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INVESTIGATING DELAMINATION MIGRATION IN MULTIDIRECTIONAL TAPE LAMINATES

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Abstract

Delamination migration was investigated at interfaces between plies with dissimilar fiber angle, θ, in composite tape laminates. The test method employed allowed to isolate and investigate a single delamination migration from a 0/θ interface into a stack of four plies oriented at θ. Tests showed that delamination propagation and migration varies across the specimen width. On one side, delamination appeared to grow at the initial interface, while on the opposite side, the damage progression was characterized by recurring kinking events initiating inside the specimen, before migration was completed. The occurrence and extent of kinking varies with the fiber angle. The experimental results showed that delamination migration is affected by the local stress state at the delamination front, which varies across the specimen width, depending upon the fiber angle.

1. Introduction

Delamination is a widely studied damage mechanism that is key to failure of laminated composite structures. Early studies tended to focus on delamination growth contained within a single ply interface, and used data from characterization tests obtained from unidirectional coupons, in which delamination grows between plies with the same fiber orientation. Although valid for design purposes, this approach does not reflect the reality of delamination propagation in multidirectional laminates. In fact, delamination in composite structures usually propagates at interfaces between plies with dissimilar fiber angle (*multidirectional* interfaces) and can "*kink*" out of the interface and migrate from one interface to another [1-3], for instance, in skin/stringer joints [4] or in laminates subject to low-velocity impact damage [5]. Consequently, knowledge of delamination propagation and migration at multidirectional ply interfaces is required, in order to develop and assess methods which simulate delamination migration.

In order to understand the mechanisms controlling delamination migration, Ratcliffe et al. developed a Delamination Migration test [2]. The test allows to isolate and investigate a single kinking event through a stack of four 90° plies, starting from delamination which propagates at a 0/90 interface. This sequence of damage events is obtained by the way specimen loading affects the local shear stress at the crack front. The specimen employed is a beam containing an artificial delamination, as pictured in Fig. 1. At the beginning of the test, the shear stress sign at the crack front is oriented as in Fig. 1a and drives delamination toward the lower portion of the specimen, where the 0° fibers constrain delamination to grow at the 0/90 interface. When delamination propagates beyond the load application point, as in Fig. 1b, shear stress sign inverts and delamination is allowed to kink into the upper ply stack. Changing the position of load application point along the specimen (load offset, L, in Fig. 1) was found to affect the distance from load application point where kinking occurs [2], since it affects the shear stress state at the crack front. The study utilized a cross-ply laminate, to have a uniform migration event across the specimen, providing benchmarking data for plane strain numerical analyses [6]. However, delamination in real composite structures is likely to propagate and migrate at more general ply interfaces. Therefore, in the present work, the delamination migration test proposed in [2] was employed to investigate interfaces between plies with generic fiber directions. The ply interfaces investigated were 0/60 and 0/75. A new stacking sequence was designed, to minimize coupling effects arising in the specimen because of the non-symmetric 0/θ interface. Specimens were tested at different positions of the load application point, similar to what was previously done on cross-ply specimens [2]. Damage progression was monitored by X-ray Computed Tomography to obtain the three-dimensional evolution of the migration process.

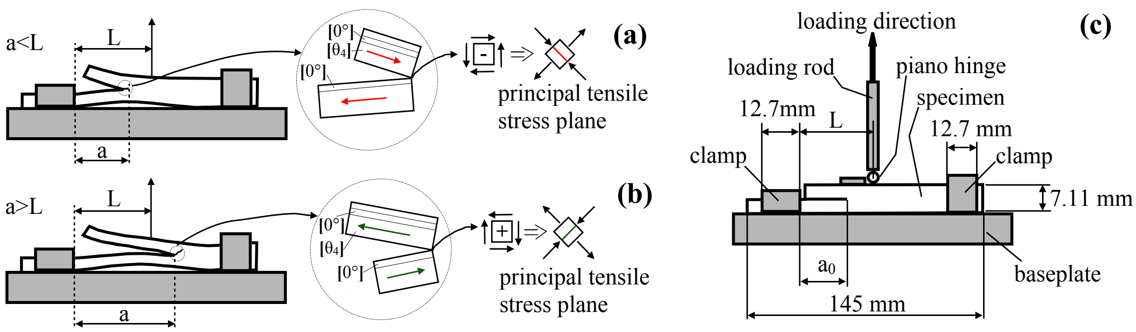

Figure 1. Effect of local shear stress at the delamination front producing delamination growth (a) or kinking (b), and schematic of delamination migration specimen (c).

2. Experimental

The delamination migration specimen is a beam containing a polytetrafluoroethylene (PTFE) film insert at an interface between a 0° ply (specimen length direction) and a stack of four plies oriented at a given angle θ, in a sub-laminate sequence $0/T/\theta_4/0$ (bottom to top, where "T" indicates the PTFE insert). The lower 0° ply constrains delamination to grow at the 0/θ interface before kinking through the θ_4 ply stack. The kinked crack is eventually stopped by the top 0° bounding ply. In this work, the stacking sequence of the delamination migration specimen was modified to investigate migration at a 0/60 and at a 0/75 interface. Classical laminated plate theory analysis [7] was performed to minimize the bending/twisting coupling arising from the central non-symmetric block in the stacking sequence. A 56-ply stacking sequence was selected for testing, as follows:

[$+\theta$/ 0/ $+\theta_3$/ $-\theta_4$/ -(90-θ)/ -θ/ -(90-θ)/ 90/ -(90-θ)/ (90-θ)/ 90/ (90-θ)/ +θ/ (90-θ)/ $+\theta_4$/ $-\theta_4$/ **0/ T/ $+\boldsymbol{\theta_4}$/ 0**/ $-\theta_4$/ -(90-θ)/ -θ/ -(90-θ)/ 90/ -(90-θ)/ (90-θ)/ 90/ (90-θ)/ +θ/ (90-θ)/ $+\theta_4$/ 0/ $-\theta_4$]

where left to right represents bottom to top ply in the specimen, and “T” indicates the location of the PTFE insert. Because of the fiber orientation at the interface, in the new specimens the shear stress field at the crack front varies across the specimen width, rather than being uniform as in the original cross-ply specimen [2]. Consequently, delamination migration is expected to vary across the specimen width.

A panel of IM7/8552 carbon epoxy material [8] for each fiber orientation was made and cured in an autoclave. Panels contained a 12.7 µm thick PTFE film insert to create a 52 mm long artificial delamination in the specimens (dimension a_0 in Fig. 1c). Specimens were 145 mm long, 12.7 mm wide and the total thickness was 7.11 mm (Fig. 1c).

The specimen is clamped at both ends on the test fixture and loaded by means of a hinge bonded to its upper surface, as illustrated in Fig. 1c. Tests were conducted in displacement control at a loading/unloading rate of 0.127 mm/min. Applied load and machine crosshead displacement were recorded during tests. Tests were performed at load offset $L=0.35a_0$, $1.0a_0$, $1.1a_0$, $1.2a_0$, $1.3a_0$. Each testing condition (fiber angle and load offset) was repeated 4 to 9 times. A number of specimens were tested incrementally. During the incremental tests, specimens were partially loaded and then unloaded and inspected by X-ray Computed Tomography (CT scan), to monitor the mechanism of delamination growth and migration in the interior of the specimen. Specimens were then repositioned in the test fixture to continue the test.

During the test, damage development on the specimen edges was monitored by a camera on each side, synchronized with the load acquisition system on the testing machine. In the rest of this paper, edge views will be referred to as “front edge view”, if delamination grows from left to right (as in the side visible in Fig. 1c) and “rear edge view”, to refer to the opposite lateral view of the specimen. After testing, specimens were inspected by X-ray CT scan.

3. Results and Discussion

Test results for the two ply orientations, 0/60 and 0/75, are discussed separately in the following sections. For each ply orientation, results for specimens loaded at $L=a_0$ are presented as the reference case, and the effect of load offset ‘L’ is then described.

3.1. Specimens containing a 0/60 interface

3.1.1. Specimens loaded at the PTFE insert front

The load-displacement curve for specimens loaded at different load offsets is shown in Fig. 2. The load-displacement curve obtained for $L=a_0$ shows that the specimen response was predominantly linear until a maximum load was reached. At this point, an unstable event occurred, during which unstable delamination growth was observed on both edges of the specimen, as shown in the edge views A in Fig. 2. Continued specimen loading caused more stable delamination propagation, until migration was observed on the edges of the specimens. Appearance of delamination on the edges of the specimen was different on the two sides. On the front edge, delamination appeared to propagate uniformly at the 0/60 interface (front edge views A and B in Fig. 2), until it kinked through the 60_4 ply stack (front view C in Fig. 2) and migrated to the next 60/0 interface (front view D in Fig. 2). On the rear edge, delamination propagated by repeatedly kinking part way through the upper ply stack (creating arrested kinked cracks) and then turning back to the initial 0/60 interface, as it can be seen in the rear edge views B and C in Fig. 2. This process continued until kinking and migration were completed on the rear edge of the specimen (rear edge view D in Fig. 2).

The different delamination propagation on the two edges of the specimen indicates that the mechanism of delamination growth and migration varies across the specimen width. This variation is attributed to the non-uniform distribution of shear stress at the delamination front in the specimen. Incremental tests and associated X-ray CT scan inspections allowed to reconstruct the exact sequence of damage events occurring in the interior of the specimen. X-ray CT scan images of a section of the specimens, taken at the top 60° delamination surface, are shown in Fig. 3, for specimens tested at each load offset.

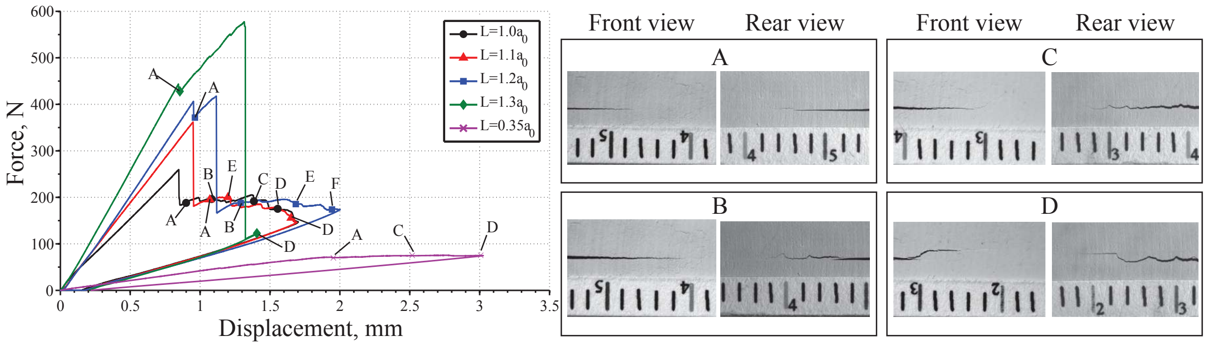

Figure 2. Load-displacement response for specimens containing a 0/60 interface loaded at each load offset and edge views at key stages during the test (A to D), of the front edge of the specimen ("Front view") and the rear edge of the specimen ("Rear view"). Each edge view couple is representative of the point indicated by the same letter on the load curves.

X-ray CT scan inspection of specimens tested in increments revealed that kinking initiated inside the specimen, in a location between the central line in the width direction and the rear edge of the specimen, indicated by "1" in Fig. 3b). The first kinked cracks in this location were formed during the unstable event occurring at the beginning of the test, although kinking events were not visible on the edges of the specimen at this point (edge views A in Fig. 2). Under continued specimen loading, the kinked cracks formed inside the specimen propagated along the 60° fiber direction toward the rear edge of the specimen, where they appeared in the rear side view B in Fig. 2. This process was repeated several times, creating a number of kinking events indicated in Fig. 3b in location "2". Here, delamination kinked through the upper 60_4 ply stack and stopped when it reached the top 0° bounding ply. Eventually, one of the kinked cracks caused delamination onset at the upper 60/0 interface, completing the migration process. These recurring kinking events did not occur in the region of the specimen between the front edge and approximately the center of the specimen in the width direction. In this region, the delamination surface showed fiber bridging or fiber imprints from the lower 0° ply at the interface until migration was completed, in point "3" in Fig. 3b.

This damage progression is explained by the fact that at a 0/θ interface the shear stress at the delamination front varies across the specimen width. At the beginning of the test, the shear stress sign tends to drive delamination into the lower portion of the specimen (as illustrated in Fig. 1a), causing the observed initial delamination growth at the 0/60 interface. As delamination propagates, the shear stress sign inverts and it becomes possible for delamination to kink into the upper ply stack at the interface (as in Fig. 1b). In case of a 0/90 interface, the shear stress at the delamination front is uniform across the specimen width, therefore kinking occurs uniformly across the specimen [2]. In case of a 0/θ interface, instead, shear stress varies across the specimen width, because of the fiber angle at the interface. As a consequence, the inversion of shear stress sign and the subsequent kinking is not uniform across the specimen, but it starts inside the specimen, between the center and the rear edge (as in point "1" in Fig. 3b). Delamination kinks at this point, but it continues to propagate at the 0/60 interface in the remainder of the specimen. As delamination length increases further, the shear stress sign inverts over a wider region of the specimen. This causes further kinking events and the propagation of the kinked cracks along the fiber direction in the 60° ply stack, until they reach the rear edge of the specimen. In the region of the specimen toward the front edge, the shear stress sign inverts later and therefore delamination propagates at the 0/60 interface for a longer length before kinking.

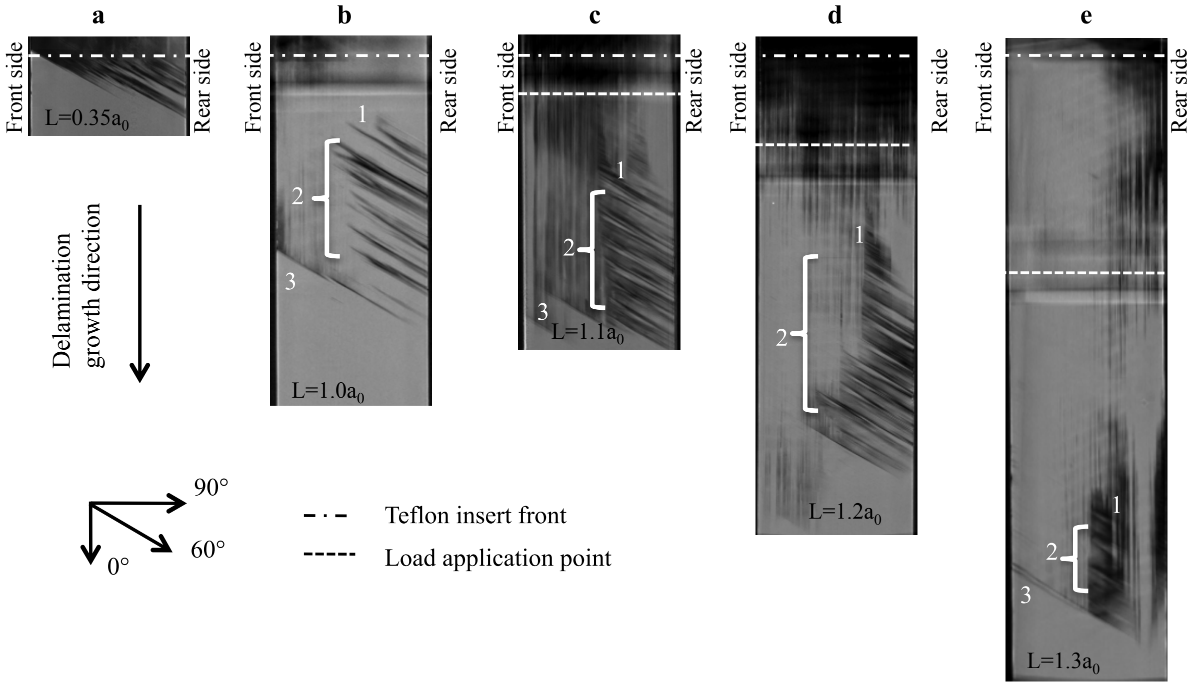

Figure 3. X-ray CT scan images of a section of the specimen taken at the top 60° delamination surface for specimens containing 0/60 interface loaded at each load offset.

3.1.2. Effect of load offset on migration

In all the specimens tested with load offset greater than a_0, delamination growth was observed prior to migration. A representative load-displacement curve for each load case is shown in Fig. 2. In specimen loaded on the delaminated portion, ($L=0.35a_0$), the shear stress sign is favorable for migration from the beginning of the test, therefore migration occurred immediately from the PTFE insert front. In all the other cases, the load curves and general damage sequence was similar to what described for $L=a_0$.
In specimen tested at higher load offset ($L=1.2a_0$, $1.3a_0$) the delamination onset was stable and it produced an initial small load drop on the load-displacement curves (as indicated at point A in Fig. 2 for these load offsets). After this point, load continued to increase until it reached a maximum value and delamination propagated in a stable manner for about 9 - 10 mm. During this phase, delamination seemed to dive into the lower 0° ply at the interface, driven by the shear stress, which is oriented as in Fig. 1a. Once a maximum force was reached, an unstable event took place. After this point, the test continued as described in case of load offset $L=a_0$.
The initial diving of delamination in the lower ply in specimens with higher load offset is due to the way the loading position affects the shear stress sign at the crack front. Reversal of shear stress sign can only occur after delamination grows beyond the load application point. Therefore, as the load offset is increased, delamination needs to propagate for a greater length before kinking events start to take place inside the body of the specimen. As indicated by point “1” in the X-ray CT images in Fig. 3, delamination starts to kink later along the specimen, for increasing load offset. In some of the specimen tested with $L>a_0$, delamination

migration was not visible on one of the edges of the specimen, usually the front edge, as in case of Fig. 3d. However, even in these cases, X-ray CT inspection revealed that delamination had kinked inside the specimen. In general, the loading position on the specimen affected the location where kinking occurs, since changing the load offset varies the shear stress at the delamination front. This result confirms the effect of shear stress at the crack front on kinking.

3.2. Specimens containing a 0/75 interface

3.2.1. Specimens loaded at the PTFE insert front

Delamination migration at 0/75 ply interface showed similar behavior to the 0/60 interface. Representative load-displacement curves and edge views are shown in Fig. 4. As in the 0/60 interface, specimens responded linearly to loading until a maximum load was reached, at which point an unstable event took place, followed by more stable delamination propagation. In the 0/75 interface specimens, fewer and smaller arrested kinked cracks appeared on the rear side edge of the specimen prior to migration. On the front edge, delamination propagation and migration developed in the same way as in case of 0/60 interface.

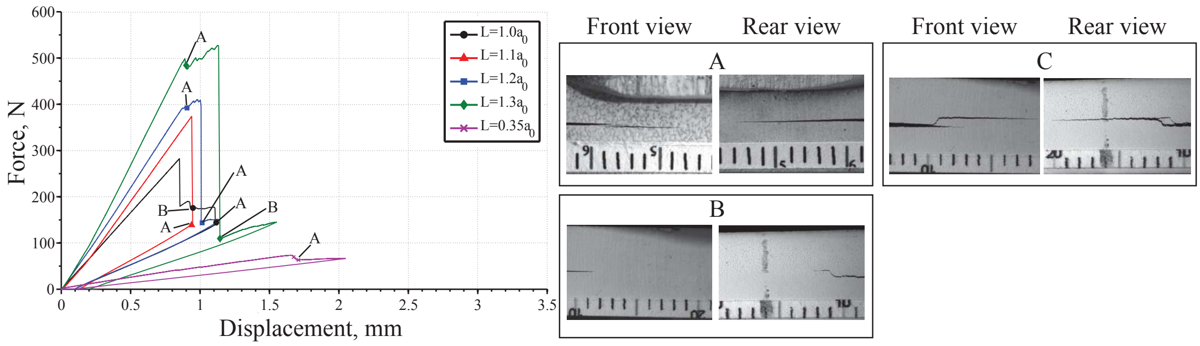

Figure 4. Load-displacement response for specimens containing a 0/75 interface loaded at each load offset and edge views at key stages during the test (A to C), of the front edge of the specimen (“Front view”) and the rear edge of the specimen (“Rear view”). Each edge view couple is representative of the point indicated by the same letter on the load curves.

Incremental tests followed by X-ray CT inspection revealed that delamination kinking started inside the specimen, approximately between the center and the rear edge (point “1” in Fig. 5b), similar to what observed in the 0/60 interface. However, upon continued loading, additional kinking took place across the width of the specimen, toward the front side edge, in location “2” in Fig. 5b).

This different behavior is attributed to the fiber angle at the interface. At a 0/75 interface, the variability of the shear stress across the specimen width is less than in case of 0/60 interface. Therefore, at a given delamination length, shear stress sign reversal takes place over a wider region of the specimen, so that delamination is allowed to kink in multiple points across the width of the specimen.

Even in this case, the kinked cracks formed inside the specimen propagate along the θ fiber direction until they reach the specimen edges and completed the migration process. The last portion of the specimen where delamination kinked and migrated was the zone close to the front edge, indicated by “3” in Fig. 5b. In both the ply interfaces tested, migration across the specimen was completed by two independent kinking events.

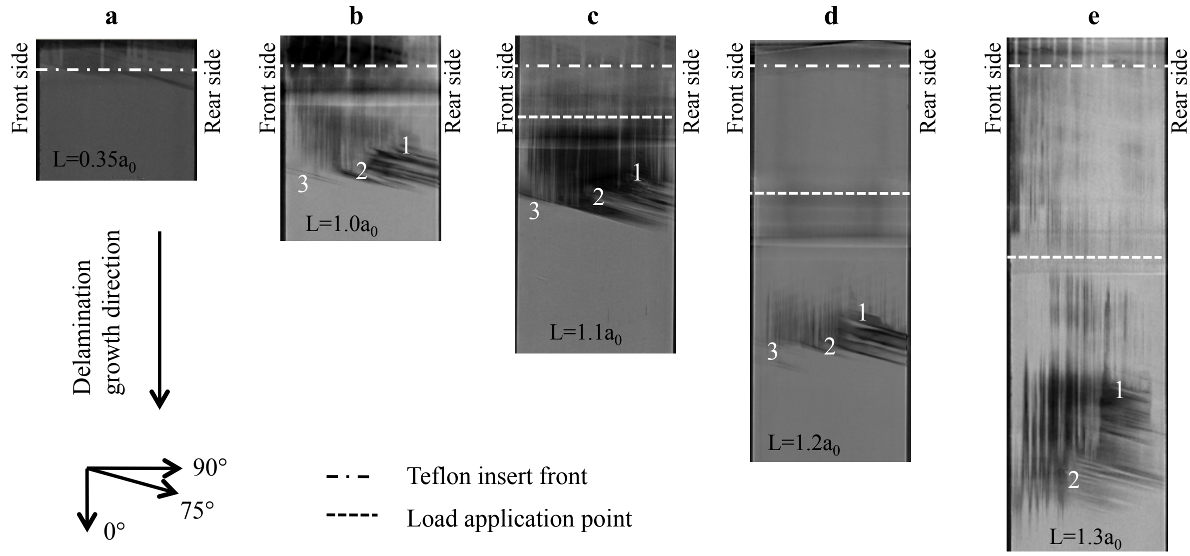

Figure 5. X-ray CT scan images of a section of the specimen taken at the top 75° delamination surface for specimens containing 0/75 interface loaded at each load offset.

3.2.2. Effect of load offset on migration

The effect of the load offset on specimens containing a 0/75 interface was the same as that observed in case of 0/60 interface. This result confirms that delamination kinking and migration depend upon the local shear stress state at the delamination front, which is affected by the load offset. Load-displacement curves for specimens tested at each load offset are shown in Fig. 4. As it can be noted, specimens with this ply interface loaded at $L>a_0$ exhibited a more unstable response, during which the unstable delamination growth was immediately followed by simultaneous kinking on both edges of the specimen. As in the 0/60 interface, load offsets $L=1.2a_0$ and $1.3a_0$ caused delamination to initially dive in the lower portion of the specimen, before shear stress sign reversed and kinking started.
X-ray CT images in Fig. 5 revealed that the distance along the specimen where kinking occurs increases with the load offset, because the shear stress sign reversal occurs at a greater delamination length for higher load offset.

4. Concluding Remarks

Delamination migration was studied at 0/θ interfaces in laminated composites. The test method employed in [2], applied to a new specimen design, allowed to isolate a single migration event in a 0/60 and a 0/75 interface. Experimental results showed that the kinking of delamination from an interface is controlled by the shear stress field at the delamination front. In particular, kinking is only possible when the sign of the shear stress drives delamination toward the θ oriented ply, through which it will migrate. Because of the θ ply angle, delamination propagation and migration vary across the specimen width. In fact, the fiber angle at the interface causes the distribution of shear stress in the specimen to vary, which has two main consequences. First, delamination propagation is uneven across the width of the specimen, in the sense that delamination grows within either one of the plies at the interface. Second, kinking initiates inside the specimen in a location which depends on the shear stress distribution, and hence on the fiber angle, and is not uniform across the specimen width. The dissimilar nature of delamination propagation suggests that characterization of 0/θ interfaces may be needed to better deal with damage at multidirectional ply interfaces in real structure. In general, results obtained by the delamination migration tests can help the understanding of failure of composite structures where delamination is observed to migrate through several ply interfaces. The study offers an insight into delamination propagation and migration at multidirectional ply interfaces in laminated composites, and provides valuable validation data for models aiming to simulate delamination migration.

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