High-Speed Microscale Imaging of Damage in Composite Laminates

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1. Abstract

Microscale damage in composite laminates evolves too quickly and too locally to be resolved with conventional imaging. This paper presents a microscope-coupled high-speed optical approach for observing transverse cracking in glass fiber-epoxy cross-ply laminates under quasi-static three-point bending. Two representative image sequences are presented: a Single-90-ply laminate that shows debonding-mediated crack initiation and stepwise propagation, and a Double-90-ply laminate that yields faster through-thickness advance in a thicker 90° block. The images, captured at very high rates, reveal that isolated fiber-matrix debonds commonly precede sudden crack jumps, that local defects can override the nominal strain gradient, and that neighboring microstructural features can arrest or redirect crack growth. The results provide direct evidence that the onset of transverse cracking is not continuous, but instead proceeds through discrete, debonding-controlled events lasting milliseconds or less.

2. Introduction

Damage in fiber-reinforced composites is governed by interacting micro-mechanisms such as fiber-matrix debonding, matrix cracking, delamination, and fiber breakage. Although these events are well established in the literature, their timing and sequence at the microscale are still difficult to capture because the relevant events are both small and extremely fast.

Transverse cracking is especially important because it often marks the start of progressive damage in laminated composites. Previous work has combined (electron) microscopy, surface replication, digital image correlation, and synchrotron X-ray methods to study cracking and delamination, but each approach faces trade-offs among temporal resolution, spatial resolution, field size, loading rate, or accessibility [1-9]. As a result, the early stages of crack initiation and the very first propagation steps remain only partially resolved.

Here, a microscope-coupled high-speed camera is used to capture damage evolution in glass fiber-epoxy laminates during quasi-static bending. Two representative image sequences are presented here: one from a Single-90-ply laminate and one from a Double-90-ply laminate. Together, they show how local microstructure, ply thickness, and interface conditions govern the way transverse cracks initiate, pause, re-open, and propagate.

3. Materials and methods

The laminates were manufactured from Advantex R25HX14 glass fibers in a thermoset epoxy matrix and stacked in two configurations: $[0/90/0/0/0]_S$ (Single-90-ply) and $[0/90/90/0/0]_S$ (Double-90-ply). After curing, the panels were cut into 145 mm by 12.5 mm specimens, and the cut edges were ground and polished to remove machining damage and to expose the microstructure for optical observation.

Three-point bending tests were carried out in an inverted configuration on an Instron 5567 machine according to ASTM D7264. The 100 mm span and 1 mm/min crosshead speed were selected to keep the loading quasi-static while increasing the chance of capturing crack initiation and the earliest propagation steps. As shown in Figure 1, the inversion of the fixture helped keep the field of view stationary near the tensile-side mid-span region, where the first transverse cracks were most likely to appear.

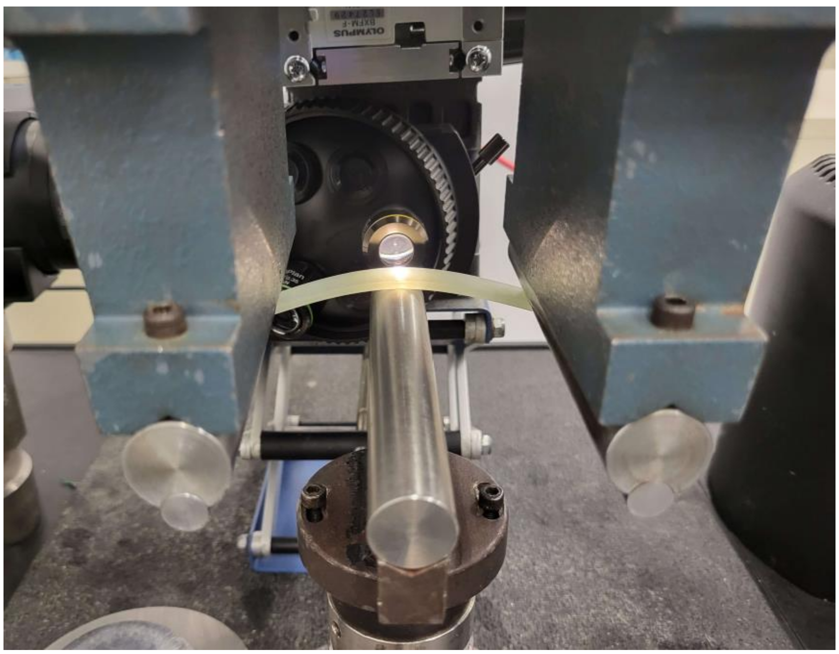

Figure 1. Three-point bending setup with inverted loading pins to stabilise the field of view during in situ high-speed, high-magnification imaging. The microscope-coupled high-speed camera is visible behind the specimen.

In situ imaging was performed with a Photron FASTCAM Mini AX100 camera coupled to an Olympus BxFM-F microscope with a 20× long-working-distance objective. The recorded field of view was approximately 1.5×1.0 mm^2 with an effective spatial resolution of about 4 µm/pixel at 25,000 frames per second and an exposure time of about 37 µs. Difference images were generated by subtracting each frame from the first image in the sequence, which makes subtle damage evolution easier to see. Table 1 presents the key study parameters.

Table 1. Overview of the retained experimental conditions.

Parameter	Value
Layups	Single-90-ply: $[0/90/0/0/0]_S$; Double-90-ply: $[0/90/90/0/0]_S$
Dimensions	145 × 12.5 mm; thickness 2.80 mm and 3.50 mm
Standard / loading	ASTM D7264, inverted three-point bending, 100 mm span
Optics / sampling	20× objective, 25,000 fps, ~37 µs exposure, ~4 µm/pixel
Field of view	About 1.5 × 1.0 mm2 at the tensile-side mid-span

4. Results and discussion

The two selected cases clearly show the contrast between stepwise cracking in a single 90° ply and rapid through-thickness crack advance in a thicker 90° block.

4.1. Single-90-ply laminate

The Single-90-ply sequence shows an almost complete initiation-and-growth event in a time window of less than 40 ms (Figure 1). A local fiber-matrix debond first appears near the lower interface of the transverse ply, even though the upper interface is nominally under higher tensile strain. This indicates that a local defect or fiber arrangement dominated the initiation site rather than the global strain gradient.

Within a few frames, the debond evolves into a transverse crack that advances in a clearly discontinuous manner. The sequence contains alternating short pinning intervals and sudden jumps, with isolated debonds repeatedly forming ahead of the crack tip before the next advance. A second crack segment also appears and later merges with the first, confirming that the local damage field is highly heterogeneous. The full event develops over roughly 37 ms, and the abrupt advances occur within a single 0.04 ms frame interval, so a speed of ~1 m/s is calculated as a lower-bound value for crack propagation.

The main message from this sequence is that transverse cracking does not proceed as a smooth front when captured at high imaging speeds. Instead, it is controlled by a repeated cycle of local debonding, crack arrest and sudden re-activation.

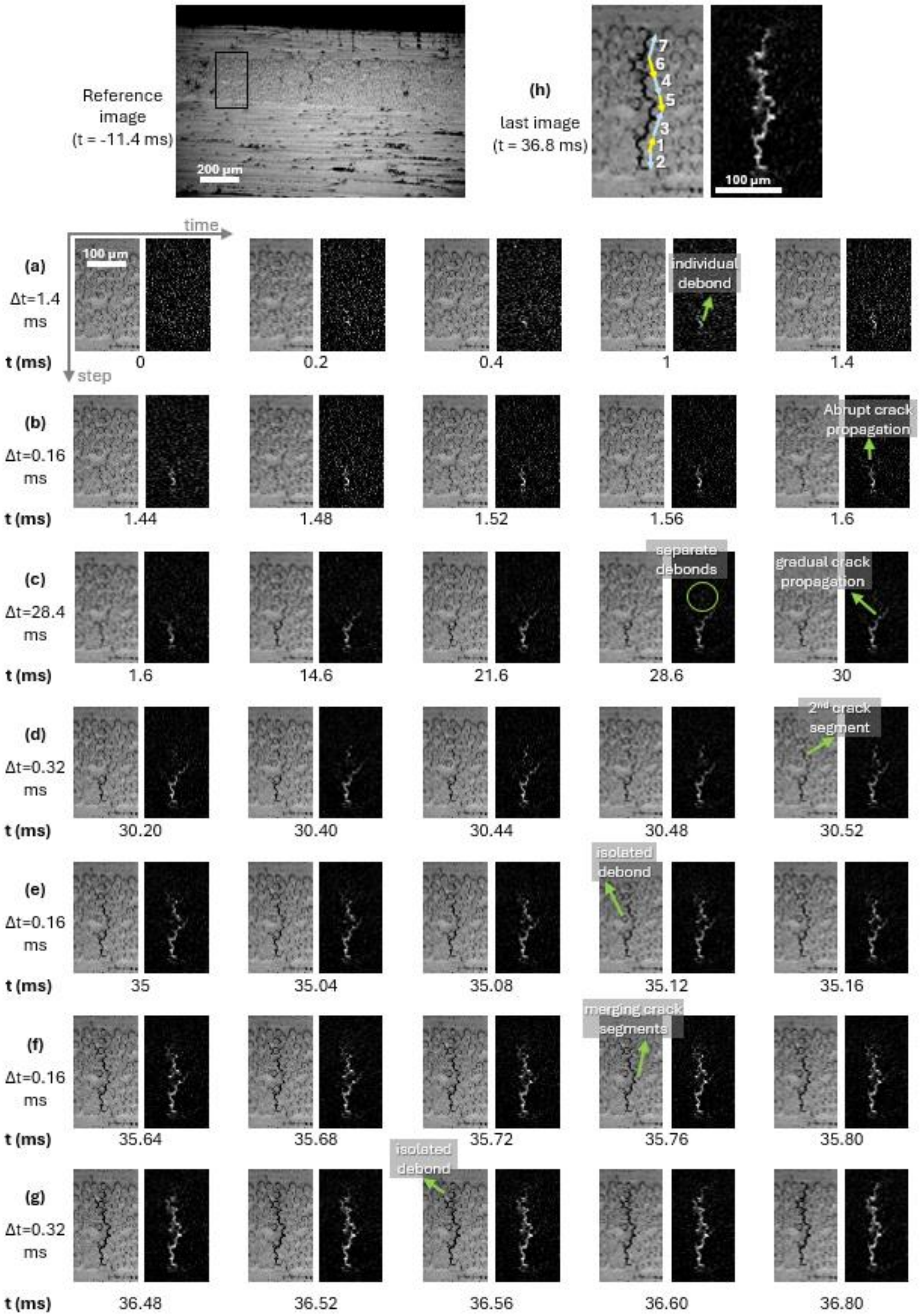

Figure 2. Single-90-ply sequence: debond-mediated initiation and stepwise transverse crack propagation under quasi-static bending. The crack advances through repeated arrest and re-activation events, with isolated debonds appearing ahead of the crack tip before later jumps.

4.2. Double-90-ply laminate

The Double-90-ply sequence (see Figure 3) contrasts with the single-ply case. Here, a transverse crack initiates near the top interface and traverses the entire 90° block within 2.2 ms. A short pause is visible around the interface between the two 90° plies, after which the crack continues through the second ply. The lower-bound propagation speed for the fastest step is about 3.5 m/s, substantially higher than in the Single-90-ply case.

This faster response is consistent with the larger effective crack-driving force and the different constraint condition in the thicker 90° block. A small micro-delamination forms shortly after the crack reaches the top interface, suggesting that the interface itself becomes active once the crack penetrates through the ply thickness. Taken together, the sequence shows that ply thickness and local interface structure can change not only the speed of crack growth, but also whether the crack pauses at an internal interface or proceeds almost immediately to the next step.

The contrast between the two cases is the main experimental message of the paper: local microstructure determines where cracks start and how they jump, while stacking sequence and ply thickness control how quickly the crack can traverse the 90° region.

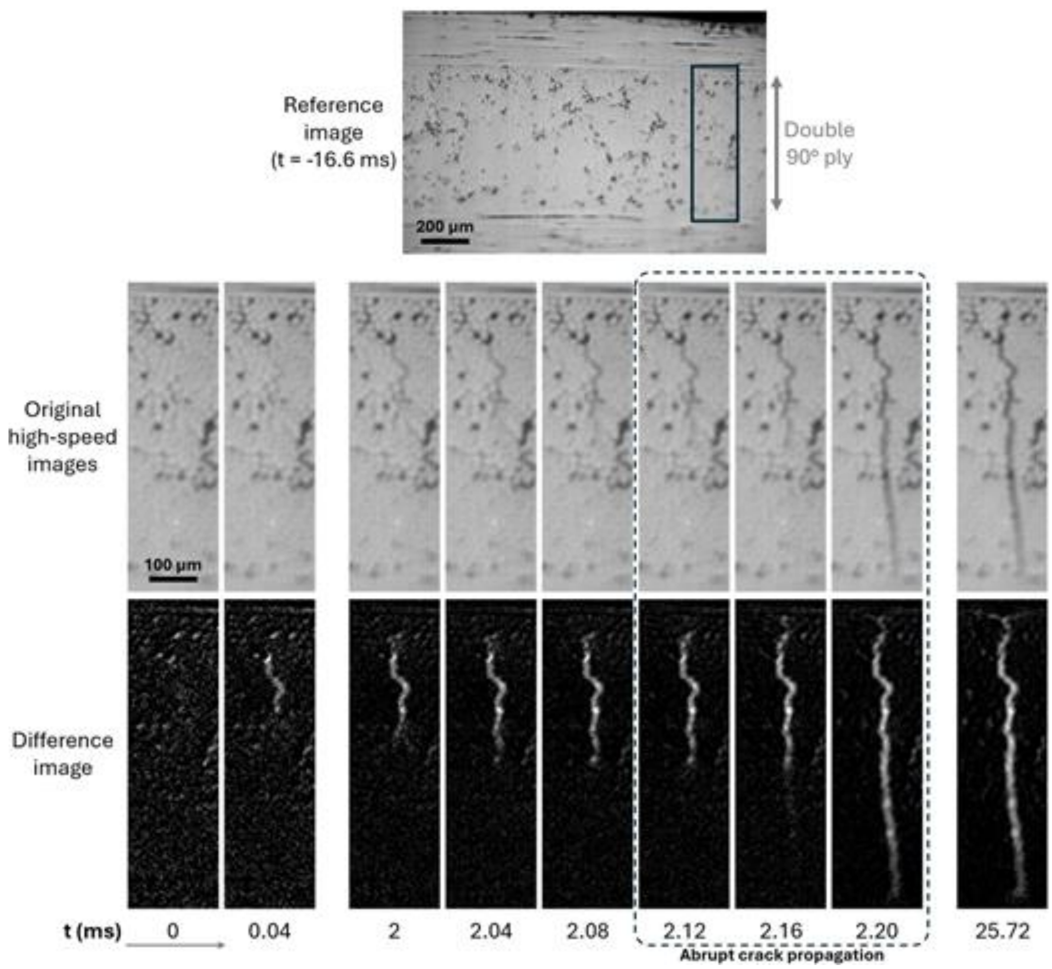

Figure 3. Double-90-ply sequence: rapid through-thickness crack propagation across a thicker 90° block, with a brief pause at the interface between the two 90° plies and subsequent micro-delamination.

5. Conclusions

A compact high-speed imaging workflow was established to observe damage at the microscale in composite laminates under quasi-static bending. The Single-90-ply sequence showed that transverse crack growth is stepwise and debond-controlled, with local defects able to override the nominal bending strain gradient, while the Double-90-ply sequence showed faster through-thickness propagation, a brief arrest at the interface between the two 90° plies, and subsequent micro-delamination after the crack reached the top interface. More broadly, the results demonstrated that transverse cracking evolves through rapid, non-continuous propagation strongly influenced by local microstructural features, neighbouring cracks, and ply thickness, while also interacting closely with fibre breaks and final ply failure.

Overall, the images demonstrate that high-speed microscopy can reveal transient damage events that are invisible in conventional inspection and can therefore support improved mechanistic modelling and non-destructive evaluation. Future work should combine automated triggering and quantitative image analysis with volumetric imaging techniques and varied loading/configuration conditions to further resolve and quantify transient microscale damage mechanisms in composites.

6. Acknowledgements

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7. References

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