Ply Curving Termination to Suppress Delamination in Composite Ply Drop-Off

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In a lightweight aircraft composite structure, it is desirable to decrease the plate thickness in low load areas by terminating unnecessary plies (i.e., ply drop-off, Fig. 1). It is possible to significantly save the structural weight by steeply changing the thickness in response to the local load distribution. However, tapered sections with steep taper angles act as initiation points of delamination. It is known that stress concentrates at the edge of the terminated 0° plies that have the fiber direction in parallel to the loading direction. As a result, current aircraft composite structures use quite gradual taper angles and have unnecessary thick parts in the low-load areas. Structural modification that can suppress the stress concentration at the edge of the terminated 0° plies is necessary to realize further-optimized lightweight structures with steeper taper angles.

This study proposes a new approach called "ply curving termination (PCT)" that locally changes the fiber orientation at the edge of the termination 0° plies. Figure 2 shows the most basic form of ply drop-off where one 0° ply is laminated on the base laminate. In the conventional part in Fig. 2 (a), in-plane tensile loading induces stress concentration at the edge of the terminated 0° ply and secondary bending due to the eccentric load path along the ply drop-off, which leads to delamination initiation. In contrast, the PCT structure in Figure 2 (b) has the curved edge that has significantly low stiffness in the loading direction (e.g., when the curved angle is 45° with standard carbon/epoxy, the elastic modulus decreases to about 10%). This modification suppresses the stress concentration and secondary bending at the edge of the terminated ply, so stress is gradually transferred from the base laminate to the terminated ply. In addition, even if delamination occurs from the edge, its propagation is suppressed in the curved area because the stiffness of the delaminated edge is low. Meanwhile, the terminated ply far away from the edge can fulfill the original purpose of strengthening the base laminate because the fiber direction is along the loading direction. It is important to note that introduction of PCT into a structure can be automated and is not limited by the molding method and the stacking sequence. In the case of manufacturing using prepreg sheets, for example, it is possible to introduce this curved part by laminating prepreg sheets after shearing only the terminated part in the in-plane direction (Fig. 3).

This study validated the effectiveness of the proposed concept through numerical analysis and experiments. Finite element analysis was first conducted (Fig. 4). It was confirmed that secondary bending due to the eccentric load path along the ply drop-off is suppressed by PCT (45° specimen), and the out-of-plane stress at the edge of the terminated ply is significantly reduced. Validation tests were then performed under static and fatigue loading conditions (Fig. 5). It was successfully demonstrated that the proposed structure significantly delays delamination initiation and propagation.

*Keywords: Composites, delamination, suppression, new design*

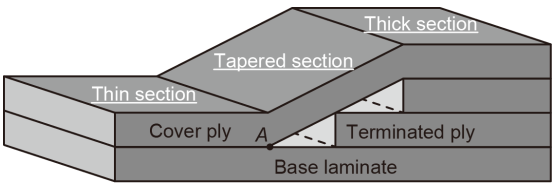
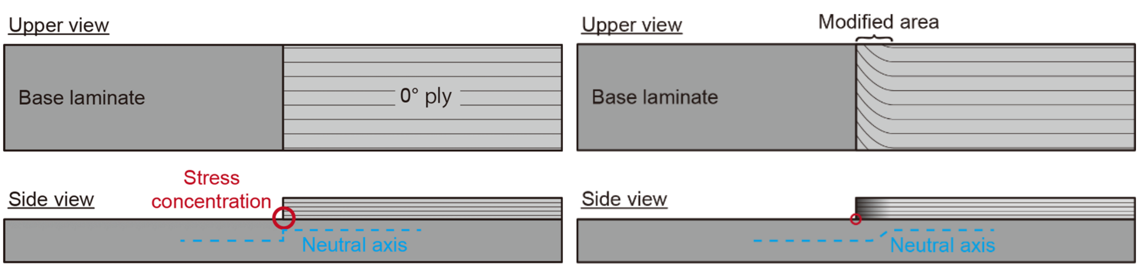



*Figure 1. Schematic of ply drop-off.*




(a) *Conventional structure.* (b) *Proposed structure with PCT.*

*Figure 2. Stress concentration at edge of terminated 0° ply.*

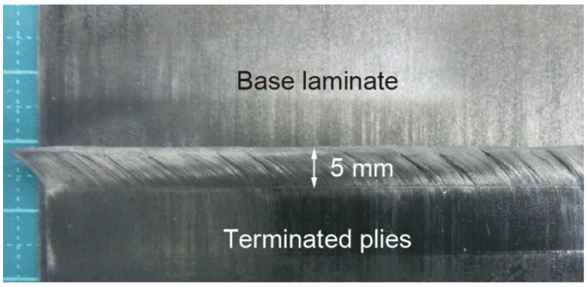



*Figure 3. Introducing PCT using prepreg sheets.*

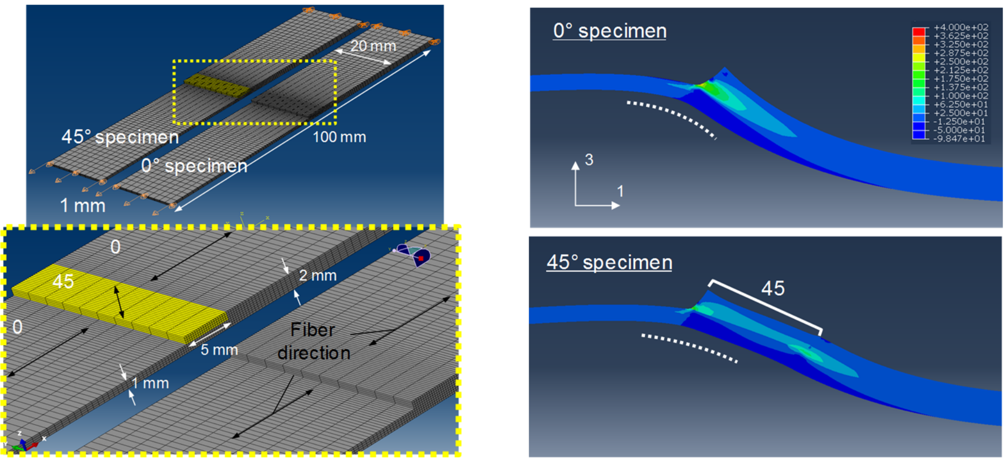



*Figure 4. Finite element analysis.*
*(Left) Finite element models. 45° specimen includes PCT.*
*(Right) Deformation and out-of-plane shear stress $\tau_{13}$ at edge of terminated ply. Displacement magnification factor is 20.*

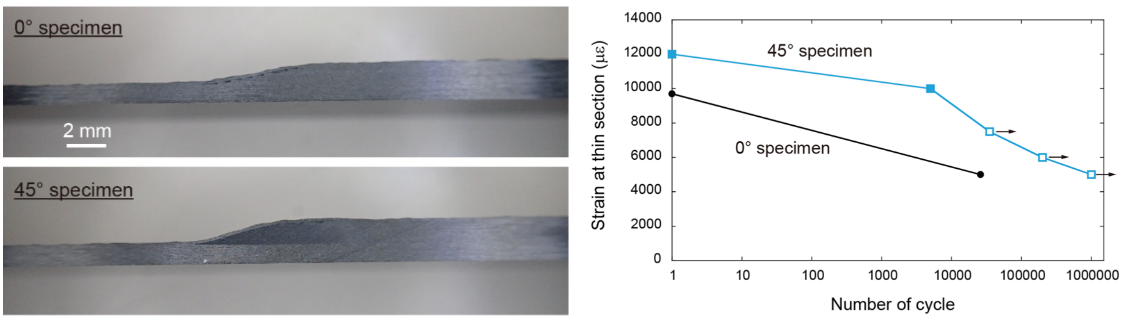



*Figure 5. Validation test results using specimens with taper ratio of 1:5.*
*(Left) Cross-section of tapered specimens. Fiber direction of base laminate and terminated plies were 0°.*
*45° specimen had 5 mm long PCT section at edge of terminated plies.*
*(Right) Static and fatigue test results. White markers indicate that specimens did not fail.*