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COMPARING DD AND QUAD LAMINATES FOR SINGLE LAP JOINTS

Glosdemberger C. Cardoso
Center for Technology and Applications of Composite Materials, Department of Mechanical Engineering, Federal University of Rio de Janeiro, Macaé, RJ, Brazil
glosdemberger@gmail.com

Lucas L. Vignoli
Center for Technology and Applications of Composite Materials, Department of Mechanical Engineering, Federal University of Rio de Janeiro, Macaé, RJ, Brazil
ll.vignoli@mecanica.coppe.ufrj.br

Ranulfo M. Carneiro Neto
Center for Technology and Applications of Composite Materials, Department of Mechanical Engineering, Federal University of Rio de Janeiro, Macaé, RJ, Brazil
ranulfocarneiro@macae.ufrj.br

Abstract. *Design composite structures is a challenge due to the large amount of variables from micro to macroscale. Regarding the macromechanical analysis, one of the most important design definitions for unidirectional laminates is the layup, which is the orientation of each lamina. The most usual layup family, namely QUAD, has the plies oriented at 0°, 90°, +45° and -45° and follows the ten percentage rule. Basically, the ten percentage rule implies that laminate must be symmetric and it must have at least 10% of laminae in each orientation, i.e. 0°, 90°, +45° and -45°. Alternatively, Double-Double (DD) laminates were recently propose, where plies are oriented at* $\pm\Phi$ *and* $\pm\Psi$*, where* Φ *and* Ψ *are continuous variables ranging between 0° and 90°, improving the structural optimization. DD laminates have been demonstrated better structural response than QUAD for strength and buckling analysis, saving weight and cost. The present research is an effort to compare the response of QUAD and DD laminates in bonded joints, specifically single lap joints. The damage onset is evaluated using the commercial finite element software Ansys and considering the Drucker-Prager and Tsai-Wu damage criteria for the adhesive and the laminate, respectively. Considering the following QUAD laminate* $[45/90/\text{-}45/0]_{2s}$ *as reference, the proposed methodology is validated against experimental data from literature, resulting in an error of 0.47%. To obtain the stiffness equivalence according to the classical laminate theory, the DD family* $[\pm 67.5/\pm 22.5]_4$ *is selected. The results indicate that all DD layups improve the joint damage onset. Additionally, there is an increasing on the damage onset forces up to 25% for the DD laminates* $[67.5/\text{-}22.5/22.5/\text{-}67.5]_4$ *and* $[67.5/22.5/\text{-}22.5/\text{-}67.5]_4$ *than for the equivalent QUAD* $[45/90/\text{-}45/0]_{2s}$*. A very smooth stress distribution is realized for DD laminates due to the homogenization capability, decreasing the stress concentration from abrupt geometry variation in bonded joints.*

Keywords: *CFRP, SLJ, Double-Double, laminates, damage onset*

1. INTRODUCTION

Prof. Tsai's group have been proposed some novel and efficient approaches for carbon fiber reinforced polymers (CFRP). In summary, three main recent advances can be pointed out: trace theory (Tsai & Melo, 2014), or Tsai's modulus (Arteiro *et al*., 2020); unit circle failure criterion (Tsai & Melo, 2016); and double-double laminates (Tsai, 2021).

Tsai's modulus aims to decrease the quantity of mechanical tests required to obtain CFRP effective elastic properties from 5 to 1 independent property. Assuming that the trace of the stiffness matrix is an invariant, a normalized relation is proposed and just lamina longitudinal elastic modulus, E_1, is required. Also, to decrease the amount of experimental tests required and simplify the design, a unit circle on the normalized strain space is proposed to evaluate laminate strength, where the strains are normalized in relation to the tensile and compressive failure strains. A more comprehensive explanation is presented by Tsai *et al*. (2019) and Vignoli *et al*. (2023).

The goal of the present investigation is the Double-Double (DD) laminates. The main idea is replace the traditional QUAD laminates, where plies are oriented in 0°, +45°, -45° and 90°, by DD laminates, where the layup is $[\pm\Phi/\pm\Psi]_n$. Note that Φ and Ψ are general angles between 0º and 90°. QUAD must be symmetric and obey the 10% rule (*i.e.* there is at least 10% of plies in each orientation); on the other hand, DD are not symmetric and the angles Φ and Ψ are continuous variable, allowing structural optimization. According to Vermes *et al*. (2021a), the asymmetry issues are fixed for due to DD homogenization capability.

Because of the advantage of continuous ply angles variable (Furtado *et al.*, 2021), many investigations about optimization have been performed considering the cost (Vermes *et al.*, 2021b), mass (Shrivastava *et al.*, 2020), manufacturing (Yamaguchi *et al.*, 2020) and buckling (Vijayachandran & Waas, 2021; York, 2021). Additionally, Kappel (2022) evaluated DD advantages for aerospace structures and Zhang *et al.* (2022) proposed the application of machine learning algorithms to decrease design time. A summary of DD developments can be found in Tsai *et al.* (2022).

For many industrial applications, including aerospace (Katnam *et al.*, 2012; Kupski & Freitas, 2021) and automotive (Silva *et al.*, 2020a), a very popular technique to join different parts of the structure is the application of adhesive (Banea & Silva, 2009; Budhe *et al.*, 2017). Many aspects of bonded composite joints are reported in the literature, like adhesive thickness (Fernández-Canadas *et al.*, 2021), laminate thickness (Kupski *et al.*, 2020), temperature effect (Fernandes *et al.*, 2016) and fatigue (Part *et al.*, 2020).

Considering the adherent laminate layup, Kupski *et al.* (2019) investigated the influence of plies stacking sequence in QUAD laminates in damage onset. Demiral & Kadioglu (2018) studied angle-ply laminates considering the damage propagation up to final failure. Both are considering single lap joints (SLJ) and indicate that damage may take place in the adhesive or in the adherent, depending on the ply angle around the bonded region. However, due to the very recent advances related to DD, there is an absence of investigation about the mechanical behavior of this family of laminates in bonded joints; there is none report in the literature.

To deal with this issue, the damage onset in SLJ made by DD laminates is numerically investigated and compared with a QUAD laminate. A three-dimensional finite element model is developed and introduced in Section 2. Drucker-Prager and Tsai-Wu failure criteria are considered to evaluate damage onset in the adhesive and adherent (laminate), respectively. The results are discussed in Section 3, where first the proposed methodology is validated using an experimental data for QUAD laminate and next it is applied for DD laminates. The main conclusions are summarized in Section 4.

2. NUMERICAL MODEL

The finite element method is used to numerically simulate a solid 3D-model of the SLJ. The dimensions, boundary conditions and mesh of the model are illustrated in Fig. 1. All degrees of freedom are restricted on the right side, while on the left side only longitudinal displacement is allowed. The force reaction of this applied displacement is computed to evaluate the joint strength. The composite adherents are modeled with 16 layers of 125μm thickness each (*i.e.*, a total of 2 mm per adherent). The adhesive thickness along the bonding line is set as 0.0625 mm and a 45º triangular fillet is defined on its longitudinal edges.

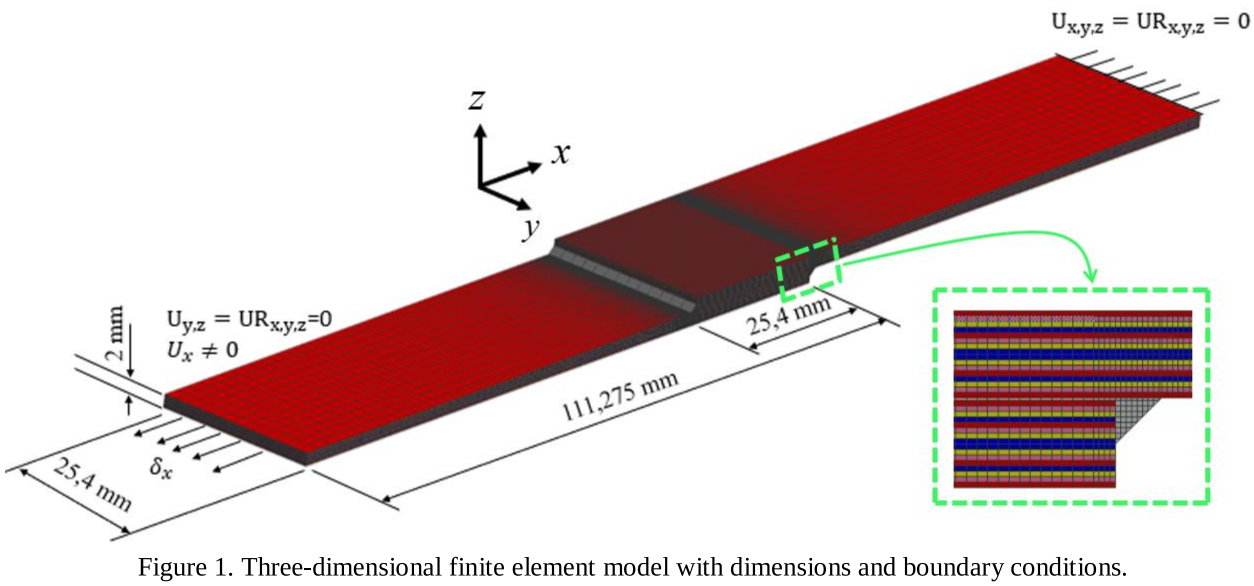

Figure 1. Three-dimensional finite element model with dimensions and boundary conditions.

The quadratic 3-D 20-node solid element (SOLID186) is adopted in a mesh with 697130 elements. The element size is refined near the overlap in order to improve the accuracy in regions with stress concentration.

To evaluate the adhesive damage, Drucker-Prager criterion is used since adhesive strength is different in tension and compression (Özera & Öz, 2017; Sánchez-Arce *et al.*, 2021). Drucker-Prager failure function is defined by (Lubliner, 2008)

$$f_{DP} = a\sqrt{3J_2} + bI_1 \tag{1}$$

where $I_1 = \sigma_{ii}$ is the first invariant of the stress tensor σ_{ij}, $J_2 = s_{ij}s_{ij}/2$ is the second invariant of the deviatoric stress tensor $s_{ij} = \sigma_{ij} - (\sigma_{ii}/3)\delta_{ij}$, δ_{ij} is the Kronecker delta, $a = (S_c + S_t)/(2S_cS_t)$, $b = (S_c - S_t)/(2S_cS_t)$, S_c is the adhesive compressive strength and S_t is the adhesive tensile strength.

For the laminate strength, Tsai-Wu failure criterion (Tsai & Wu, 1970) is applied based on the results of the World-Wide Failure Exercise (Soden *et al.*, 2004). Despite it is a traditional criterion, some recent works (Li *et al.*, 2017; Li *et al.*, 2022) proposed some developments based in analytical geometry that avoid any necessity of calibrated parameters, obtaining the following equation

$$f_{TW} = \left(\frac{1}{S_{11}^t} - \frac{1}{S_{11}^c}\right)\sigma_{11} + \left(\frac{1}{S_{22}^t} - \frac{1}{S_{22}^c}\right)(\sigma_{22} + \sigma_{33}) + \frac{\sigma_{11}{}^2}{S_{11}^t S_{11}^c} + \frac{(\sigma_{22}{}^2 + \sigma_{33}{}^2 - \sigma_{22}\sigma_{33} + 3\sigma_{23}{}^2)}{S_{22}^t S_{22}^c} - \frac{\sigma_{11}(\sigma_{22} + \sigma_{33})}{\sqrt{S_{11}^t S_{11}^c S_{22}^t S_{22}^c}} + \left[\frac{\sigma_{12}{}^2 + \sigma_{13}{}^2}{(S_{12}^s)^2}\right] \tag{2}$$

where S_{11}^t is the lamina longitudinal tensional strength, S_{11}^c is the lamina longitudinal compressive strength, S_{22}^t is the lamina transversal tensile strength, S_{22}^c is the lamina transversal compressive strength and S_{12}^s is the lamina in-plane shear strength. For a detailed derivation of Eq.(2), see Tsai *et al.* (2022). Note that the stress components in Eq.(2), σ_{ij}, are computed considering the lamina material coordinate system, where x_1 is parallel to the fibers direction.

3. RESULTS AND DISCUSSION

In order to determine whether the mesh is reliable, the damage onset of the QUAD laminate $[45/90/-45/0]_{2s}$ is evaluated and compared with the experimental result measured using acoustic emission by Kupski *et al.* (2019). The adhesive and unidirectional lamina properties are listed in Table 1 and 2, respectively. The damage onset force obtained numerically using the finite element model presented previously is 2552N, while the experimental value was 2540N, both indicating damage at the adhesive. Since the error is 0.47%, the finite element model is considered validated.

Table 1: Adhesive properties (Kupski *et al.*, 2019).

Properties	**Symbol**	**Value**	**Units**
Elastic modulus	E	2.02	GPa
Poisson's ratio	ν	0.34	-
Tensile strength	S_t	48	MPa
Compressive strength	S_c	69.6	MPa

Table 2: Unidirectional lamina properties (Kupski *et al.*, 2019).

Properties	**Symbol**	**Value**	**Units**
Longitudinal elastic modulus	E_1	142	GPa
Transversal elastic modulus	E_2	9.1	GPa
In-plane Poisson's ratio	ν_{12}	0.27	-
In-plane shear modulus	G_{12}	5.2	GPa
Out-of-plane shear modulus	G_{23}	3.5	GPa
Longitudinal tensile strength	S_{11}^t	2274	MPa
Longitudinal compressive strength	S_{11}^c	1849	MPa
Transversal tensile strength	S_{22}^t	162	MPa
Transversal compressive strength	S_{22}^c	296	MPa
In-plane shear strength	S_{12}^s	126	MPa

The QUAD layup $[45/90/-45/0]_{2s}$ is used as reference to the DD angles. As explained by Tsai *et al*.(2022), the elements of the main diagonal of the in-plane stiffness matrix of the classical laminate theory must be equal to obtain an equivalent DD laminate. Mathematically, this condition means that $A_{ii} = \int C_{ii} dz (i = 1,2,3)$ is equal for DD and QUAD laminates, where C_{ij} is the plane stress stiffness matrix of each ply. Carrying out this equivalence, the angles $\Phi = 67.5°$ and $\Psi = 22.5°$ are obtained.

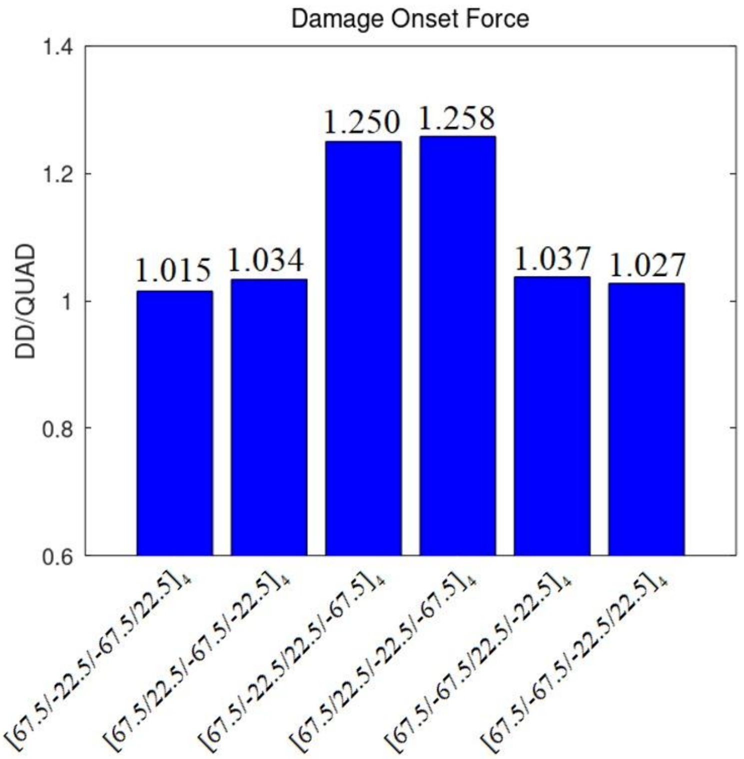

Figure 2: Damage onset forces for all DD configurations normalized by QUAD.

The damage onset force results for all DD configurations normalized by quad found from the equivalence are presented in Fig. 2. All DD configurations presented higher forces than QUAD, with four configurations very close and two considerably higher. The $[67.5/-22.5/-67.5/22.5]_4$ configuration showed the lowest force (1,5% above QUAD), while the highest force was observed in the $[67.5/22.5/-22.5/-67.5]_4$ configuration, with 25.8% above. Note that $[67.5/-22.5/22.5/-67.5]_4$ presented an improvement of 25%. Additionally, the damage onset is always observed on the adhesive for the laminates studied.

4. CONCLUSIONS

This paper presents an investigation about QUAD and DD laminates behavior considering a single lap joint. The joints with DD laminates obtained higher damage onset forces than QUAD for all the configurations. The best performance is observed for $[67.5/22.5/-22.5/-67.5]_4$ and $[67.5/-22.5/22.5/-67.5]_4$, both improvements around 25%.

There is an absence of experimental data in the literature for bonded joint made by DD laminates. This issue limits the results only for the damage onset because the critical fracture energies, which are fundamental for numerical simulations of the damage propagation, depends of the laminate stacking sequence. Hence, an experimental program need to be performed to investigate the maximum load for DD laminates and improve the comparative discussion with QUAD laminates.

5. ACKNOWLEDGEMENTS

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