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LOW-VELOCITY IMPACT (LVI) AND COMPRESSION AFTER IMPACT (CAI) OF DOUBLE-DOUBLE COMPOSITE LAMINATES

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ABSTRACT

Tailorability is a key advantage of fiber-reinforced composites. While tailoring a single laminate is relatively simple, challenges arise when designing larger components with multiple adjacent laminates while ensuring compatibility between laminates and maintaining stiffness continuity. The Double-Double (DD) laminate design method is an innovative concept that incorporates 4-ply building blocks consisting of +φ, −φ, +ψ, and −ψ ply orientations to enable simplification of design optimization and processing of composite laminates. The current study assesses the effectiveness of replacing quadriaxial (QUAD) laminates consisting of 0°, 90°, and ±45° ply orientations with equivalent DD laminates under both Low-Velocity Impact (LVI) and Compression After Impact (CAI) loadings. To this end, a validated three-dimensional high-fidelity finite element model capable of capturing fiber breakage, splitting, kinking, as well as matrix cracking and delamination, was used. A computer tool was developed to quickly identify equivalent DD laminates with a similar in-plane stiffness [A] or flexural stiffness [D], and to find the best stacking sequence for achieving homogenization. Three equivalent DD laminates were selected for the $[0/45/90/\text{-}45]_{4S}$. The first laminate had an equal [A] matrix ($[67.5/\text{-}22.5/22.5/\text{-}67.5]_{8T}$), the second laminate had an equal [D] matrix ($[64.5/\text{-}17/17/\text{-}64.5]_{8T}$), and the third laminate ($[65.5/\text{-}18.5/18.5/\text{-}65.5]_{8T}$) had a similar [D] matrix, while keeping the overall difference between the [A] matrices below 10%. Based on simulations of a 75 J energy impact, the first and third DD laminates exhibited 1.9% and 4.4% higher CAI strength, respectively, and the second DD laminate showed a 1.9% lower CAI strength. The results indicate that the QUAD laminates can be replaced by equivalent DD without compromising impact damage tolerance, while benefiting from the improved design and manufacturing ease of the DD laminate configuration.

1 INTRODUCTION

Conventional quadriaxial (QUAD) composite laminates consisting of 0°, ±45°, and 90° plies have been used since the 1960s in advanced composite components. By changing the relative percentage of each ply orientation and the stacking sequence, the laminate can be tailored for a specific loading condition. The tailorability advantage of fiber-reinforced composites is occasionally compromised by design complexity, leading to the adoption of quasi-isotropic layups as a safe and well understood design choice. To ensure manufacturability and damage tolerance, some layup rules are usually applied such as mid-plane symmetry to avoid warpage, having at least 10% of each QUAD angle to withstand unforeseen loads, and ply groups of less than 4 plies each to minimize interlaminar stresses. However, even with these layup constraints, the number of QUAD stacking permutations is so high that it makes optimization a difficult task. Double-Double (DD) is an innovative concept introduced by Tsai [1] which incorporates 4-ply [±φ/±ψ] building blocks that simplifies design and processing of composite laminates by reducing design complexity from millions of choices to selecting the φ and ψ angles and determining the number of building block repetitions. The DD concept broadens the possibilities of adjusting thickness by adding or removing building blocks, avoiding stacking sequence changes, and providing opportunities to optimize design.

To date, only two references are available on low-velocity impact (LVI) and compression after impact (CAI) of DD laminates. Cunha et al. [2] conducted LVI and CAI tests on a QUAD $[0_3/90/\pm45/0_2/\pm45]_{2s}$ laminate and an equivalent DD with a similar in-plane stiffness matrix [A] with a stacking sequence of $[\pm0/\pm50]_{10T}$, where "T" denotes total. Both laminates were impacted at a 74 J energy level. The delamination areas were compared through X-ray CT inspections. The difference between the CAI strengths of QUAD and DD (3%) was within the standard deviation (11.5%). However, the delamination area in the DD laminate was larger. The lower flexural stiffness of the equivalent DD was mentioned as the reason for this observation. Millen et al. [3] conducted a numerical study on LVI and CAI responses of DD laminates. An equivalent DD of $[0_2/45_2/90_2/-45_2]_s$ with a similar flexural stiffness matrix [D] was found to be $[9.5/-39.5/39.5/-9.5]_{4T}$. After a 25 J impact event, the CAI strength of the equivalent DD was 40% higher than that of the QUAD. The 47% higher stiffness in the loading direction (A_{11} component of [A]) was identified to be the reason for this significant difference.

Based on the published studies, it remains unclear whether replacing a QUAD with an equivalent DD would yield any benefits in terms of impact damage tolerance and residual strength after impact. In the current study, a validated three-dimensional (3D) high-fidelity finite element model [4], able to capture fiber breakage, splitting, kinking, pull-out, and crushing, as well as matrix cracking and delamination, was used to assess the effectiveness of replacing QUAD laminates with equivalent DD laminates under both LVI and CAI loadings. Three equivalent DD laminates for 254 mm × 304.8 mm $[0/45/90/-45]_{4s}$ IM7/977-3 were selected for investigation: 1) with equal [A] matrix, 2) with equal [D] matrix, and 3) with a similar [D] matrix while its [A] matrix overall difference is below 10%.

2 EQUIVALENT DOUBLE-DOUBLE LAMINATE

A computer tool, with a graphical user interface shown in Figure 1, was developed to determine the DD laminate with an equivalent in-plane stiffness [A] or flexural stiffness [D], evaluating the material homogenization conditions, and finding the best DD stacking sequence. For comparing the stiffnesses of the DD and QUAD laminates, the stiffness matrices were normalized by the laminate thickness:

$$[A^*] = \frac{1}{h}[A], \quad [B^*] = \frac{2}{h^2}[B], \quad [D^*] = \frac{12}{h^3}[D] \tag{1}$$

The equivalent DD laminate with an equal normalized in-plane stiffness [A*], has the same A_{11}^*, A_{22}^*, A_{66}^*, and A_{12}^*, and the equivalent DD laminate with an equal normalized flexural-plane stiffness [D*], has the same D_{11}^*, D_{22}^*, D_{66}^*, and D_{12}^*, where A_{ij}^* and D_{ij}^* (i,j=1,2,6) are components of the normalized in-plane and flexural stiffness matrices. Depending on whether the in-plane stresses or the bending stresses dominate in the desired application, an equivalent DD with equal [A*] or [D*] could be found. In the case of LVI, since the bending stiffness plays the main role in the impact response of the laminate, an equivalent DD with similar [D*] will exhibit a similar response to the original QUAD laminate. Conversely, in the compression test, the in-plane stiffness [A*], specifically A_{11}^*, is more important in determining the effective compressive modulus of the laminate. In the current study, since both impact damage tolerance and CAI strength were of interest, a DD laminate was chosen with a similar [D*] matrix while keeping the difference between each element of [A*] matrices of DD and QUAD below 10%. In this way, the DD laminate would have similar (but not equal) in-plane and flexural stiffnesses to those of the QUAD laminate.

The DD characteristics comes from their homogenized properties. When a laminate is homogenized, it means that its properties are uniform across the thickness direction. Homogenization is a key feature of DD laminates that allows for the addition and removal of 4-ply building blocks without altering the laminate's normalized stiffness and without the need to worry about violating stacking sequence symmetry. This feature enables several manufacturing advantages, such as tapering, which can save weight and result in more highly optimized parts.

A laminate is homogenized when its normalized in-plane and flexural stiffnesses are equal ([A*] or [D*]), and its coupling matrix is zero ([B*] = 0) [1]. In practice, since the DD laminate is not symmetric, it is not possible for [B*] to become zero. Therefore, the following criteria have been suggested for checking the homogenization condition [1]. These criteria ensure a uniform stress distribution along the thickness and prevent warpage.

$$[A^*] - [D^*] < 0.02 \times Tsai's\ modulus$$
$$[B^*] < 0.02 \times Tsai's\ modulus \tag{2}$$

where Tsai's modulus is:

$$Tsai's\ modulus = A^*_{11} + A^*_{22} + 2 \times A^*_{66} \tag{3}$$

There are four types of DD laminates referred to as "staggered 1" ($[+\phi/-\psi/-\phi/+\psi]$), "staggered 2" ($[+\phi/+\psi/-\phi/-\psi]$), "staggered 3" ($[+\phi/-\psi/+\psi/-\phi]$), and "paired" ($[\pm\phi/\pm\psi]$). Depending on ϕ and ψ angles, the homogenization of one of these stacking sequences converge faster than the others. It means that one of them would require a smaller number of repetitions of its building blocks to meet homogenization criteria. The developed tool, "Double-Double Laminate Finder", was utilized for both finding the equivalent DD angles and selecting the best stacking sequence by checking the number of repetitions required to reach homogenization. Three equivalent DD laminates were selected. The stacking sequences and features of these laminates are shown in Table 1. For the selected DD laminates, "staggered 1", "staggered 2", and "staggered 3" reached homogenization after 5 repetitions, and "paired" configuration homogenized after 9 repetitions. Among staggered configurations, "staggered 3" was chosen because it was anti-symmetric and its stiffness components A^*_{16}, A^*_{26}, D^*_{16}, D^*_{26}, B^*_{11}, B^*_{12}, B^*_{22}, and B^*_{66} were zero.

3 HIGH-FIDELITY MODELING OF LVI AND CAI TESTS

To predict the LVI damage, a 3D FE model of a 254 mm × 304.8 mm × 4.35 mm (10 in × 12 in × 0.17 in) composite laminate was modeled in Abaqus as illustrated in Figure 2(a). The base plate and the impactor were modeled as rigid bodies. Contact interactions were established between the edges of the laminate and the three guiding pins of the base plate, between the lower surface of the laminate and the rounded frame of the base plate, and also between the top surface of the laminate and the four rubber clamps. The laminate was impacted with a hemispherical impactor with a diameter of 25.4 mm and a mass of 6.25 kg and an impact energy of 75 J.

The model captured fiber breakage, splitting, kinking, pull-out, crushing, and matrix cracking using a VUMAT user-defined material subroutine. For matrix and fiber damage initiation, the LaRC05 failure criteria [5] were employed. To predict the fiber damage evolution, a new model was introduced based on the models of Martín-Santos et al. [6] and Rivallant et al. [7]. Delamination was captured by embedded 3D cohesive elements (COH3D8) with a thickness of 0.005 mm between the adjacent composite piles. To capture the interaction between intralaminar matrix cracking and delamination, six rows of 3D cohesive elements with a thickness of 0.02 mm aligned with the fiber directions were deployed in each composite ply, as shown in Figure 2(b). The material properties of IM7/977-3 and cohesive zone modeling (CZM) parameters were taken from [4].

The predicted impact damage was transferred to the CAI model using a Python script. The CAI FE model assembly is shown in Figure 2(c). In the CAI model, the top assembly was allowed to move only in the X-direction to apply the vertical compressive force, and the movement of the laminate's lower edge was constrained in the X-direction. Both the top assembly and the anti-buckling support plates were modeled as rigid bodies. The Abaqus/Explicit was used for the analysis. To reduce running time of the CAI simulation, mass scaling with a target minimum stable time increment (STI) of 5×10^{-7} s was used. The STI before mass scaling was 5×10^{-9} s. To further reduce the running time, the displacement rate of the top assembly was increased to 5 mm/s, which was 300 times higher than the testing displacement rate of 1 mm/min. Consequently, the CAI simulation was completed in 48 hours on 32 CPU cores.

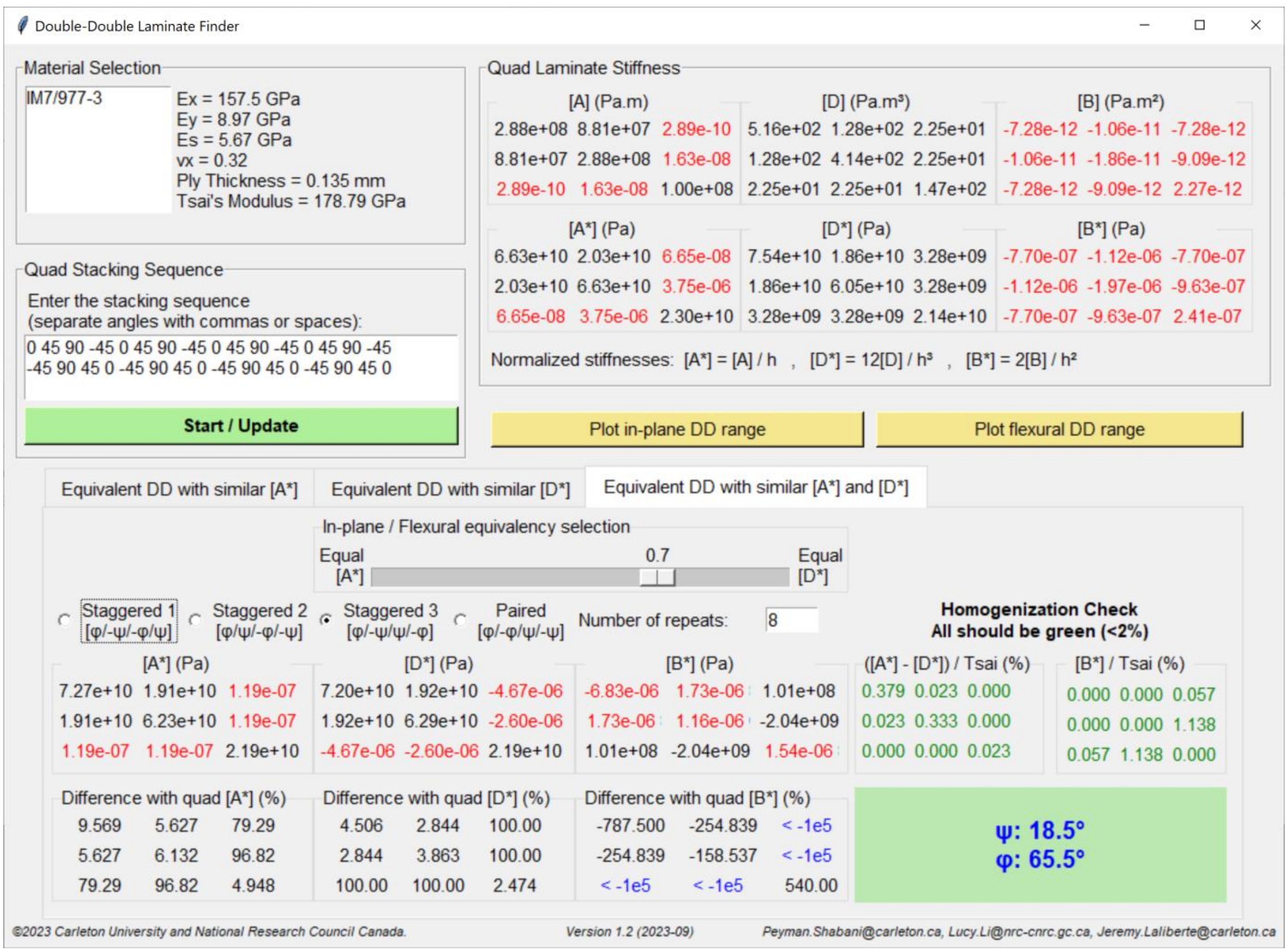

Figure 1. Developed tool for finding equivalent Double-Double laminates.

Table 1. Stacking sequences of equivalent DD laminates.

ID	Stacking Sequence	Feature
QUAD	$[0/45/90/-45]_{4s}$	Baseline configuration
DD1	$[67.5/-22.5/22.5/-67.5]_{8T}$	Equal [A*]
DD2	$[64.5/-17/17/-64.5]_{8T}$	Equal [D*]
DD3	$[65.5/-18.5/18.5/-65.5]_{8T}$	Difference in [A*] < 10%, Difference in [D*] < 5%

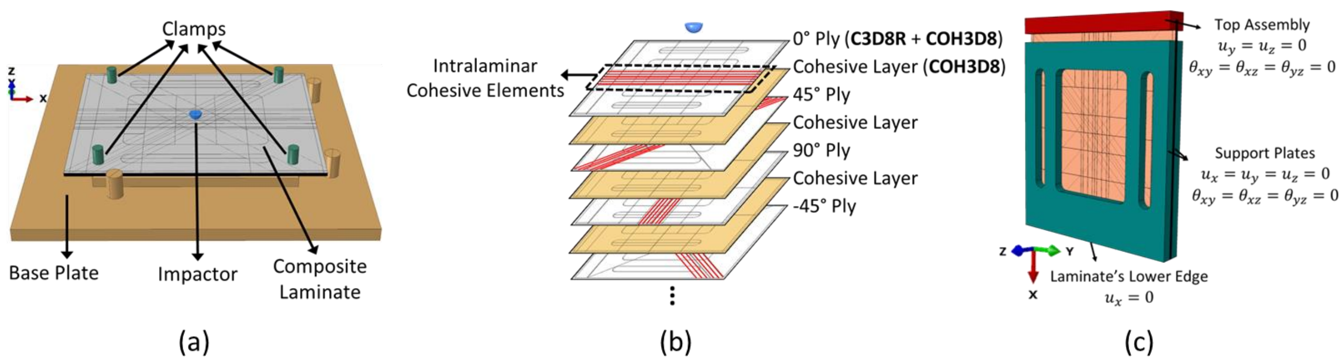

Figure 2. (a) FE model assembly for LVI simulation, (b) Embedded cohesive elements inside laminate, (c) FE model assembly and boundary conditions for CAI simulation.

4 RESULTS and CONCLUSIONS

The impact damage areas for the QUAD and DD3 laminates are compared in Figure 3(a). Overall, the impact damage areas were similar. In the DD3 laminate, the matrix cracking and fiber splitting areas were slightly larger and delamination area was slightly smaller. The impact response of the QUAD and the three DD laminates are compared in Figure 3(b) and Table 2. The difference between the QUAD and the equivalent DD laminates in peak load, maximum displacement and impact duration were less than 7%. The impact response of DD2, which had a similar flexural stiffness [D*], was the most similar to that of the QUAD laminate. The CAI behavior of QUAD and its equivalent DD laminates are compared in Figure 3(c) and Table 2. DD1 and DD3 exhibited 1.9% and 4.4% higher CAI strength, respectively, and DD2 showed a 1.9% lower CAI strength. The effective modulus of DD1 was 1.5% lower, and those of DD2 and DD3 were 12.1% and 8.5% higher, respectively. The CAI characteristics of DD1, which had a similar in-plane stiffness [A*], was the most similar that of the QUAD.

Overall, the DD1 laminate exhibited a similar behavior under CAI loading, DD2 showed a similar behavior under impact loading, and DD3's behavior was in between. Considering both overall impact damage areas and the CAI strengths, the conclusion can be drawn that QUAD laminates can be replaced by equivalent DD without compromising impact damage tolerance, while simultaneously providing the design and manufacturing ease benefits associated with the DD design. One limitation of using DD laminates is the minimum number of building block repetitions required to achieve a homogenized condition. This sets a limit for the minimum thickness of the laminate. Whereas replacing QUAD laminates with their DD equivalents shows potential as an innovative approach, further research is required to assess other aspects of DD laminates, such as the effect of ply dropping on the performance of components made with DD layup.

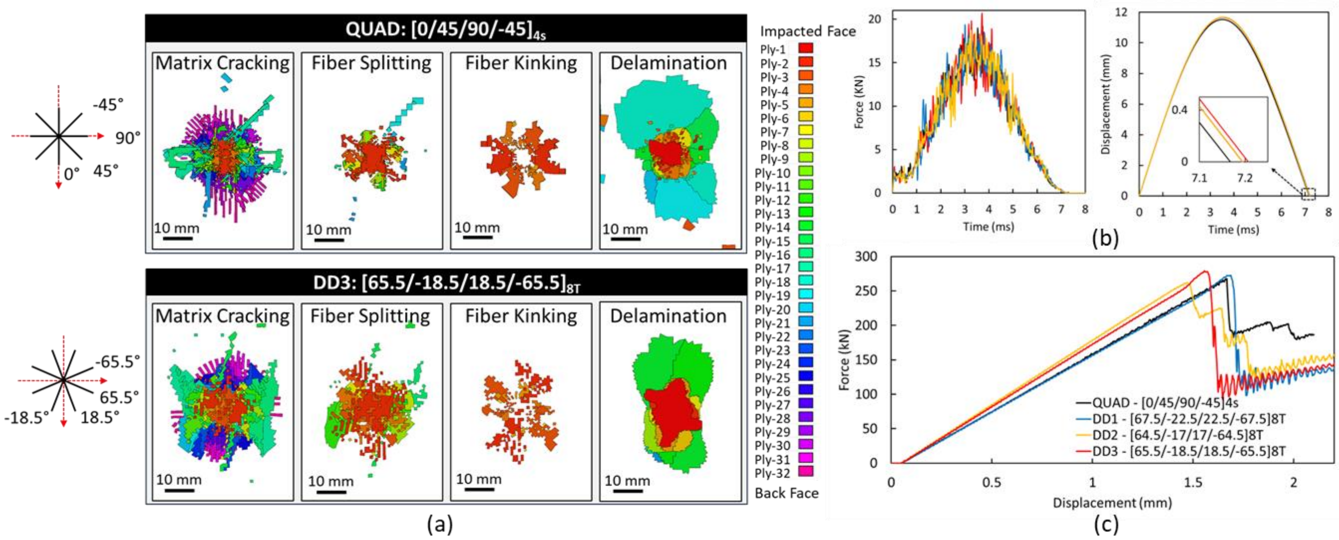

Figure 3. (a) Inter- and intra-laminar failure modes predicted for QUAD and the chosen DD laminate after a 75 J impact event, (b) LVI responses of QUAD and DD laminates, (c) CAI force-displacement diagrams.

Table 2. LVI and CAI responses of QUAD and its equivalent DD laminates.

	QUAD	DD1	DD2	DD3
Impact Peak Load (kN)	19.1	19.5 (+2.1%)	18.8 (-1.5%)	20.4 (+6.8%)
Impact Maximum Displacement (mm)	11.5	11.6 (+0.9%)	11.6 (+0.9%)	11.6 (+0.9%)
Impact Duration (ms)	7.17	7.19 (+0.3%)	7.19 (+0.3%)	7.21 (+0.5%)
CAI Residual Strength (MPa)	267.5	272.6 (+1.9%)	262.2 (-1.9%)	279.4 (+4.4%)
CAI Effective Modulus (GPa)	167.0	164.4 (-1.5%)	187.3 (+12.1%)	181.2 (+8.5%)

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