DAMAGE TOLERANCE OF DOUBLE-DOUBLE LAMINATES

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ABSTRACT

Double-double (DD) lay-up is a new configuration strategy for the design of composite laminates, which allows the use of simplified stacking sequences that leads to potential advantages, such as improved manufacturability and design optimization, as compared to traditional quadriaxial laminates (Quad), which are limited to ply angles of 0°, ±45° and 90°. With the double-double concept, through-the-thickness homogenization is facilitated using thinner sub-laminates and, consequently, profile optimization through thickness tapering becomes possible. In this work, damages after impact and after CAI tests of a double-double laminate $(+50/0/-50/0)_{10}$ and a hard conventional laminate of equivalent in-plane stiffness $(0_3/90/\pm45/0_2/\pm45)_{2S}$ are compared. According to the data presented, maximum delaminated areas were of the same order of magnitude for the quad and for the DD laminates, under both conditions: after impact and after CAI tests. The results contribute to the understanding of potential benefits of the double-double concept to damage resistance and damage tolerance of composite laminates.

1 INTRODUCTION

The conventional use of legacy laminates with plies at fixed angles of 0°, ±45°, and 90° often leads to composite structures which are bricky and with patchy layups. The resulting point design solution for each section of the component, combined with the need for considering mid-plane symmetry for ply drop of tapered structures, greatly increases simulation costs, and makes manufacturing and global optimization very complicated.

Double helix angle laminates of the family $[\pm\phi/\pm\psi]$, or simply double-double, have been proposed as a replacement of the legacy laminates [1,2], sharing equivalent stiffness and strength with many potential advantages. The double-double family has two sets of continuous ply angle variables that can replace legacy laminates.

With double-double laminates, the number of plies in a sub-laminate can be reduced from 6, 10 or even more plies, to four plies, only. With these thinner sub-laminates, the minimum gage is reduced proportionally, and through-the-thickness homogenization is achieved with fewer repetitions. Then, with homogenization, mid-plane symmetry is no longer necessary and ply stacking can be continuous. In addition, ply drops can be smoother, with one ply at the time, without the need of symmetric ply drops [3]. The use of unconventional ply angles of double-double laminates has been proven effective for the mechanical properties and manufacturing efficiency [4].

An important characteristic of double-double laminates to be further investigated is their damage resistance. Because these laminates are homogeneous, they are expected to be tougher and to display increased damage resistance. Therefore, the objective of this research is to evaluate damage resistance and damage tolerance of double-double carbon fiber reinforced laminates, as compared to the legacy laminate of equivalent in-plane stiffness.

2 EXPERIMENTAL

2.1 Material and specimen preparation

The material used in this research was T700G/G94 UD prepreg, from Toray Composite Materials America, Inc., with nominal fiber volume fraction of 55.1%, fiber areal weight of 150 g/m² and ply thickness of 0.150 mm.

Two forty-ply composite plates with dimensions of 500 mm x 350 mm (L x W) were autoclave cured, following manufacturer's specifications. The nominal thickness of the cured laminates was about 6.0 mm. One of the plates was a hard laminate, produced with stacking sequence of $(0_3/90/\pm45/0_2/\pm45)_{2S}$. The second plate was the equivalent double-double laminate, which was produced with stacking sequence of $(+50/0/-50/0)_{10}$.

Test specimens were water jet cut from the processed laminates, according to the dimensions of ASTM specifications for compression tests and compression after impact (CAI) tests.

2.2 Testing

Drop-weight impact tests were conducted at impact energy of 74 J. Compression tests and compression after impact tests were conducted using an MTS universal testing machine, according to ASTM standards D3410 and D7137, respectively. Prior to the CAI tests, impact tests were conducted following recommendations of D7136/D7136M - Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event. Specimens' damages after impact and after CAI were assessed using computed tomography (CT) Scan.

3 RESULTS AND DISCUSSION

CT images of damaged areas of the test specimens after impact have been presented in a previous paper [5] and are also shown in Figures 1 and 2 for the Quad and DD laminate, respectively, for the purpose of comparing the characteristics of the damages. An indentation produced by the impactor was observed in the first layers of both laminates, which generates stress concentrations and affects the propagation of matrix cracks and delaminations. Matrix cracks and delaminations increase towards the opposite face of the impact (tensile region), where larger delamination areas and crack sizes are observed (Figures 1 and 2) [5].

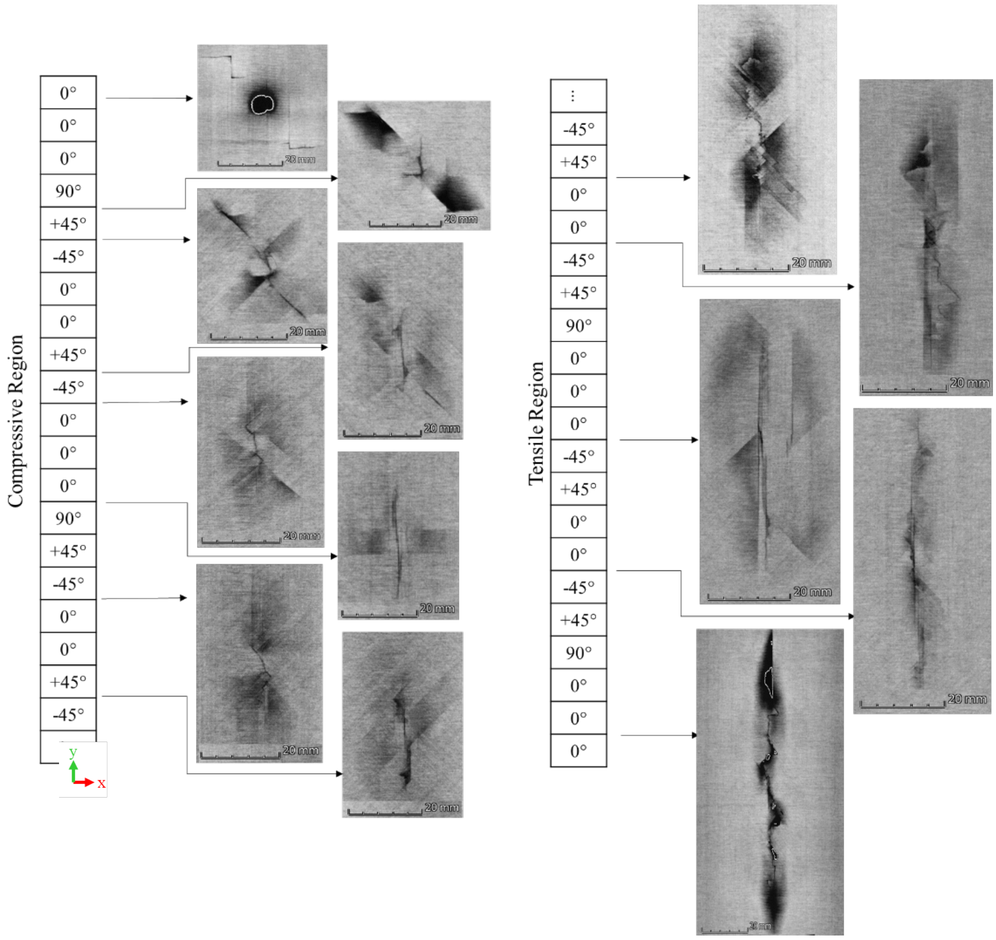

Figure 1: CT Scan images of typical delaminations and cracks in quad laminates after 74 J impact [5].

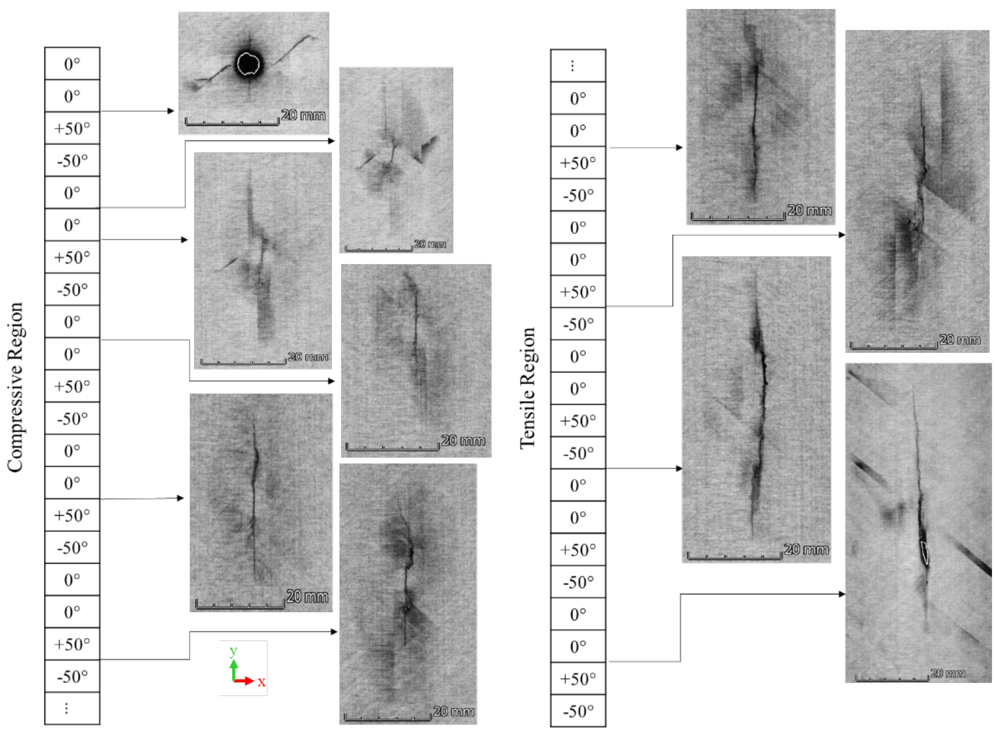

Figure 2: CT Scan images of typical delaminations and cracks in DD laminates after 74 J impact [5].

Figures 3 and 4 show the typical damage verified in laminates quad and DD, respectively, after the CAI tests. A lateral crack through the impact damage area is observed in all layers, for both materials, which is a commonly observed failure mode in CAI tests of composite materials. As the impact-damaged specimen is loaded in compression, crack propagation becomes unstable from the damage generated by the impact towards the edges of the specimen [6] [7].

Cracks in the matrix generated by the impact also change the stress field over the damaged areas and propagation of delaminations, which extends towards the opposite face of the specimens (tension region), where the largest areas of delamination generated are observed in the central part of the specimen.

For both laminates, it was observed that the layers of greatest delamination areas were those in the region where the tension forces are predominant during the impact event (Figures 3 and 4). Thus, these are the layers that most influenced the compressive residual strength properties of the damaged specimens.

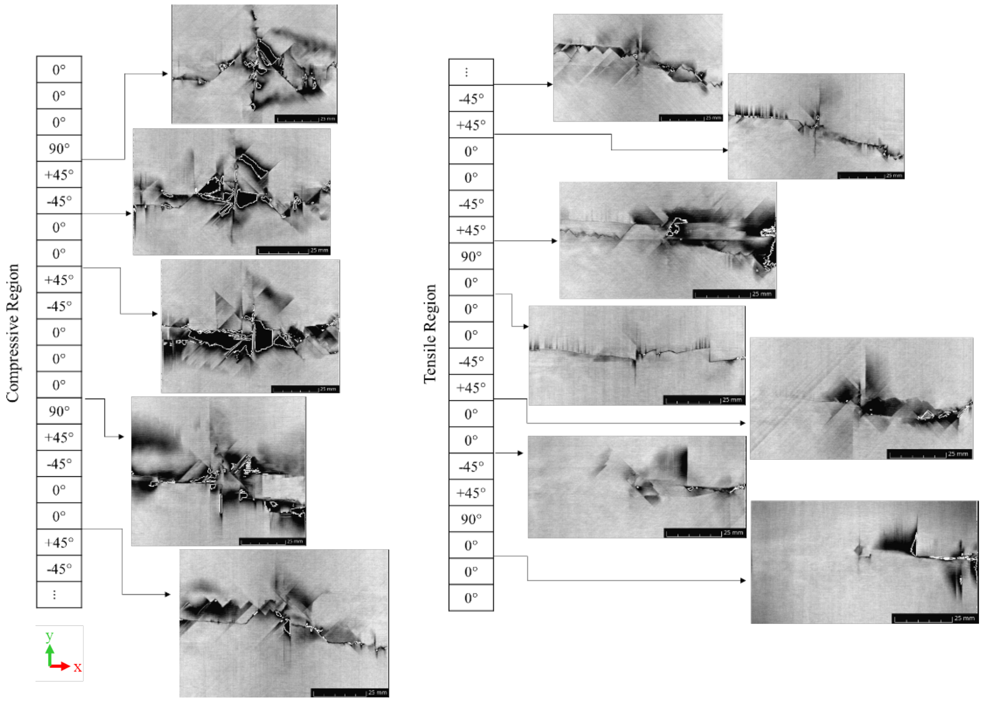

Figure 3: CT Scan images of typical damage of quad laminates after CAI testing.

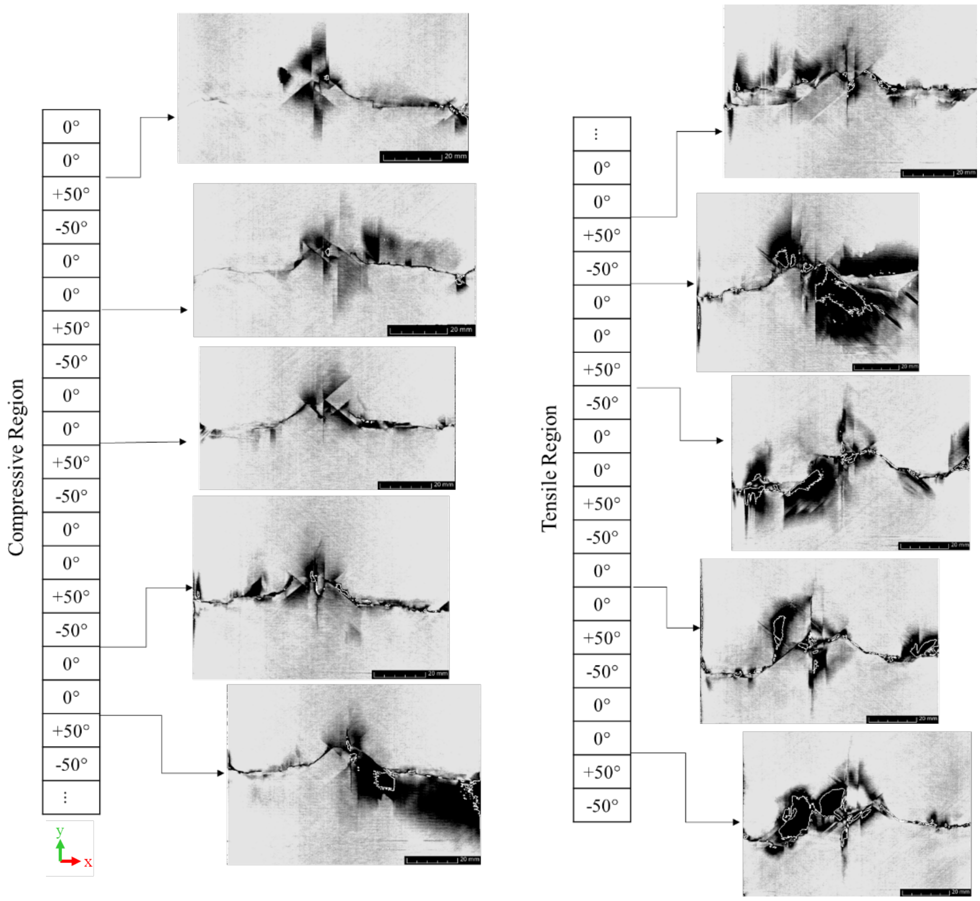

Figure 4: CT Scan images of typical damage of DD laminates after CAI testing.

Figures 5 and 6 show delaminated areas before and after the CAI tests, for quad and DD laminates, respectively. According to the data presented, maximum delaminated areas after impact were of the same order of magnitude (about 1000 mm²) for both laminates: quad and DD. Similar maximum delaminated areas (about 2700 mm²) were also observed after the CAI tests for both laminates. When total delaminated areas after the CAI tests are compared to those caused by the impact (before CAI test), an increase in damaged areas of about 60% is observed. It is also observed that the layers that most influenced the compression properties were the layers under tension, which were the layers of greater delamination.

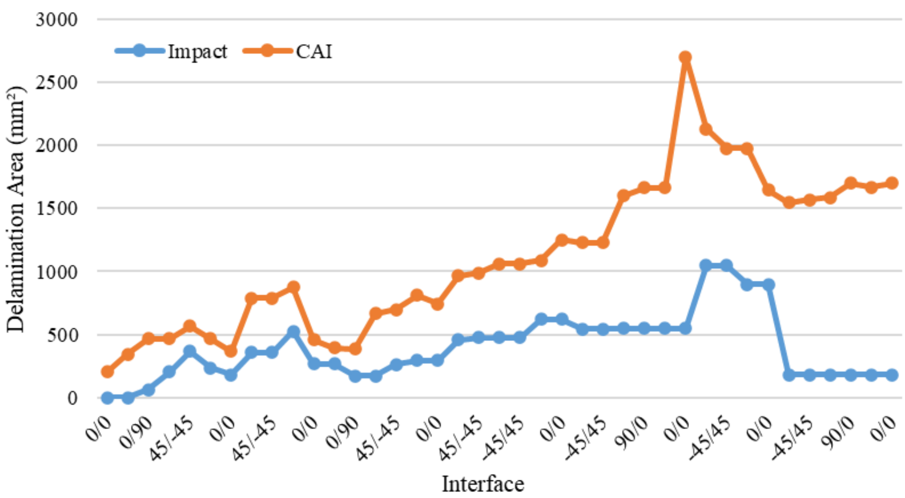

Figure 5: Typical delaminated areas of quad laminate before and after CAI test.

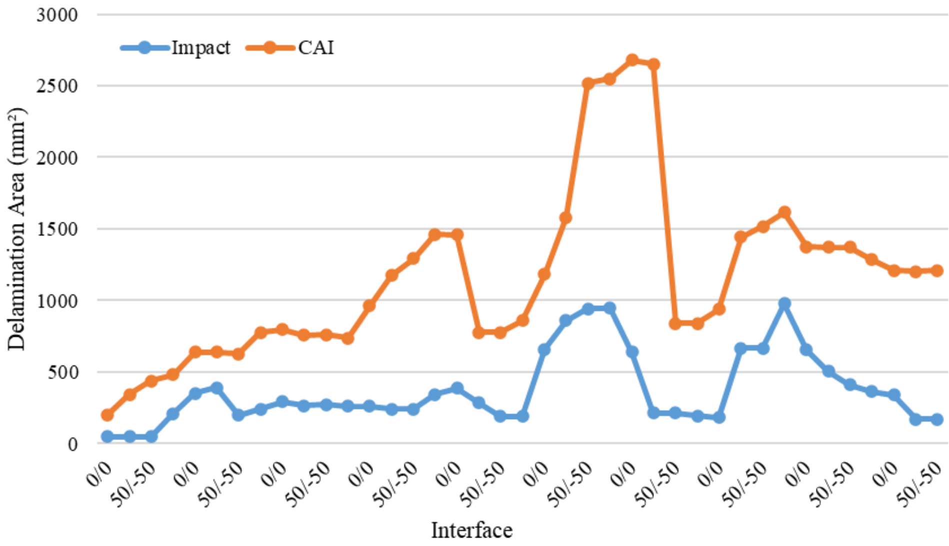

Figure 6: Typical delaminated areas of DD laminate before and after CAI test.

4 CONCLUSIONS

Double-double composite laminates offer great potential as a replacement of legacy laminates, with improvements in mechanical properties and manufacturing efficiency. This research assessed damage resistance and damage tolerance of these laminates, as compared to conventional laminates of equivalent in-plane stiffness. Maximum delaminated areas observed were of the same order of magnitude for the conventional quad and for the DD laminates, under both conditions: after impact and after CAI tests. The purpose was to contribute to the understanding of the mechanical behavior of these laminates regarding damage, considering the already known advantages for design optimization and manufacturability.

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