

Experimental and numerical comparison of Double–Double and QUAD laminates in open-hole tension tests

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ABSTRACT

Double–Double laminates attract increasing attention as a potential alternative to conventional laminates in aerospace practice. This trend is mainly driven by DD-related simplifications of laminate optimization and manufacturing processes. For a broad integration of DD-laminates in the industry their mechanical behavior needs to be examined, especially in comparison to the established conventional laminates (QUAD). Therefore, the present article examines open-hole-tension tests experimentally as well as by finite element methods. The samples cover quasi-isotropic and more-orthotropic stackings, made from conventional laminates and their $[A^*]$ -matrix-based Double–Double equivalents. Open-hole-tension experiments cover the two relevant aerospace prepreg materials M21E/IMA and 8552/IM7. The latter, is examined in more detail in this manuscript, with detailed finite-element modeling and accompanying digital-image-correlation during the tests. This paper focuses on comparing the failure loads of the QUAD laminates and their corresponding DD laminates, as well as on determining the first-ply failure loads. The experimental test series serves for the strength failure loads determined in the FE calculations. For the design case based on the first-ply-failure criterion, the values calculated using FE are compared with the analytical FPF envelopes. The two main findings of this article are: The studied DD laminates show equivalent OHT strength properties compared to their corresponding QUAD ones, which indicates that the novel DD laminate architecture is similarly capable in OHT load cases. The executed FE simulations verify that DD laminates can be simulated with the same methods that have been validated earlier for conventional laminates.

1. Introduction

DD laminates promise simplified optimization and manufacturing processes, as well as improved lightweight construction properties due to eased stacking and load-adapted ply orientations [1]. However, due to the novelty of these laminates, it is mandatory to understand their properties and characteristics, in order to demonstrate at least structural equivalence with classic QUAD laminates. As part of the verification process for aviation applications, this requires standardized test methods on coupon level, such as tensile and compression tests, compression after impact or OHT. Those tests are common practice in composite design, when comparing different materials or stacking sequences. They refer to Level 1 of the building-block approach for composite structures [2].

An investigation into the CAI behavior of DD compared to QUAD has already been carried out in a previous publication [3]. Very limited data in DD context is available for OHT tests, as outlined in [4]. Seneviratne [5] performed tests with more-orthotropic laminates, made from

a composite with Toray T700 fibers. He examined a symmetric QUAD laminate $[0_5, (\pm 45)_2, 90]_s$ (50%, 40%, 10%) and the DD competitor with a $[\pm 0, \pm 50]_{5T}$, while the tests show little advantages for DD. Huang et al. [6] investigated quasi-isotropic QUAD and in-plane stiffness equivalent DD laminates under cyclic open-hole tension loading. One of their findings is that the DD laminates shows an earlier decrease in residual strength compared to the respective QUAD. This is due to an additional twisting of the DD laminates, caused by the combination of their asymmetric layup and curing- and loading-induced stresses. Li et al. [7] also studied OHT tests of quasi-isotropic and soft QUAD laminates and their corresponding DD equivalents. They focused on the effect of the open-hole diameter. In their article they state that the notched strength of QUAD and DD behave in opposite ways, with the QUADs strength decreasing with increasing hole diameter and the DDs strength increasing with increasing hole diameter. Hawkins et al. [8] carried out a number of mechanical tests including unnotched tension and compression, open-hole tension as well as open-hole compression of QUAD laminates and their corresponding so called ‘extended

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Abbreviations

Notation	Description	Notation	Description
BB	building block	FPF	first-ply failure
CAI	compression after impact	LPF	last-ply failure
CLT	classical laminate theory	OHT	open-hole tension
CNC	Computerized Numerical Control	ORTHO	orthotropic
DD	Double-Double	PDA	progressive damage analysis
DIC	digital image correlation	PSCC	principal-strain cut off circle
FE	finite element	QI	quasi isotropic
FEM	finite-element model	QUAD	conventional laminate
FMC	Failure-mode concept	UD	Unidirectional

Double-Double' (ExDD) laminates. A main finding in their work is the difference in unnotched and notched properties form ExDD and QUAD. For the unnotched case the tensile strength of QUAD laminates exceeds those of ExDD. In contrast, for the unnotched compression load case the ExDD exceeds those of the QUAD laminates. For the OHT load case the ExDD showed equivalent or even increased strength, compared to the QUAD laminates. The present article aims for widening DD related data. The article utilizes the OHT coupon-test setup to examine DD's performance, by comparing it to results of stiffness-equivalent conventional laminates (QUAD). This test allows to assess the load-bearing capacity of a structure and also load redistribution characteristics. The present study compares DD and conventional QUAD laminates. The comparison quantifies how the different laminate architecture of DD impacts samples' performance. Since the laminate stacking affects the through thickness damage progression in OHT test scenarios, as Hallett et al. stated [9], it becomes mandatory to test novel laminates like DD in comparison to the established QUAD ones. This is essential, although the corresponding $[A^*]$ -matrix is almost identical and the corresponding DD and QUAD laminates should therefore behave similarly for in-plane loads in the elastic domain.

A comprehensive experimental understanding of DD laminates is also essential in order to validate FE models using this data. These will then enable savings to be made in the future in terms of expensive and time-consuming test campaigns in test laboratories. Therefore, it is crucial to enable the models to predict both reliable failure loads and behavior for laminates and components based on the DD architecture. In addition to experimental tests, analytical calculations based on the CLT are another method of evaluating the plausibility of FE model results, thereby ensuring reliable FEM results in the field of double-double laminates.

In this article, the aim is to compare the performance of unconventional Double-Double laminates and classic QUAD laminates for the OHT testing scenario. The investigated parameters are the laminate architecture – DD vs QUAD – and the in-plane properties – quasi-isotropic vs orthotropic. The used material is Hexcels 8552/IM7 [10] epoxy based carbon fiber UD prepreg. The study is done by experimental testing, analytical calculations, and finite element modeling. Finally, the results of the three procedures are compared to each other.

Experimental testing is also conducted with Hexcels M21E/IMA [11] prepreg as an alternative series-type material. This allows for a comparison between two aerospace-grade prepreps and adds another parameter to the experimental part of this script. Table 1 indicates the topic presented in this manuscript.

Table 1

Undertaken analyses and materials.

Material	Topics covered and presented in article			
	Analytical QUAD→DD transfer	OHT tests	Numerical study	FEM/DIC comparison
8552/IM7	x	x	x	x
M21E/IMA	x (see A.2)	x		

2. Methods and procedures

2.1. DD laminate design - notation basics

Classical laminate theory is commonly used in composite practice today [12–17]. A normalized formulation is used in context of DD by Tsai and Melo [18, p.164], which can be deduced from CLT.

$$\underbrace{\begin{pmatrix} \{N\} \\ \{M\} \end{pmatrix}}_{\text{CLT}} = \underbrace{\begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix}}_{\text{Normalized, see Tsai and Melo}} \cdot \underbrace{\begin{pmatrix} \{\epsilon^0\} \\ \{\kappa\} \end{pmatrix}}_{\text{Normalized, see Tsai and Melo}} \rightarrow \underbrace{\begin{pmatrix} \{\sigma^0\} \\ \{\sigma^f\} \end{pmatrix}}_{\text{Normalized, see Tsai and Melo}} = \underbrace{\begin{bmatrix} [A^*] & [B^*] \\ 3[B^*] & [D^*] \end{bmatrix}}_{\text{Normalized, see Tsai and Melo}} \cdot \underbrace{\begin{pmatrix} \{\epsilon^0\} \\ \{\epsilon^f\} \end{pmatrix}}_{\text{Normalized, see Tsai and Melo}}. \quad (1)$$

Therein, the normalized matrices are defined as

$$[A^*] = \frac{1}{t_{lam}} \cdot [A], \quad [B^*] = \frac{2}{t_{lam}^2} \cdot [B], \quad [D^*] = \frac{12}{t_{lam}^3} \cdot [D], \quad (2)$$

and stresses and strains are $\{\sigma^0\} = \frac{1}{t_{lam}} \cdot \{N\}$, $\{\sigma^f\} = \frac{6}{t_{lam}^2} \{M\}$ and $\{\epsilon^f\} = \frac{t_{lam}}{2} \{\kappa\}$. This thickness normalization leads to the fact that all matrices have the same unit of type [Pa].

The notation of the DD architecture is generally described by $[\pm\Phi, \pm\Psi]_T$. Though, Φ and Ψ denote the ply-angles, r equals the number of repeats and T equals 'total'. This notation is also in line with the work of Nettles [19]. Resulting 4 ply building blocks $[\Phi, -\Psi, -\Phi, \Psi]$ are simply stacked until the desired laminate thickness is reached. There are no symmetry requirements for DD. Once a BB is defined, individual laminate zones differ only in the number of BB repeats. As mentioned above, the ply angles Φ and Ψ are defined based on the relevant load cases, as it is outlined in a previous publication [20].

2.2. Determining DD-laminate equivalents

The mechanical properties of the QUAD and DD samples have to be harmonized, in order to focus the comparison on the influence of the

Table 2

Ply properties and Engineering constants for 8552/IM7 cases used for the analysis. Values in (...) indicate measured thicknesses of manufactured and test samples.

Ply/ laminate	E_x in GPa	E_y in GPa	G_{xy} in GPa	ν_{xy}	$t_{ply/lam}$ in mm
8552/IM7 UD ply	148.4	9.4	4.7	0.336	0.131 (0.126)
QI laminate	63.829	63.829	24.204	0.319	4.192 (4.032)
ORTHO laminate	81.324	45.040	24.204	0.447	4.192 (4.032)

Table 3

Laminate stackings for 8552/IM7 laminates.

ID	Quantity	Material	Laminate stacking
QUAD, QI	6	8552	$[0, 45, 90, -45]_{4s}$
QUAD, ORTHO	6	8552	$[0, 45, 0, -45, 0, 45, 90, -45]_{2s}$
DD, QI	6	8552	$[22.5, -67.5, -22.5, 67.5]_8$
DD, ORTHO	6	8552	$[12.1, -57.2, -12.1, 57.2]_8$

Table 4

$[A^*]$ and $[a^*] = 1.0E6 \cdot [A^*]^{-1}$ matrices for 8552/IM7 configurations, determined with ply properties from Table 2.

ID	$[A^*]$ in N/mm ²			$10^{-6} \cdot [a^*]$ in mm ² /N		
QUAD, QI	71 039.5	22 631.8	0.0	15.7	-5.0	0.0
	22 631.8	71 039.5	0.0	-5.0	15.7	0.0
	0.0	0.0	24 203.9	0.0	0.0	41.3
QUAD, ORTHO	91 437.9	22 631.8	0.0	12.3	-5.5	0.0
	22 631.8	50 641.1	0.0	-5.5	22.2	0.0
	0.0	0.0	24 203.9	0.0	0.0	41.3
DD, QI	71 039.5	22 631.8	0.0	15.7	-5.0	0.0
	22 631.8	71 039.5	0.0	-5.0	15.7	0.0
	0.0	0.0	24 203.9	0.0	0.0	41.3
DD, ORTHO	91 449.3	22 580.2	0.0	12.3	-5.5	0.0
	22 580.2	50 732.8	0.0	-5.5	22.1	0.0
	0.0	0.0	24 152.3	0.0	0.0	41.4

two different laminate philosophies. Therefore laminate stackings using typical 'QUAD' fiber orientations ($0^\circ, \pm 45^\circ, 90^\circ$) with quasi-isotropic and more orthotropic characteristics were conceived. The respective fiber angle percentages are (25%, $\pm 45\%$, 25%) for the quasi-isotropic and (37, 5%, $\pm 45\%$, 12, 5%) for the more orthotropic layup. As a generalization for the latter layup, based on the distribution ($a\%, b\%, c\%$), one can assume that $a > b/2$ and $a > c$, where $a, b, c > 10\%$. The DD laminates were determined, by mimicking the mechanical properties of those QUADS. For the preliminary work, the 8552/IM7 ply parameters in Table 2 have been used.

Table 3 provides the stackings of the QI and the ORTHO laminates and their corresponding DD equivalents. The latter were determined by using a Python-based optimization framework, which basically minimizes $\min : (|A_{11}^* - A_{11,DD}^*| + |A_{22}^* - A_{22,DD}^*| + |A_{66}^* - A_{66,DD}^*|)$, by adapting the building-block angles, considering 0.1° increments.

The thickness-normalized stiffness matrices of the laminates $[A^*]$ and their inverted counterparts $[a^*]$ are shown in Table 4. Note, that for the QI stackings the entries in $[A]$ are exactly the same, while for the more-orthotropic layups the terms of the QUAD are approximated by the DD, which is a consequence of the $|0.1|^\circ$ ply-angle increments, considered.

Similar conversions have been determined for M21E/IMA samples. For sake of conciseness, the applied ply data and the corresponding calculations are provided in Appendix A.2. Note, the differing ply angles in the specific BBs for the DD equivalents of M21E samples, which are a consequence of the different Engineering constants of both examined prepreg materials.

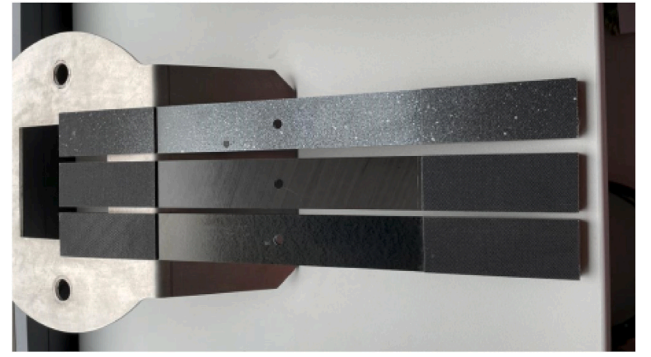


Fig. 1. OHT specimens made from the different prepreps (bottom: M21E/IMA, middle: 8552/IM7) and sample with sprinkled surface (top) for DIC measurements.

2.3. Specimen manufacturing and experimental methods

2.3.1. Materials and manufacturing

For the experimental tests a group of AITM1-0007 compliant OHT specimens were manufactured using Hexcel's unidirectional 8552/IM7 and M21E/IMA epoxy-prepreg material. The plies were cut via a CNC cutting system and eight different laminates were stacked by hand, consisting of 32 (8552) and 24 (M21E) plies respectively. The laminates were autoclave cured using the manufacturer's recommended cure cycle and six specimens per configuration were cut. The specimen dimensions are according to AITM specimen type B1, as stated in Table 5.

Measuring the specimens' thickness led to an average of 4.02 mm for the 8552 prepreg and 4.44 mm for M21E. Fig. 1 shows example samples prior to testing.

2.3.2. Experimental open-hole tension tests

The tests were conducted in the test laboratory of the DLR Institute of Lightweight Systems in Braunschweig. A Zwick Z400E test machine used was, which is capable of applying a maximum tensional force of 400 kN. The testing speed was set to 1 mm/min for the quasi-static tests. To harmonize the specimen conditions, these were conditioned in the laboratory's climate with a temperature of 23°C and a humidity of 48%. A single specimen at a time was placed centric and axial in the clamping jaws for the OHT test. The lower jaw was then closed to fix the specimen in the tab area. Afterwards, the upper jaw was closed as well (see Fig. 2). During the closing process, the machine was running a load stabilization routine to minimize forces on the specimen before the actual test started. Once the desired clamping force was applied, the uniaxial tensile test started. Each test was run until the specimen fractured, which correlates with the sample's tensile strength.

Six specimens were tested for each configuration and one test per configuration was recorded using the ZEISS ARAMIS DIC system (see Fig. 2). This system allows for measuring the strains on a specimen's surface, which is compared with strains calculated by the FE analysis.

2.3.3. DIC measurement facts

The DIC measurement was performed using the 24-megapixel Zeiss ARAMIS system. The measurement volume was set to 210 mm length and 185 mm width. With a mesh size of 19 pixels, this corresponds to an average mesh size with a strain reference length of approximately 1.3 mm. The measurement frequency was set to 5 Hz, using a ring buffer for capturing the failure, and 2 Hz during the rest of the test. The coordinate system origin was positioned at the edge of the specimen, with the Y-axis aligned through the center of the hole, the x-axis oriented along the tension direction, and the z-axis representing the out-of-plane direction. For evaluation, colored strain plots of ϵ_x and

Table 5
Tested OHT specimen type according AITM1-0007 [21].

Specimen type	Thickness (t /mm)	Width (w /mm)	Gauge length (l_{gauge} /mm)	Tab length (l_{tab} /mm)	Total length (l /mm)	Hole diameter mm
B1	4–7 mm	32 ± 0.2	180 ± 0.5	50	$2 \cdot l_{tab} + 180$	6.3

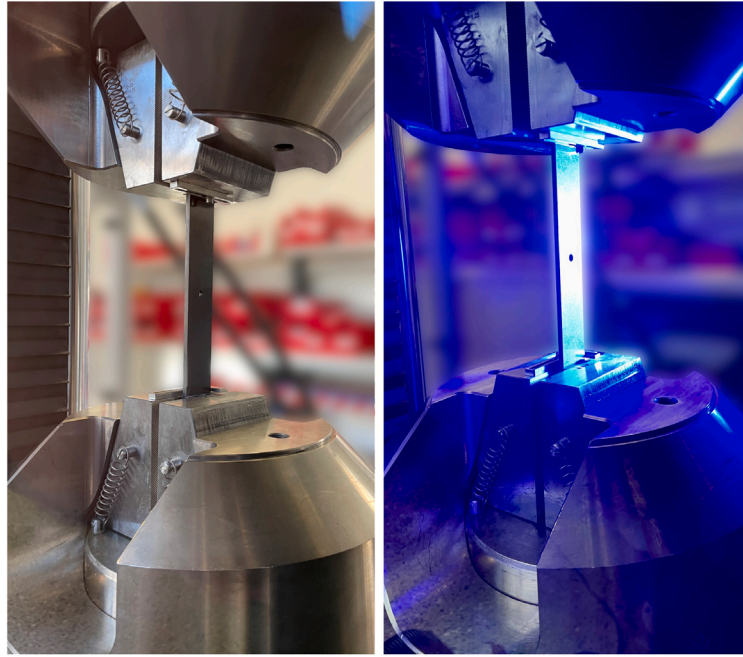


Fig. 2. Clamped OHT specimen in test machine (left) and with active DIC system (right).

γ_{xy} were calculated. Furthermore, a virtual extensometer with 50 mm in length (± 25 mm around the center), was generated for comparison with FE displacement results (see Figs. 12 and 15).

2.4. Numerical methods and simulation model

The 8552/IM7 experiments, carried out in this work, are accompanied by FE simulations with failure and damage analysis. The simulations are intended to verify whether DD laminates can be modeled using the same methods as QUAD laminates and to provide additional information on failure behavior. This section briefly describes the modeling and simulation approach.

2.4.1. Modeling approach

The OHT specimens are represented on the mesoscale, so that each individual layer is modeled separately. The basis of the FE-based progressive damage analysis is a user-defined material model developed by one of the authors [22], that represents the intra-laminar behavior of the individual plies. The model takes into account the three-dimensional state of stress and, in addition to the transversely isotropic constitutive law, includes pseudoplasticity with the model of Sun and Chen [23]. Pseudoplasticity includes both the effects of the plastic yielding of the matrix material, as well as the effects of fiber rotation. Failure is detected using Cuntze's FMC [24], and the progression of damage is then modeled using a linear energy-based degradation model. The FMC distinguishes five different failure modes. The mathematical formulation of the damage-initiation criteria and the damage-evolution law is provided in Appendix A.3, following [22]. Two fiber failure modes differentiate between failure due to tension (Mode FF1) and compression (Mode FF2) loading. The remaining three are the inter-fiber failure modes due to tension (Mode IFF1), compression (Mode IFF2) and shear (Mode IFF3) loading. Delamination is not modeled explicitly e.g. with Cohesive Zone Modeling or Virtual Crack

Closure Technique. Plies are instead connected via common nodes. Delamination is thus only implicitly reflected through the degradation of the through-thickness stiffnesses, without predicting discrete delamination shape or extent. This approach has previously been applied successfully. Additional information about the modeling including verification, validation, and application to different use cases can be found in [22,25,26]. As the simulations are solved explicitly using Abaqus/Explicit 2018, the material model is implemented as VUMAT written in Fortran. The explicit solver is used because of nonlinearities due to plasticity and damage, which impede the convergence of an implicit solver.

2.4.2. Simulation models

The finite element model represents the full cross section and does not exploit the symmetry, since the DD laminates are not symmetric about the mid plane. Fig. 3 shows an example FE model.

To ensure comparability, the test specimens with QUAD laminates are also modeled with their full thickness, although in this case it would be possible to exploit the symmetry. To save computing time, only a segment of the test specimen is modeled, namely 50 mm (± 25 mm from the hole center). This length was chosen to ensure that no significant strain gradients occur at the cut faces where the boundary conditions are applied; see the strain fields presented in Figs. 12 and 15. Preliminary studies were conducted with a longer (100 mm) model, but no significant effect on the results was observed, which justified the reduction to 50 mm model length. For the QI-QUAD configuration, the predicted failure load differs by only 0.18% between the 50 mm and the 100 mm model, while the local strain field around the hole remains essentially unchanged and the reduced model length lowers the computation time until failure by a factor of ≈ 3.2 . Quantitative details are provided in Appendix A.4. At one cut face, displacements in the x -direction and rotations about the y - and z -axes are constrained.

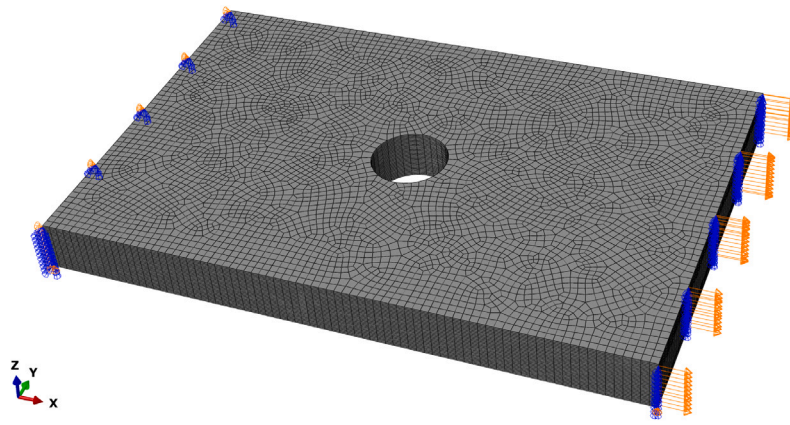


Fig. 3. Simulation Model of OHT specimen with mesh and boundary Conditions. Each ply (32) is modeled with a single FE-layer.

Table 6

Material properties and model parameters for 8552-IM7 from [29].

Elasticity [30–32]	E_{11} 171.4 GPa	$E_{22} = E_{33}$ 9.1 GPa	$G_{12} = G_{13}$ 4.5 GPa	G_{23} 3.0 GPa	$\nu_{12} = \nu_{13}$ 0.32	ν_{23} 0.45
Plasticity [29]	a 2.6	α 0.252	β 950.1			
Strength [30,33,34]	$R_{\parallel}^c$ 2500.4 MPa	$R_{\parallel}^c$ 1200.1 MPa	$R_{\perp}^c$ 50.8 MPa	$R_{\perp}^c$ 253.0 MPa	$R_{\perp\parallel}$ 91.1 MPa	
Failure criterion (FMC) [29]	$b_{\parallel}$ 0.44	$b_{\perp}$ 1.266	m 3.0			
Fracture toughness [34–36]	G_{fI} 133.3 N/mm	G_{fC} 61.0 N/mm	$G_{mI} = G_{mC}$ 0.24 N/mm	G_s 0.74 N/mm		
Ply thickness [10]	t_{ply} 0.125 mm					

A displacement load in the x -direction is applied at the opposite cross section face, while rotations about the y - and z -axes are simultaneously constraining. The amplitude of the displacement is increased linearly over the simulation time using a smooth step function. Each ply of the laminate is discretized with a single element through-the-thickness. The individual layers are connected to each other via common nodes. Reduced integrated solid elements (C3D8R) with an in-plane edge length of 0.625 mm are used. The mesh is unstructured and the edge length is determined as the maximum element size for the Crack Band Approach of Bažant and Oh [27], which aims to reduce mesh dependency, in accordance with the methodology described by Bažant and Oh and taking into account the material data used. The relevant material parameters of a unidirectional ply can be found in Table 6. Furthermore, the in-situ effect in embedded for outer plies. This effect is caused by the constraining effect of adjacent plies with different fiber orientations, is taken into account by the in-situ transverse tensile and shear strength. These modified strength values are determined analytically according to the approach proposed by Camanho et al. [28].

3. Results and discussion

Aside to the detailed FE analysis of the OHT sample, the strength of undamaged QI and QUAD laminates, made from 8552/IM7, is estimated utilizing the FPF envelope analysis (see [37]). The results should help to compare FE-based total strains.

3.1. Analytical strength prediction for undamaged laminates

FPF envelopes are well suited to visualize the load-carrying capacity of laminates, made from a specific material [37]. An FPF envelope visualizes laminate limits based on principal strains. Those envelopes can be determined based on different failure criteria. The Tsai–Wu

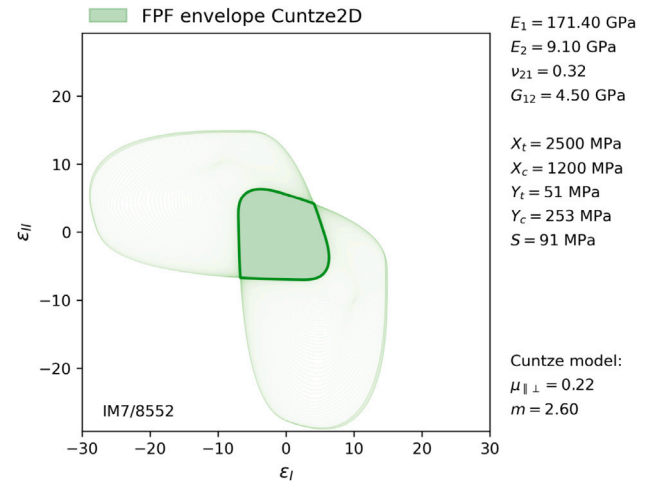


Fig. 4. Cuntze FPF Envelope. Strains in ‰.

criterion is often used in DD context (see [38]). Hereafter, Cuntze's failure-mode-concept is used for the envelope creation, as it is also part of the simulation procedure presented later in this article (see details in (see [37])). For creating an envelope for Cuntze 2D the ply parameters $E_1, E_2, \nu_{12}, G_{12}$ and X_t, X_c, Y_t, Y_c, S and the FMC parameters $\mu_{\perp}$ and m are required. The reader is also referred to [39,40] for a more detailed explanation of Cuntze-FPF-envelopes and their application. Fig. 4 shows the determined FPF envelope for the 8552/IM7 material, determined based on the parameters outlined on the right (in line with Table 6 data.)

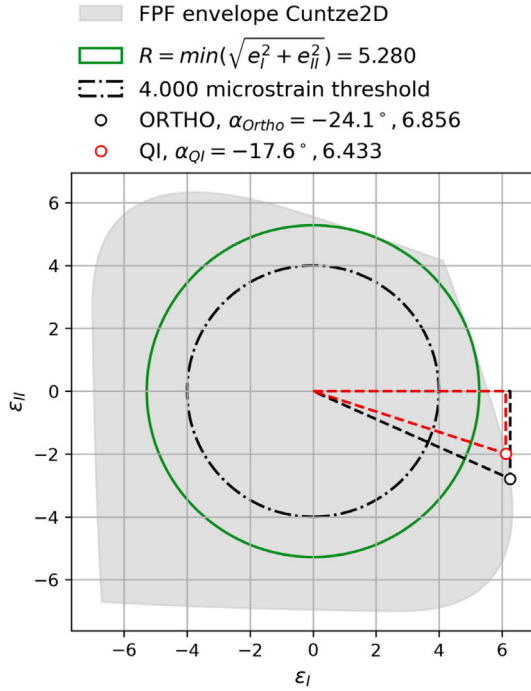


Fig. 5. Cuntze Envelope, PSSC, 4000 microstrain circle and QI/ORTHO strain limits. Strains in ‰.

The determined FPF envelope can be used for estimating the principal strain state limits for pristine QI and the ORTHO laminate configurations, as is shown hereafter. As a most simple approach, the envelope can be used to define a PSSC (see [39,40]). The radius R_{min} of the PSSC is defined by the particular strain-state, which refers to $\min(\sqrt{\epsilon_I^2 + \epsilon_{II}^2})$. The PSSC simplifies the material-effort assessment to an easy comparison of scalar values R/R_{min} , similar to a reserve factor or a margin of safety. The PSSC concept is similar to the unit-circle failure criteria [41] and its simplified version, the Nettles circle [42]. However, neither the unit- nor the Nettles circle is applicable for Cuntze's envelope, due to the particular envelope shape for the FMC. For the determined 8552/IM7 envelope, the radius $R_{min} = 5280$ microstrain is determined, which refers to the solid green circle in Fig. 5.

The black dashed circle is added to demonstrate that typical established strain limits, such as the often used 4000 microstrain threshold, can also be used. That the black circle lays within the green one, underlines the validity of the use of a 4000 microstrain threshold in practice. The OHT samples are tested under uniaxial tension, which can be described by

$$\begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{bmatrix} = \frac{1}{w} \cdot [A]^{-1} \cdot \begin{bmatrix} N_x \\ 0 \\ 0 \end{bmatrix} = \frac{1}{w \cdot t_{lam}} \cdot [A^*]^{-1} \cdot \begin{bmatrix} N_x \\ 0 \\ 0 \end{bmatrix}. \quad (3)$$

The examined laminates show uncoupled behavior between in-plane strain and in-plane shear ($A_{16} = A_{26} = 0$). Thus, principal strains are equal to the global laminate strain, while the x -direction is aligned with the sample's length direction.

$$\epsilon_I = \epsilon_x, \quad \epsilon_{II} = \epsilon_y \quad (4)$$

Similar to a polar-plot, each principal strain state can be described by an radius R and a case-specific angular value α_{case} . The radius $R_{\epsilon_I, \epsilon_{II}}$ is calculated as

$$R_{\epsilon_I, \epsilon_{II}} = |\epsilon_{I, II}| = \sqrt{\epsilon_I^2 + \epsilon_{II}^2} \quad (5)$$

$$R_{\epsilon_I, \epsilon_{II}} = \sqrt{\left(a_{11}^* \cdot \frac{N_x}{(w \cdot t_{lam})}\right)^2 + \left(a_{12}^* \cdot \frac{N_x}{(w \cdot t_{lam})}\right)^2} \quad (6)$$

$$= \frac{N_x}{w \cdot t_{lam}} \cdot \sqrt{a_{11}^{*2} + a_{12}^{*2}}, \quad (7)$$

while the angle for a specific strain state is determined by using

$$\tan(\alpha_{case}) = \frac{\epsilon_{II}}{\epsilon_I} = \frac{a_{12}^*}{a_{11}^*} = -\nu_{xy}. \quad (8)$$

Interestingly, it is found that the case specific angle relates to the negative Poisson-ratio of the examined laminate $-\nu_{xy}$. Thus, QI and the ORTHO case yield to different angles, as laminate Poisson-ratio (see Table 2) differ. One finds

$$\alpha_{QI} = \arctan\left(\frac{-5.0}{15.7}\right) = -17.6^\circ \quad \text{and} \quad \alpha_{ORTHO} = \arctan\left(\frac{-5.5}{12.3}\right) = -24.1^\circ \quad (9)$$

for the examined laminates, respectively. The FPF-envelope-based limits for the examined laminates are determined by identifying the envelope points along the specific directions, as it is illustrated above in Fig. 5. For the case at hand, 6856 microstrain are determined for the ORTHO case and 6433 microstrain are determined for the QI case. Therefrom, axial elongation limits are estimated to $\epsilon_{x, lim, ORTHO} = \cos(-24.1^\circ) \cdot 6856 = 6258 \approx 0.626\%$ for the ORTHO case and $\epsilon_{x, lim, QI} = \cos(-17.6^\circ) \cdot 6433 = 6132 \approx 0.613\%$ for QI.

3.2. Experimental results

This section outlines the results of the experimentally executed OHT tests. This includes the force over crosshead displacement graphs in Fig. 6, the thickness-normalized force over crosshead displacement graph in Fig. 7, the failure load plot in Fig. 9 and the figures of the fracture patterns of all configurations, 8552 and M21E, in Figs. 8, 10 and A.18.

The force-displacement curves for all tested specimens – six per configuration – are plotted in two subplots, in Fig. 6. The deviating sample thicknesses for the M21E/IMA (≈ 4.44 mm) and 8552 (≈ 4.02 mm) affect the force-displacement graphs, leading to apparent stiffness differences at first sight. To improve comparability, Fig. 7 provides thickness-normalized M21E plots (scaled with $0.905 = 4.02/4.44$) in addition.

The comparison outlines very similar force-vs.-displacement characteristics for both tested materials, which is in line with the preliminary engineering constants estimates, provided in Tables 2 and A.10.

Even though the individual materials show remarkable differences after failure, as Fig. 8 indicates.

The differences can likely be attributed to deviating inner laminate architectures, with M21E/IMA showing discrete interleaf layers as shown in [43], while 8552/IM7 does not show this discrete domains. The force-displacement graphs, in Figs. 6 and 7, show congruent and almost linear development within one configuration, which substantiates the repeatability of the specimens' properties until failure. The plots clearly show remarkably higher failure loads for the M21E samples, with approximately 20%–30% higher failure strain, at a maximum crosshead travel of ≈ 2.7 mm, for a free sample length of 180 mm. 8552/IM7 samples, in contrast, show failure at cross-head travels of around 2.0 mm, only. The FPF analysis above reveals conservative 8552/IM7 failure strain estimates of 6258 microstrain for QI and 6132 for the ORTHO case. The tests show elongations of around 2.0 mm for 8552/IM7, which is equivalent to $\epsilon_x = \Delta L/L = 2.0/180 = 1111$ microstrain, when the full free sample length is considered (even up to 2.7 mm = 15000 microstrain for M21E/IMA samples). This is far beyond the FPF-envelope-based thresholds for pristine QI and ORTHO, with 6132 microstrain and 6258 microstrain, respectively, as outlined in Section 3.1. Thus, it must be assumed that ply-failure of selected plies already occurred earlier in the test, at lower elongation. The plots, however, do not clearly indicate 'kinks' or abrupt stiffness changes.

The averaged failure loads and error bars for all tested configurations are plotted in Fig. 9. For all four corresponding configurations

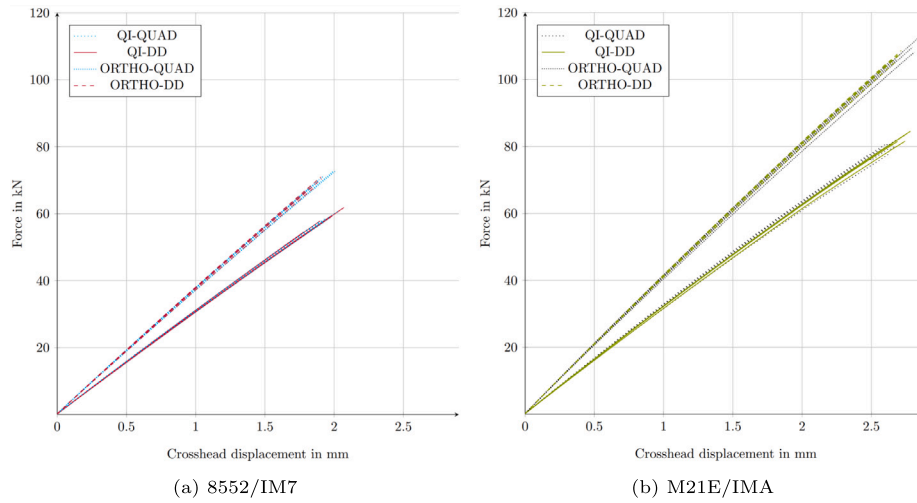


Fig. 6. Experimental force crosshead-displacement data, illustrated material-specific.

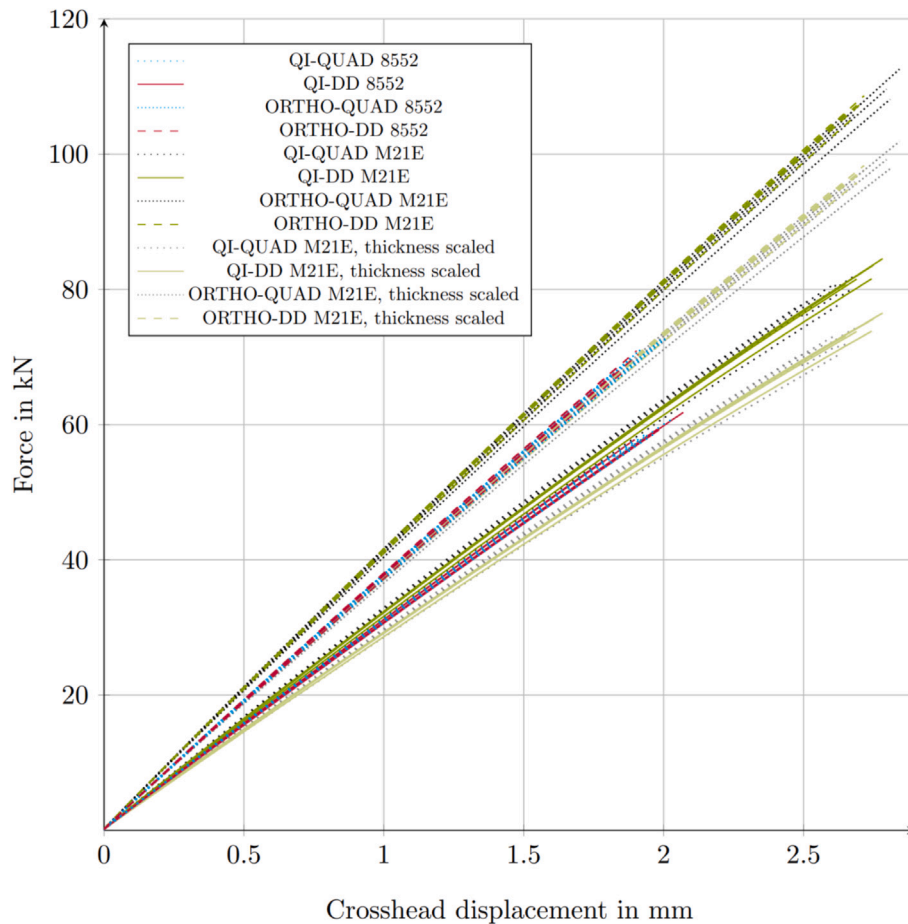


Fig. 7. Thickness-normalized force of M21E/IMA and 8552/IM7 samples compared to capture Force over crosshead-displacement data.

– each QUAD and DD for QI/ORTHO and 8552/M21E – the error bar ranges of equivalent DD/QUAD cases overlap. This implies very similar strength values for the two laminate architectures. The ORTHO laminates reach higher values for both materials, as expected due to the load adapted orientation of the layout. On overall three out of four DD laminates show less variation in strength compared to the QUAD pendants. For the 8552 specimens this only applies to the ORTHO variants with the QI laminates showing it the other way

around. The QUAD-ORTHO laminates reach slightly higher strength values compared to the DD-ORTHO configurations. However, it must be considered that the QUAD laminate has 0° -plies aligned in load direction, which can transfer loads, even in cases where angle-ply have already failed. The DD configurations of the QI laminates reach slightly higher values for the M21E material and are even with the QI-QUAD for the 8552 materials, respectively. In summary, the influence of the laminate architecture – QUAD or DD – on the strength properties of

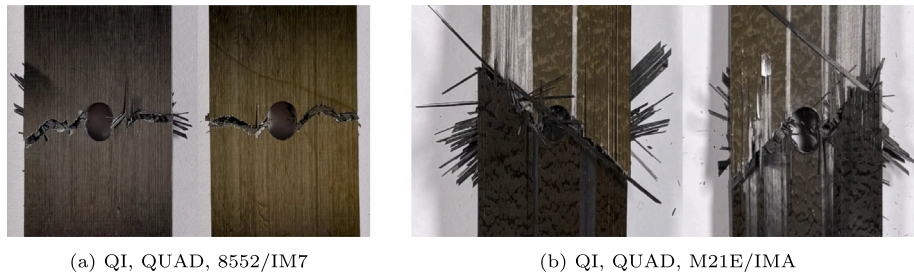


Fig. 8. Material-specific comparison of fractured samples.

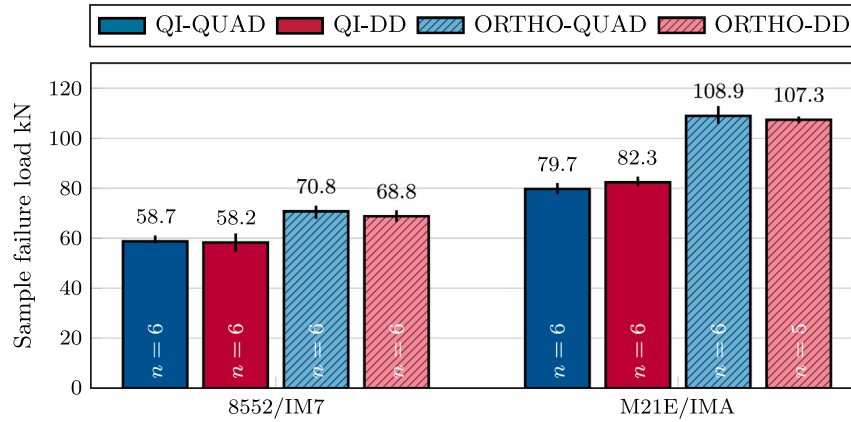


Fig. 9. Comparison of OHT strength. *n* indicate number of tested samples.

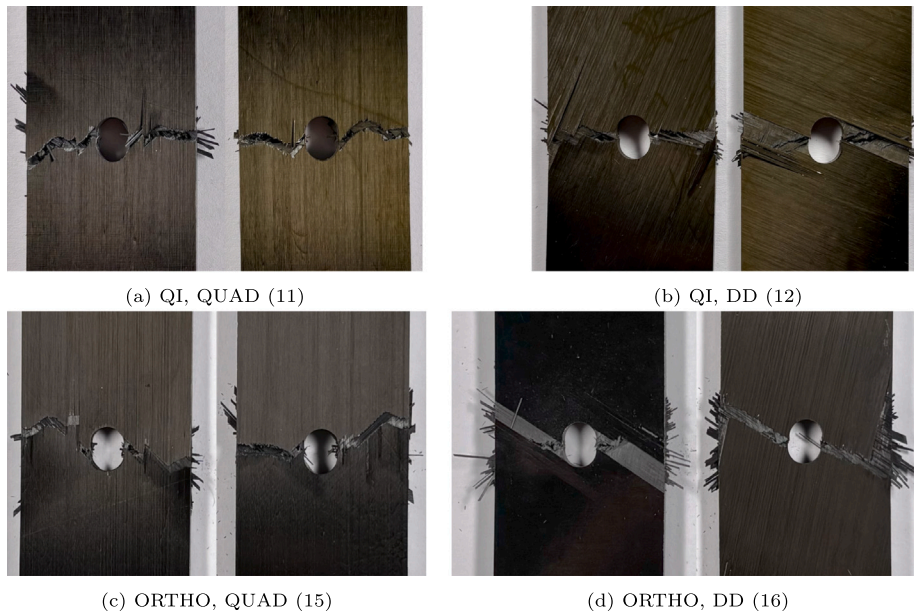


Fig. 10. Fracture patterns on front and back of the different 8552/IM7 laminate configurations.

the specimens are comparatively small. The layup – QI or ORTHO – as well as the material – 8552 or M21E – each show an influence which is at least an order of magnitude greater than that of the laminate architecture. Overall, and substantiated by the fact of overlapping error bars (ranges), the tests reveal neither clear advantageous nor disadvantageous for QUAD or DD. The resulting fracture patterns of the tested specimens vary between the different configurations. Selected example samples are provided in [Figs. 10](#) and [A.18](#).

In the aforementioned figures one specimen per configuration is shown exemplarily. The left image shows the front and the right picture the rear surface of the laminate. While the QUAD laminates show very similar fracture patterns, regardless of whether viewed from the front or rear, the DD laminates show different failure patterns on front and rear surface. This is a result of DD's asymmetric laminate stacking, which results in differently oriented plies on the surface of the DD specimens. The QUAD laminates show the symmetric fracture pattern

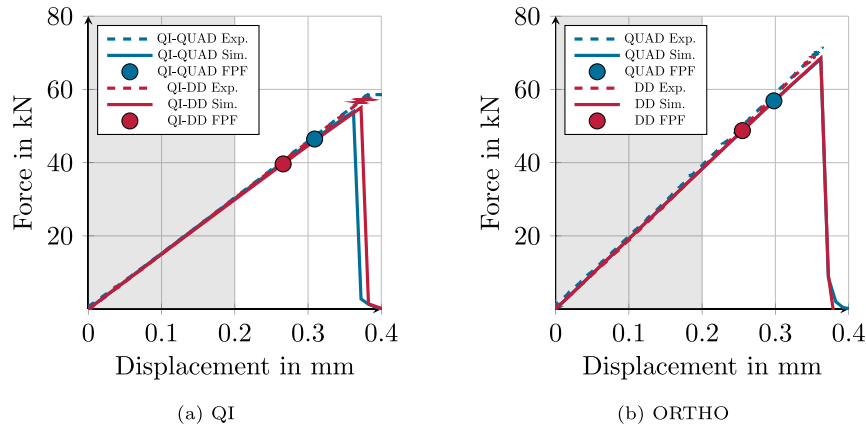


Fig. 11. Comparison of experimental and numerical force–displacement curves for open-hole tension (OHT) specimens made from 8552-IM7. The simulated first-ply failure (FPF) onset lies well beyond the conventional strain limit of $4000 \mu\epsilon$ bounds (equivalent to 0.20 mm displacement over a 50 mm gauge length).

(mirrored around the vertical axis) and a very similar fracture path on the outer most layer, as these layers have the same orientation on both sides. The DD laminates, in contrast, show different fracture paths on the outsides. Depending on the fiber orientation the paths run along the fiber or transverse, which indicates the different failure modes of the individual plies — FF1 or IFF1/IFF3. Therefore a DD laminate makes the different failure modes visible on the laminate's surface. This characteristic applies universally to all tested laminate configurations and is simply a result of the differing laminate architectures of QUAD and DD.

3.3. Numerical results

3.3.1. Progressive damage analysis

The results of the numerical PDA are presented and compared with the experimental findings from Section 3.2 in this section. Theoretical considerations suggest that both types of laminate should show similar behavior, cf. Table 4, and the experimental results agree with this. The question remains open as to whether the authors' method of progressive damage analysis, which was validated on QUAD laminates, can also predict the behavior of the DD test specimens and whether the failure behavior differs in detail. Note, that the following analysis, discussion and comparisons are focused solely on the 8552/IM7 material.

Fig. 11(a) shows the force–displacement plot for the QI specimens, while Fig. 11(b) presents the plot for the orthotropic ORTHO specimens. It is important to note that the comparison is made based on the actual displacement experienced by the 50 mm long section of the specimens modeled in the simulation, rather than on the crosshead displacement used in Fig. 6, which refers to 180 mm free sample length. The corresponding experimental displacement data, used for validating the simulations, were obtained through recorded DIC data, wherein the displacement between two points at $x = \pm 25$ mm from the hole's center (spanning a total distance of 50 mm) was evaluated. For the given samples, the gray areas in Figs. 11(a) and 11(b) visually represent the zone with displacements ≤ 0.20 mm, which is a conservative strain limit for undamaged laminates used in the composite design rules of aviation.

In general, regarding stiffness, the results show good agreement between simulations and experiments for both QI and ORTHO laminates. A small discrepancy is that the stiffness above 50% of the failure load is lower in the simulations compared to the experiments, which may indicate inaccuracies in the simulation approach. These discrepancies could be attributed to premature and excessive plastic flow or a rapid decrease in stiffness following failure initiation, which may be caused by low fracture toughness values.

Upon examining failure loads, slight deviations are summarized in Table 7. The mean experimental failure load for the QI QUAD laminate

Table 7

Comparison of mean experimental and numerical failure loads.

Series	Mean experimental Failure load in kN	Numerical Failure load in kN	Relative error Criterion (REC) in %
QI-QUAD	58.710 ± 1.196	53.956	−8.10
QI-DD	58.227 ± 2.590	55.032	−5.49
ORTHO-QUAD	70.759 ± 2.070	68.332	−3.43
ORTHO-DD	68.752 ± 1.764	68.556	−0.29

is 58.710 ± 1.196 kN, while the numerical prediction is 53.956 kN, resulting in a relative error of 8.10%. Similarly, for the QI DD laminate, the experimental failure load is 58.227 ± 2.590 kN, compared to a numerical value of 55.032 kN, leading to a relative error of 5.49%.

The mean experimental failure load for the ORTHO QUAD laminate is 70.759 ± 2.070 kN, with a calculated numerical failure load of 68.332 kN, resulting in a smaller relative error of 3.43%. The ORTHO DD laminate shows an experimental failure load of 68.752 ± 1.764 kN, which closely aligns with the numerical prediction of 68.556 kN, yielding a minimal relative error of 0.29%.

The slightly lower predicted stiffness before failure and the consistently lower predicted failure load indicate that the simulations are conservative overall. This enhances the usefulness of the simulations for design applications, as the predicted performance is on the safe side.

The executed numerical analysis allows for determining First-Ply-Failure (FPF) in the sample within the simulated samples. In this context, notable distinctions in behavior were observed between DD and QUAD.

For the QI QUAD specimen, the FPF occurs in an inner 90° ply, identified as IFF1, at the hole edge with a critical load of 46.5 kN. In contrast, the DD specimen exhibits FPF in the outermost 67.5° layer at the hole edge, occurring at a load of 39.65 kN, followed by failure in the -67.5° layer at 44.4 kN. In the ORTHO specimens, both QUAD and DD exhibit IFF1 as FPF at the hole edge in the outermost layers. However, the numerically determined FPF again occurs significantly earlier in the DD laminate. In this case, the FPF is detected in the outer 57.2° ply at a load of 48.7 kN, whereas for the ORTHO-QUAD specimen FPF in the outer 45° ply is only reached at a load of 56.9 kN.

To further quantify this margin, the onset loads of first IFF, i.e. FPF as discussed above, and first FF are compared in Table 8. For the QUAD laminates, the two events occur close together: for QI-QUAD, IFF and FF are predicted virtually at the same load step (within the resolution of the evaluated field-output increments), while for ORTHO-QUAD they are separated by only 1.98 kN ($\approx 3.5\%$). In contrast, for both DD laminates the onset of FF occurs considerably later than IFF, with a margin of 7.89 kN ($\approx 20\%$) for QI-DD and 8.09 kN ($\approx 17\%$) for

Table 8

Comparison of the numerically predicted onset loads of first interfibre failure (IFF) and first fiber failure (FF).

Series	First	
	IFF in kN	FF in kN
QI-QUAD	46.455	46.455
QI-DD	39.653	47.542
ORTHO-QUAD	56.876	58.856
ORTHO-DD	48.748	56.838

ORTHO-DD. This confirms and quantifies the larger margin between first (matrix-dominated) damage and fiber failure observed for the DD laminates. Combined with the finding that FPF in the DD laminates consistently occurs in the outermost, visually inspectable ply, this further substantiates the potential inspection benefit of the DD laminate architecture discussed above.

Overall, the results indicate that the PDA approach using Cuntze's FMC is suitable for analyzing DD laminates, even though it has predominantly been validated for QUAD laminates in earlier studies. This finding underlines the versatility of the material model, developed in [22], in capturing the complex failure mechanisms associated with different laminate architectures. Despite the apparent similarity in the global mechanical behavior of the laminate architectures, subtle differences in the failure behavior could be revealed by the numerical analysis.

In the present study, the DD laminate show a larger margin between FPF and LPF, which is in line with the larger margin between the onset of first IFF and first FF discussed above (see Table 8). However, the total failure loads are found nearly independent from the choice between QUAD and DD. To add, FPF in the DD laminates is consistently detected in the outermost layer in the simulations. If further investigations can prove this also for other QUAD and DD laminates as well as for other load cases, DD laminates could have a benefit in terms of inspection. While FPF in DD laminates occurs well above the typical in-service loads, together with the outermost plies failing first, there is a larger safety margin between first damage visibility and total failure of the structure.

3.3.2. Strain field comparisons for FEM and DIC results

This section provides comparisons of FEM results and the DIC strain fields, captured during the tests. The plots focus on axial strain ϵ_x and shear strain γ_{xy} . The axial strain plots feature a consistent legend range of $[0.2\% \leq \epsilon_x \leq 0.6\%]$, while shear strain plots feature a $[-0.2\% \leq \gamma_{xy} \leq 0.2\%]$ legend.

The postprocessing and illustration has been executed, as described by Koord et al. [44]. For sake of conciseness, the following comparison is limited to 8552/IM7 samples, even though DIC data for M21E/IMA samples has been captured.¹

A meaningful comparison of DIC and FEM results, requires the selection of adequate force levels. It is important to compare states, where all plies can be considered intact, as after ply failure, strain redistribution propagates.

For the following comparisons, two force levels are selected, which are slightly lower than the numerically determined FPF occurrences. For the QI samples a tensile-load of 40 kN is adopted. For the ORTHO case a load of 48.75 kN is used.

Fig. 12 shows strain ϵ_x along the tensile direction. DIC image of DD and QUAD show no remarkable differences, which is in accordance with the force-displacement graphs. The simulation result, show a satisfying match in the Center region. Conspicuous strain hot-spots, diagonally located at the sample corners cannot be fully explained.

Fig. 13 shows shear strain field γ_{xy} in a similar format. Overall, a good match is observed between DIC and simulations. The simulations, consistently shows larger high-strain regions, compared to DIC, while strain magnitudes are well met. The circumscribing high-strain frames, in the FEM results, are considered unrealistic edge effects, which is outlined in Appendix A.5 in the Appendix in more detail.

Fig. 14 shows a shaded re-plot of Fig. 13, overlaid with the actual ply orientations in the laminates. The simulation results clearly show the effect of the different laminate compositions. The DIC data show less clear differences. However, a slight rotation can be anticipated for DD as well.

The ϵ_x fields of the ORTHO laminate show very similar strain-field characteristics, as expected for the same test scenario. Again the characteristics of DIC and FE are very similar.

Fig. 16 shows an overlay of ϵ_x plot with the actual fiber orientations in the specific laminates.

The shear strains for the ORTHO laminates are shown in Fig. 17. DIC results show slightly smaller high-strain regions around the hole for DD. The FE results again overestimate the high-strain region areas, while the local strain magnitudes are met well.

The DD FEM result shows again the slight clockwise rotated strain field. Overall, the QUAD samples show double symmetric strain fields for axial and shear strain, with x- (longitudinal) and y-axis (transversal) being symmetry lines. DD samples shows double-symmetric field for axial strain and a point symmetric field shape for shear strain, with respect to the hole center.

4. Conclusion

The present study focused on an OHT test campaign, examining QUAD and stiffness-equivalent DD laminates. The study examined QI and ORTHO laminates. Samples were made from the two Hexcel prepreg systems 8552/IM7 and M21E/IMA. Double-Double equivalents were determined for both materials. Tests were conducted for both materials, which DIC in place. Samples made from 8552/IM7 were in focus in accompanying analyses. A FPF-envelope based limit strain estimation, using Cuntze's FMC has been presented for 8552/IM7 laminates, to assess test results, compared to pristine samples without holes. PSCC were determined. More-advanced numerical simulation were executed for the 8552/IM7 cases, with a previously developed and validated comprehensive simulation model. The simulations were executed with ABAQUS, in combination with a VUMAT, which covers a PDA, with Pseudoplasticity aspects. The present study led to the following conclusions:

- The tested six samples per configuration showed marginal sample-to-sample variation. Failure loads of QUAD laminates and their DD equivalents are found almost identical, with 0.8% deviation for QI and 2.8% deviation for the ORTHO 8552/IM7 laminates.
- The QI OHT sample showed failure at around 58 kN, while the ORTHO laminates failed at an average of 69.75 kN.
- Average failure loads are found very similar, while error bar ranges for six samples of equivalent DD/QUAD cases overlap. This implies very similar strength values for the two laminate architectures DD and QUAD.
- An FPF analysis, based on Cuntze's FMC, for pristine laminates, predicted axial strain 8552/IM7 limits $\epsilon_x \leq 6258$ microstrain for ORTHO laminate and 6132 microstrain for QI.
- M21E/IMA samples showed 20%–30% higher failure strain values (see Fig. 7) compared to corresponding 8552/IM7 samples
- Failed M21E/IMA samples showed a more 'aggressive' fiber/ply separation compared to 8552/IM7, (see Figs. 8 and A.18), with ply segments expelling from the OHT sample to the sides.
- The executed simulations verify that DD laminate can be simulated with the same methods that have been validated earlier for conventional laminates. Comparisons of simulated and

¹ Note, that M21E/IMA samples can potentially be provided on request.

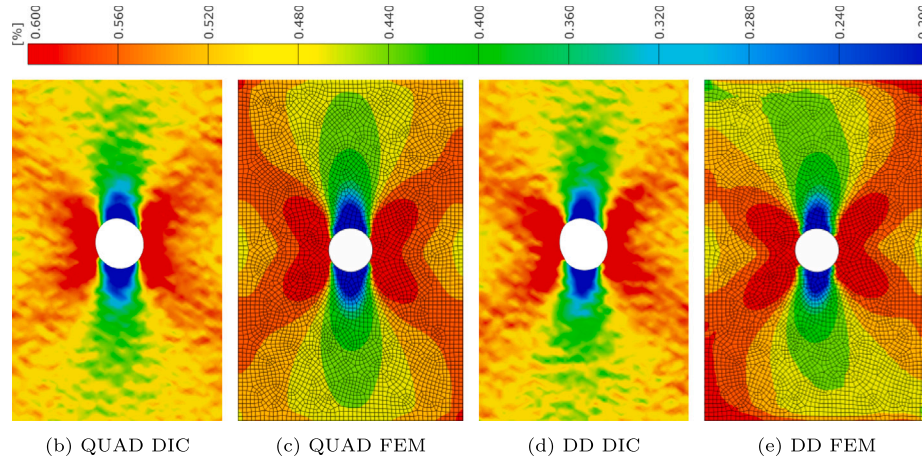


Fig. 12. ϵ_x strain fields from DIC and FEM for 8552/IM7 QI configurations.

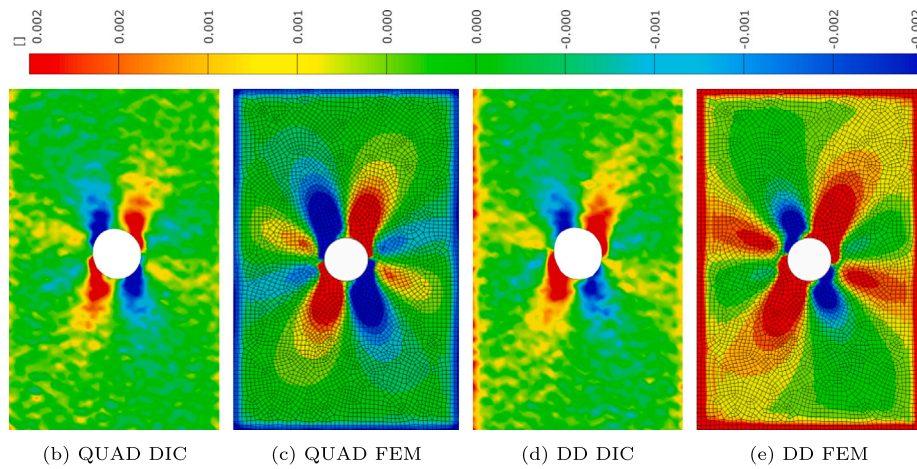


Fig. 13. γ_{xy} strain fields from DIC and FEM for 8552/IM7 QI configurations.

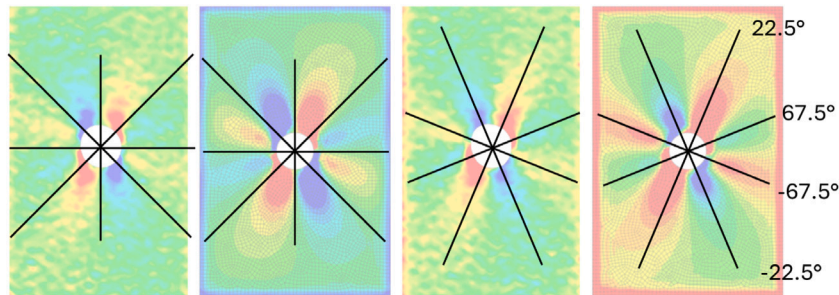


Fig. 14. QI γ_{xy} with overlaid ply orientations in laminate.

DIC-measured Uniaxial ϵ_x and γ_{xy} surface strain fields substantiate this.

- The simulations slightly underpredict the experimental tests for all cases, which is positive, as the simulations provide conservative estimates.
- Overall, the results indicate that the PDA approach using Cuntze's FMC is suitable for analyzing DD laminates, even though it has predominantly been validated for QUAD laminates in earlier studies.

- DIC and FEM results show strain of around 0.6% (6000 microstrain) in load direction, adjacent to the hole.
- DIC and simulation results show, how DD's asymmetric laminate architecture effect strain-field patterns around the samples' hole.
- While FPF in DD laminates occurs well above the typical in-service loads, together with the outermost plies failing first, there is a larger safety margin between first damage visibility and total failure of the structure.

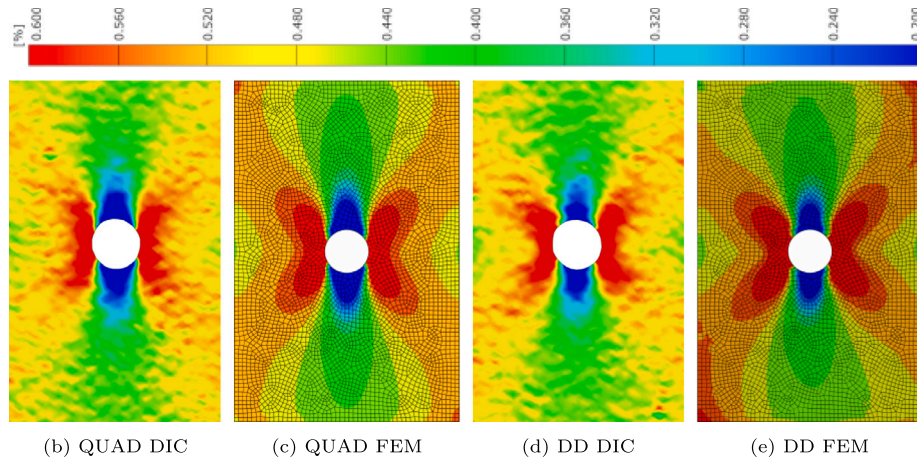


Fig. 15. ϵ_x strain fields from DIC and FEM for 8552/IM7 ORTHO configurations.

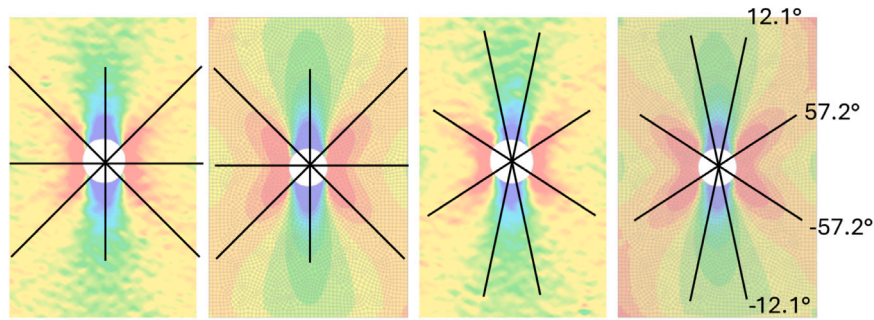


Fig. 16. ORTHO ϵ_x with overlaid ply orientations in laminate.

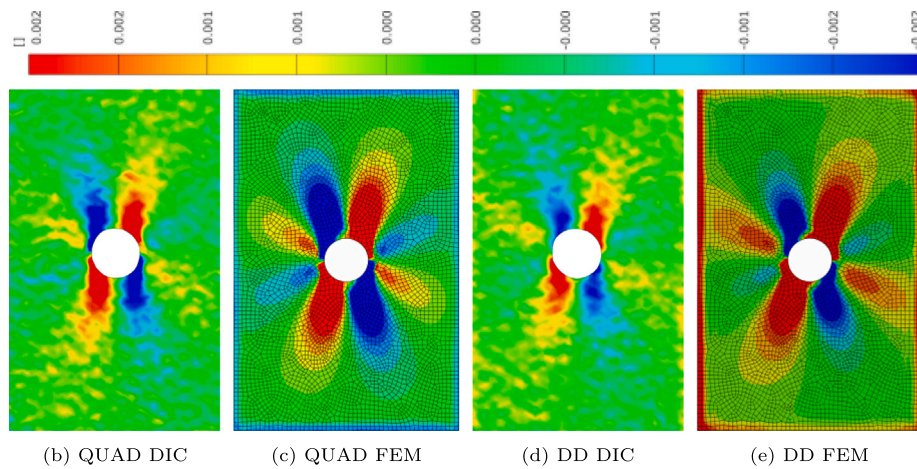


Fig. 17. γ_{xy} strain fields from DIC and FEM for 8552/IM7 ORTHO configurations.

CRediT authorship contribution statement

Y. Boose: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **E. Kappel:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **J. Kosmann:** Investigation. **O. Völkerink:** Writing – review & editing, Writing – original draft, Validation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

A.1. CLT from Nettles

From Nettles [12]

$$v_{xy} = \frac{A_{12}}{A_{22}} \quad (A.1)$$

$$[a] = [A]^{-1} = \frac{1}{A_{11}A_{22} - A_{12}^2} \begin{bmatrix} A_{22} & -A_{12} & 0 \\ -A_{12} & A_{11} & 0 \\ 0 & 0 & \frac{A_{11}A_{22} - A_{12}^2}{A_{66}} \end{bmatrix} \quad (A.2)$$

$$a_{11} = \frac{A_{22}}{A_{11}A_{22} - A_{12}^2}, \quad a_{12} = \frac{-A_{12}}{A_{11}A_{22} - A_{12}^2} \quad (A.3)$$

$$\frac{a_{12}}{a_{11}} = \frac{-A_{12}}{A_{22}} = -v_{xy} \quad (A.4)$$

A.2. M21E/IMA data collection

The present section summarizes the M21E/IMA specific data, calculations and experiments (see Table A.9 and Table A.10)

DIC data of the M21E/IMA samples were captured. Those can be, potentially provided on demand.

A.3. Governing equations of the material model used for progressive damage analyses

This section summarizes the governing equations of the material model used for the progressive damage analysis, following [22].

Damage initiation using Cuntze's failure-mode concept

Cuntze's FMC [24,45] evaluates five mode-specific stressing efforts $E f f^{mode}$, each normalized by the mode-associated ply strength:

Fiber failure due to tension

$$F F 1 : E f f^{\parallel \sigma} = \sigma_1 / R_{\parallel}^t \quad (A.5)$$

Fiber failure due to compression

$$F F 2 : E f f^{\parallel \tau} = \sigma_1 / R_{\parallel}^c \quad (A.6)$$

Table A.9

Laminate stackings M21E.

ID	Quantity	Material	Laminate stacking
QUAD, QI	6	M21E	[0, 45, 90, 135] _{3s}
DD, QI	6	M21E	[22.5, -67.5, -22.5, 67.5] ₆
QUAD, ORTHO	6	M21E	[0, 45, 0, 135, 0, 45, 90, 135, 0, 45, 0, 135] _s
DD, ORTHO	6	M21E	[8.5, -53.4, -8.5, 53.4] ₆

Table A.10

Ply properties and Engineering constants for M21E/IMA cases used for the analysis. Values in (...) indicate measured thicknesses.

ID	E_x in GPa	E_y in GPa	G_{xy} in GPa	v_{xy}	$t_{ply/lam}$ in mm
M21E/IMA UD ply	154.0	8.5	4.2	0.35	0.184
QUAD QI	57.59	57.59	21.8	0.321	4.416
DD QI	57.59	57.59	21.8	0.321	4.416
QUAD ORTHO	77.95	35.00	21.80	0.518	4.416
DD ORTHO	77.89	34.96	21.84	0.519	4.416

Table A.11

Assignment of failure modes to damage variables.

Failure mode	FF1	FF2	IFF1	IFF2	IFF3
Damage variable	d_{ft}	d_{fc}	d_{mt}	d_{mc}	d_s

Interfibre failure due to tension

$$I F F 1 : E f f^{\perp \sigma} = \sigma_{eq}^{\perp \sigma} / R_{\perp}^t, \quad \sigma_{eq}^{\perp \sigma} = (\sigma_2 + \sigma_3) + \sqrt{(\sigma_2 + \sigma_3)^2 + 4\tau_{23}^2} \quad (A.7)$$

Interfibre failure due to compression

$$I F F 2 : E f f^{\perp \tau} = \sigma_{eq}^{\perp \tau} / R_{\perp}^c, \quad \sigma_{eq}^{\perp \tau} = b_{\perp \perp} \sqrt{(\sigma_2 + \sigma_3)^2 + 4\tau_{23}^2} + (b_{\perp \perp} - 1)(\sigma_2 + \sigma_3) \quad (A.8)$$

Interfibre failure due to shear

$$I F F 3 : E f f^{\perp \parallel} = \sigma_{eq}^{\perp \parallel} / R_{\perp \parallel}, \quad \sigma_{eq}^{\perp \parallel} = \left(\frac{\sqrt{b_{\perp \parallel}^2 I_{23-5}^2 + 4R_{\perp \parallel}^2 (\tau_{13}^2 + \tau_{12}^2)} + b_{\perp \parallel} I_{23-5}}{2R_{\perp \parallel}^3} \right)^{1/2} \quad (A.9)$$

with $I_{23-5} = 2\sigma_2\tau_{12}^2 + 2\sigma_3\tau_{13}^2 + 4\tau_{23}\tau_{13}\tau_{12}$.

Here $R_{\parallel}^t$, $R_{\perp}^t$ and $R_{\perp \parallel}$ are the fiber-, transverse- and in-plane shear strengths, while $b_{\perp \perp}$ and $b_{\perp \parallel}$ are friction values. The five modes interact through a global stressing effort using the interaction exponent m :

$$E f f^m = (E f f^{\parallel \sigma})^m + (E f f^{\parallel \tau})^m + (E f f^{\perp \sigma})^m + (E f f^{\perp \tau})^m + (E f f^{\perp \parallel})^m \quad (A.10)$$

Damage initiates at an integration point once $E f f^m \geq 1$; the mode with the highest individual effort governs the initial degradation.

Damage evolution and crack-band regularization

Damage progression is modeled with a displacement-controlled, linear energy-based degradation law adapted from Lapczyk and Hurtado [46], following [22]. For each failure mode $M \in \{ft, fc, mt, mc, s\}$ (associated with FF1, FF2, IFF1, IFF2, IFF3, respectively, via Table A.11), a scalar damage variable is calculated as:

$$d_M = \frac{\delta_{M,eq}^f (\delta_{M,eq} - \delta_{M,eq}^0)}{\delta_{M,eq}^f (\delta_{M,eq}^f - \delta_{M,eq}^0)}, \quad \delta_{M,eq}^0 \leq \delta_{M,eq} \leq \delta_{M,eq}^f \quad (A.11)$$

The equivalent strain at damage initiation and at final failure ($d_M = 1$) are:

$$\delta_{M,eq}^0 = \frac{\epsilon_M^0}{L_c}, \quad \delta_{M,eq}^f = \frac{2G_M}{\sigma_M^0 L_c} \quad (A.12)$$

where ϵ_M^0 and σ_M^0 are the strain and stress at the onset of damage (stored at the increment in which $E f f^m = 1$ is reached), G_M is the mode-specific fracture toughness, and L_c is the characteristic element length. In accordance with the crack-band approach of Bažant and Oh [27], L_c regularizes the dissipated fracture energy with respect to the finite-element size, thereby mitigating mesh dependency of the softening response.

A.4. Model length study

To verify that the reduced 50 mm model length does not affect the results, a preliminary comparison was performed against a longer 100 mm model using the QI-QUAD configuration. The predicted failure loads differ by only 0.18% (53.956 kN for the 50 mm model vs. 54.053 kN for the 100 mm model). As a qualitative supporting check, Fig. A.19 additionally compares the maximum principal strain (LE, Max. Principal) contours of the outermost ply in the region of the hole immediately prior to failure. Both models show closely matching

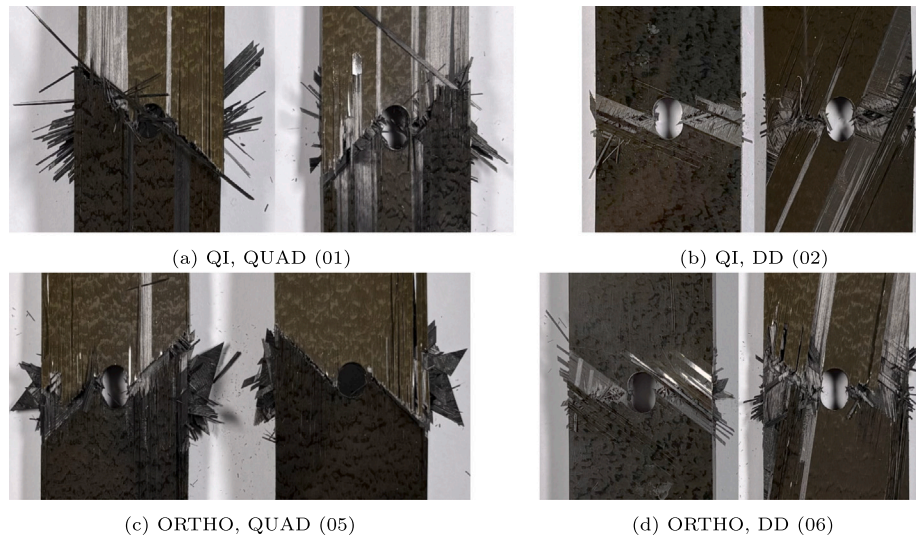


Fig. A.18. Fracture patterns on front and back of the different M21E laminate configurations.

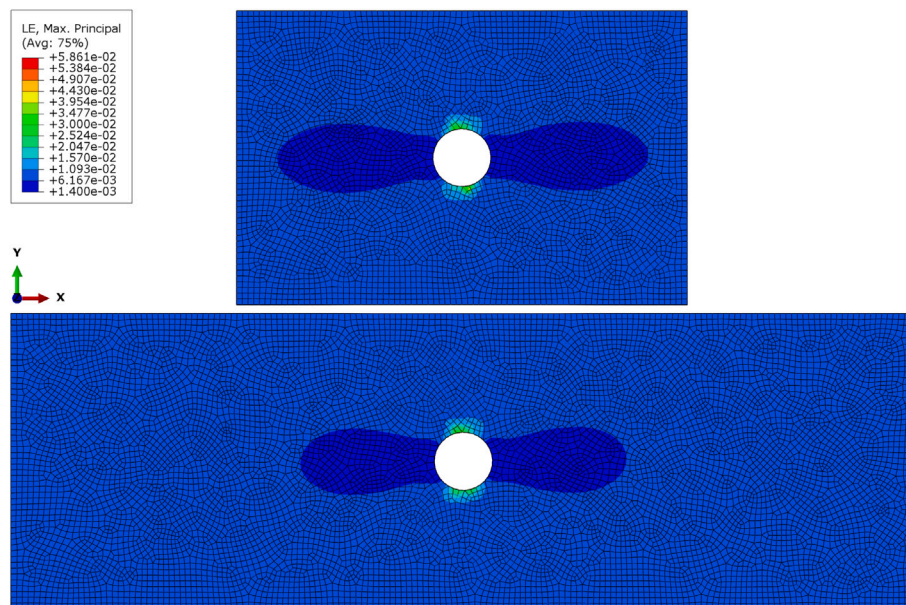


Fig. A.19. Maximum principal strain contours of the outermost ply in the region of the hole, prior to failure, for the QI-QUAD configuration: 50 mm model (top) vs. 100 mm model (bottom).

strain magnitudes and distributions around the hole, confirming that the local field solution is not affected by the reduced model length. The computation time until failure, however, differs considerably between both model lengths: 14:37 h (50 mm) compared to 47:12 h (100 mm), a reduction by a factor of ≈ 3.2 . Both simulations were performed on the TU Braunschweig Phoenix cluster (2× Intel Xeon E5-2640v4 CPUs, 8× DDR4-2400 8 GB RAM per node), using 20 CPUs per Abaqus/Explicit run.

A.5. Mesh analysis ‘high-strain’ γ_{xy} ring

A more detailed analysis has been performed to examine the conspicuous high-strain ring in the γ_{xy} simulation results (see Figs. 13

and 17). The ring is considered physically unrealistic, which is also supported by the fact that it has not been observed in the DIC results.

The analysis reveals, that the high-strain ring is related to the pursued meshing strategy, with only a single C3D8R element per CFRP ply. Fig. A.20 shows the DD-Ortho file, with some manually hidden FE elements. Conform to the DD laminate pattern one can see high-shear strain rings around the sample with inverted sign, related to the [12.1, -57.2, -12.1, 57.2] building block.

Data availability

Data will be made available on request.

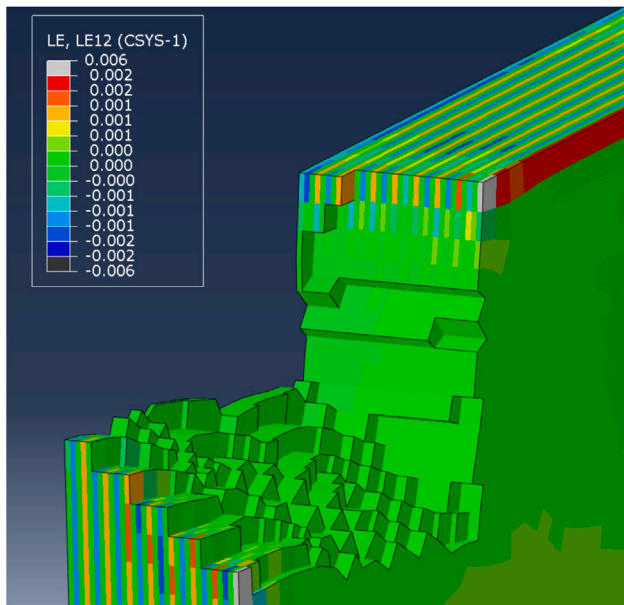


Fig. A.20. DD-Ortho result, with some manually removed C3D8R solid elements.

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