (%) inside the kink band and around it, as the band evolved. Different sections were created to determine the corresponding values of strains. The resolution of the DIC is based on the number of facets within the interested region. The resulting images had 100 pixels across the expected kink band width of 600 μm. In this case, at least 4 facets with one-facet, size of 21 × 21 pixels were used to solve for displacements and strains across the kink band. Figure 58.2a shows a kink band in a Dyneema HB80 sample. The coordinate system has been rotated to be parallel and perpendicular to the band to extract actual strains inside it. The shear strain for section 0 was approximately 8%. As the band propagated with further bending, the shear strain increased for the same section as shown in Fig. 58.2b.

The strain in section 0 of stage 12 increased by 300%. The strains shown here are the peak values within the band extracted from profiles in Fig. 58.2a. Note that, the shear strains in all stages increased as the band evolved with further beam displacement. This is because with further bending, the plies rotate (ply rotation angle dominates) cooperatively near the vicinity of the load point application. The behavior is similar to Dyneema HB26 as reported in [2]. The shear strains in these bands have been found to be as a function of ply rotation and kink band inclination angles [1, 2].

58.4 Conclusions

Oscillations on load-displacement curves indicate the presence of kink bands triggered by plastic microbuckling. The DIC results show that the bands nucleate at the compression side and propagate into the sample carrying a mixture of large shear and normal strains (∼30%), while also decreasing its bending stiffness. The shear strains in all stages increased as the band evolved with further beam displacement. This is because with further bending, the plies rotate (ply rotation angle dominates) cooperatively near the vicinity of the load point application. Dyneema HB80 has a kink band width of approximately 560 μm.
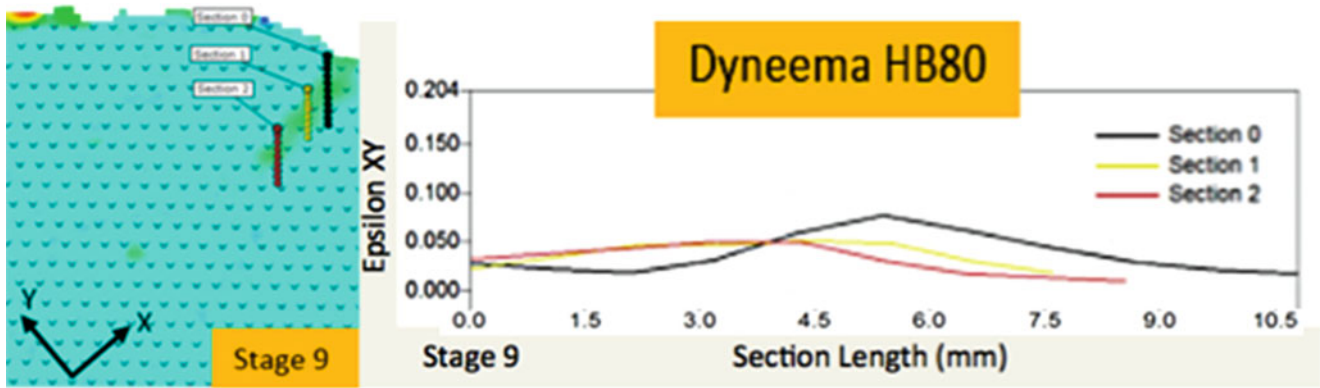
(a)
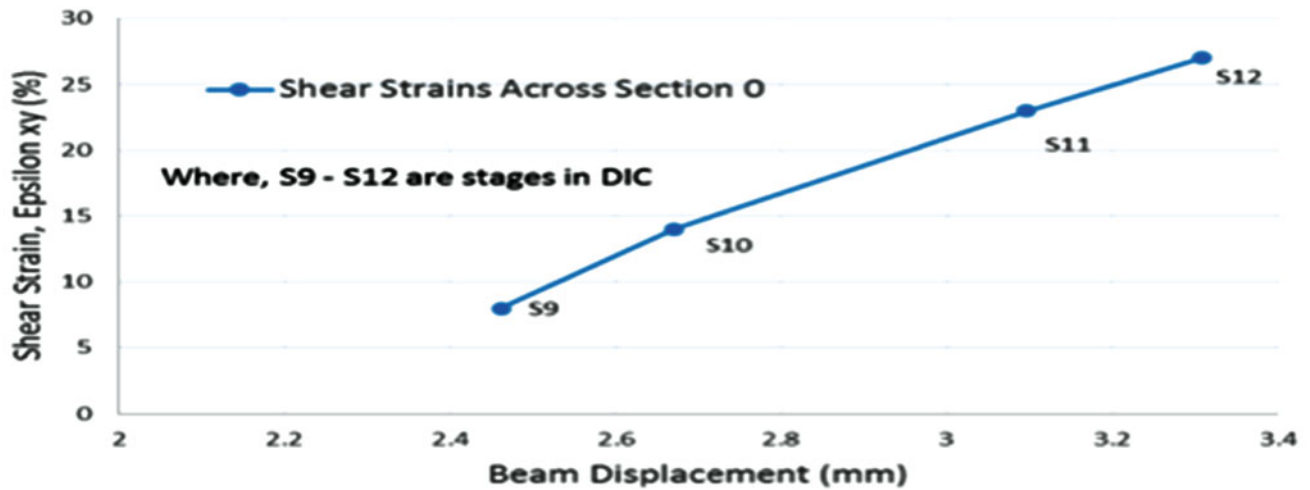
(b)

Fig. 58.2 (**a**) Kink band in rotated coordinate system along with stages and Shear strains across sections 0 (*black*), 1(*yellow*) and 2 (*maroon*) (**b**) shear strain (%) vs. beam displacement (mm) in DyneemaHB80

References

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