A SHORTHAND STRENGTH ANALYSIS IN SIMCENTER 3D TO PREDICT THE FIRST-PLY FAILURE TEST LOADS IN CASE OF FOUR POINT BENDING LAMINATE COUPONS

Marius N. Baba[1]

[1] Transilvania University of Brașov, Brașov, ROMÂNIA, mariusbaba@unitbv.ro

Abstract: *The purpose of this paper is to describe a shorthand strength analysis procedure carried out with the help of Simcenter 3D and intended to predict the first-ply failure test loads for two distinct CFRP laminate layup configurations (i.e. an off-axis* $[45_{12}]_T$ *and a symmetrically balanced cross-ply* $[45_3/\text{-}45_3]_S$*), both subjected to four-point bending. The results are compared against the experimental test data reported in literature and also with those obtained in the present work based on linear FEA performed in Simcenter 3D using layered shell elements with the appropriate boundary conditions. A special emphasis is put on the use of Laminate Modeler module for composites simulation in Simcenter 3D, provided that it allows a straightforward definition of fibre-reinforced laminate composites, an affordable assignment of laminate properties to the coupons being virtually tested and also a quick and easily evaluation of the laminate's capability to withstand the applied loads prior to run the FE solution. Finally, some comments and valuable conclusions will be presented on the accuracy of results with respect to effectiveness of the aforementioned assessment approaches as well as the related key modeling parameters.*
Keywords: *Simcenter 3D, Finite Element Analysis (FEA), CFRP laminate coupons, AS4/8552, Four-point bending test, First-ply failure, Strength Ratio (SR).*

1. INTRODUCTION

The idea to simulate the bending tests of composite laminates by analytical or numerical methods is not a new one, numerous studies more or less recent being devoted to this area of research [3], [5], [6], [7], [9], [10], [11], [12], [13]; and the main argument relies on the fact that through their proper application it is possible to substantially reduce the costs associated with the necessity of carrying further time-consuming and destructive experiments. In such a context one may also note that depending on the modelling approach and the nature of the applied failure criterion (e.g. first-ply-failure, progressive damage, multiscale progressive failure, etc.), the complexity of the analysis, the required CPU time as well as the completeness of results might look quite different. Although the former has some well-known limitations, in the sense that the matrix and fiber properties are smeared to create a single set of homogenized lamina properties that are used to evaluate the first-ply-failure response characteristics, it is advantageous as it is numerically straightforward, less time-consuming and ease of use, at least in case of preliminary design-to-cost evaluations. Factually, the method takes the loads applied to the laminate and employs a certain laminate plate theory to compute the stresses and strains in each ply. The load at which any one of the plies in the layup fails is then determined based on a specific failure criterion (e.g. Max Stress, Hill, etc.).

The analysis of Koc and al. [12], is particularly relevant to the testing methodology under discussion here since it addresses both simulation and experiments of four-point bending test carried on carbon fibre-reinforced composite laminates. Within their investigations a test setup was designed and constructed with the aim to study the failure behavior of carbon fibre-reinforced laminate coupons. Both off-axis $[\theta_{12}]_T$ laminates as well as symmetrically balanced angle-ply $[\theta_3/\text{-}\theta_3]_S$ laminates were considered. The experiments were performed and simulated using an analytical approach based on Classical Laminate Theory (CLT) as well as the Finite Element Analysis (FEA), and the maximum allowable values of the applied bending moment, as a function of fibre orientation angle, have been reported using different failure criteria.

In such a context, as pointed out by Wowk et al. [8], it must emphasized that the typical four-point bending test setup in which an angle-ply laminate coupon is supported and loaded by rollers it is not likely to produce a representative pure bending stress state, as eventually expected. This comes out mainly due to the occurrence of internal forces induced by the interactions of supporting rollers with the coupled flexural-twisting deformations that the off-axis and angle-ply laminates are experiencing in. Even in case of thin laminates, the effects of these internal forces can be significant, and thus, must be considered in the prediction of first-ply failure flexure loads.

The objective of the current work is to describe a shorthand strength analysis procedure underlying the Laminate Modeler module build-in Simcenter 3D software and intended to predict the loads required to produce first-ply failure in two distinct layup configurations (i.e. $[45_{12}]_T$ and $[45_3/\text{-}45_3]_S$) tested to four-point bending under static loading conditions. The analysis results are compared against the experimental test data reported in [12], and also with those obtained in the current work based on FEA in Simcenter 3D using layered shell elements with appropriate boundary conditions. Finally, some comparative comments and conclusions are presented on their accuracy. A special emphasis is put on the use of Simcenter 3D software for Finite Element Analysis (FEA), provided that it allows a straightforward definition of fibre-reinforced laminate composites by means of either zone-based modelling or ply-based modelling, and if necessary, the combination of both approaches. As will be pointed out in what follows, it also enables an effective evaluation of laminate's capability to withstand the membrane forces, bending moments, transverse shear forces and temperature loads, prior to run the FE solution.

2. EXPERIMENTAL BENCHMARK

To investigate the accuracy of the proposed strength assessment an experimental four-point bending benchmark procedure was used. For this study, the test data taken from Koc and al. [12], for two particular layups (i.e. an off-axis $[45_{12}]_T$ and a balanced cross-ply $[45_3/\text{-}45_3]_S$), made of 0.184 *mm* thick AS4/8552 unidirectional prepregs, are considered. As is described in their paper, the laminate coupons of 48 *mm* width, 115 or 135 *mm* length and 2,208 *mm* thickness were tested to static four-point bending by means of a test setup provided with a loading system sought to minimize the occurrence of delaminations and to increase the likelihood of intralaminar failure modes. In this regard, as shown in Figure 4, the test setup upper supports were symmetrically placed at a distance of 56 *mm* from each other (denoted by *b*) while the next distances to the lower supports (denoted by *a*) were taken equal to 20 *mm*.
The values of the elastic and mechanical properties used to define the composite laminate test coupons under investigation are described in Table 1 [12]. The fibre (AS4) and the epoxy matrix (8552) considered hereafter are supposed to be similar with the ones reported in HexPly 8552 UD carbon prepregs data sheet [15].

3. METODOLOGY

Since the results presented hereafter will be mainly expressed in terms of Strength Ratio (SR), it is worth to mention that it is nothing but a scalar given by the ratio between the maximum allowable load which can be safely applied and the actual applied load. For instance, a SR of 1,5 indicates that the laminate coupon will withstand a load that is one and a half as large as the one it was analyzed for. Thus, it can be effectively used to measure the first-ply failure bending loads of laminate coupons involved within the present analysis, based on several widely used failure criteria (i.e. Maximum Stress, Maximum Strain, Hoffman, Hill and Tsai-Wu).

3.1. The shorthand strength analysis

An effective build-in laminate evaluation module is provided by Simcenter 3D software. It enables a quick analysis of composite laminates subjected to out-of-plane loads, in-plane loads and thermal loading, prior to obtain the FE solution.

Table 1: Mechanical and strength properties of AS4/8552 [12]

Property type	Symbol	Value	Unit
Young modulus in fibre direction	E_1	134,8	*GPa*
Young modulus in transverse direction	E_2	9,6	*GPa*
Poisson's ratio	ν_{12}	0,32	-
	ν_{23}	0,487	-
Shear modulus	$G_{12} = G_{23}$	5,3	*GPa*
Tensile mechanical strength in fibre direction,	X_T	2207	*MPa*
Compressive mechanical strength in fibre direction	X_C	1531	*MPa*
Tensile mechanical strength in transverse	X_T	80,7	*MPa*
Compressive mechanical strength in transverse	X_C	199,8	*MPa*
Longitudinal shear strength	S_{12}	114,5	*MPa*
Transverse shear strength	S_{23}	102,7	*MPa*
Density	ρ	1590	kg/m^3

In fact, the laminate module built-in Simcenter 3D detaches a virtually laminate sequence from the composite under question and inspects its strength behavior layer-by-layer. As it is carried out based on the first-ply-failure methodology it is intended to quickly determine whether failure is about to or has already occurred in one of the plies. With regard to this, it should be mentioned that it does not mean the ultimate failure of the laminate has proceeded. In fact, those plies which have not failed yet may continue to carry on the applied loads, beyond the first-ply-failure.

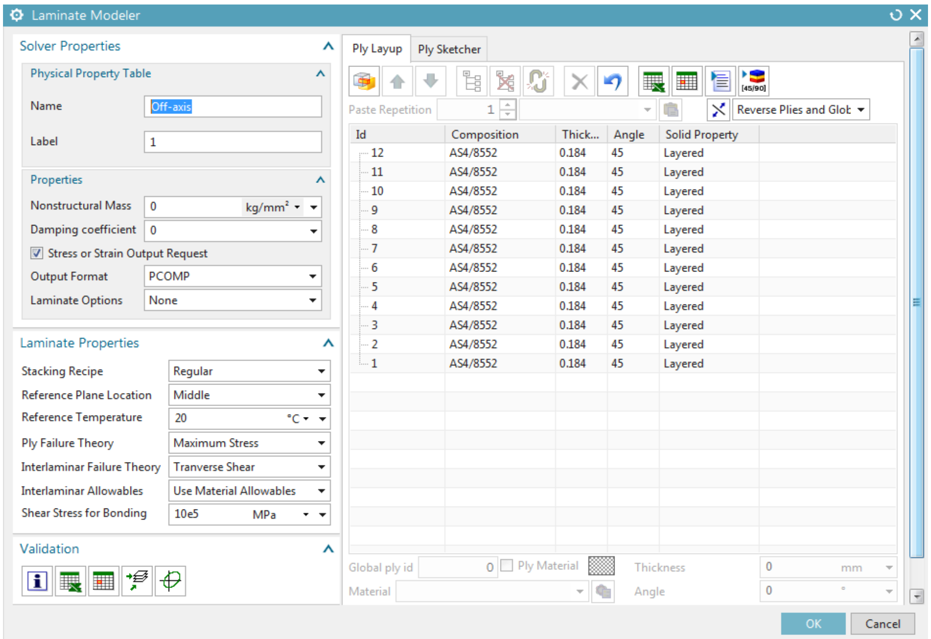


Figure 1: Input and output options in the Laminate Modeler (Simcenter 3D)

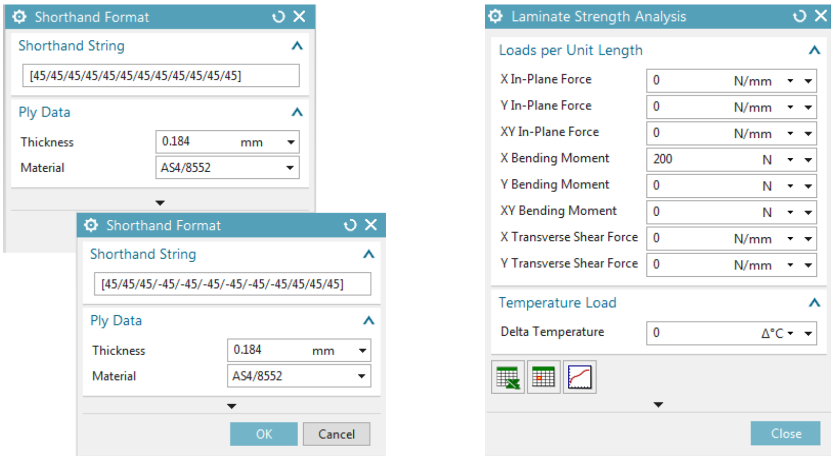
In the present work, a macroscopic analysis approach is considered; hence each ply is explicitly defined as a transversely orthotropic material with the properties reported in Table 1. Assuming an initial guess for the bending moment at first-ply failure event, let it be $M = 9600\ Nmm$, the applied bending moment per unit length m_{xx}, is obtained as:

$$m_{xx} = \frac{M}{w} = 200\ Nmm/mm \tag{1}$$

and the assumed value of the total applied load becomes:

$$F_{tot} = \frac{2M}{a} = 960\ N \tag{2}$$

where w is the coupon's width and a is the distance between one of the upper supports (loading point) and its closest lower support (see Figure 4).



a) Import Layup in Shorthand Format   b) Analyze the Laminate Strength

Figure 2: Layup definition and laminate strength analysis dialog boxes (Simcenter 3D)

After defining the orthotropic mechanical and the strength properties using Manage Materials dialog box (under Home tab), a new dummy (empty) FEM in Simcenter 3D has to be created. The Laminate Modeler module in Simcenter 3D is launched through the selection of Laminate Physical Property dialog box (under the Laminate tab). All the available input and output options are displayed in Figure 1. As can be seen, the Stress or Strain Output Request is checked, PCOMP is taken as Output Format, a dummy Transverse Shear Interlaminar Failure

Theory is considered and an arbitrary high value for Bonding Shear Stress is used. The feature Import Layup Using Shorthand Format from the top-right corner of Ply Layup tab in Laminate Modeler module, allows a quickly definition of stacking in a shorthand string fashion as exemplified in Figure 2-a.

Ply Results Table													
Element	Ply	Global Ply	Computation	Laminate	Failure Theory	Stresses					Failure Index	Strength Ratio	Margin of Safety
Id	Id	Id	Location	Name	Ply	Stress11	Stress22	Stress12	Maximum Principal	Minimum Principal	Max Stres:	Max Stres:	Max Stress
						mN/mm^2	mN/mm^2	mN/mm^2(	mN/mm^2(	mN/mm^2(	Unitless	Unitless	Unitless (%)
1	1	1	Bottom	Laminate	Maximum Stress	-1,23E+05	-1,23E+05	1,23E+05	1,16E-09	-2,46E+05	1,075	0,930	-6,964
1	1	1	Middle	Laminate	Maximum Stress	-1,13E+05	-1,13E+05	1,13E+05	9,90E-10	-2,26E+05	0,985	1,015	1,494
1	1	1	Top	Laminate	Maximum Stress	-1,03E+05	-1,03E+05	1,03E+05	9,90E-10	-2,05E+05	0,896	1,116	11,644
1	2	2	Bottom	Laminate	Maximum Stress	-1,03E+05	-1,03E+05	1,03E+05	9,90E-10	-2,05E+05	0,896	1,116	11,644
1	2	2	Middle	Laminate	Maximum Stress	-9,23E+04	-9,23E+04	9,23E+04	9,90E-10	-1,85E+05	0,806	1,240	24,048
1	2	2	Top	Laminate	Maximum Stress	-8,20E+04	-8,20E+04	8,20E+04	8,44E-10	-1,64E+05	0,717	1,396	39,554
1	3	3	Bottom	Laminate	Maximum Stress	-8,20E+04	-8,20E+04	8,20E+04	8,44E-10	-1,64E+05	0,717	1,396	39,554
1	3	3	Middle	Laminate	Maximum Stress	-7,18E+04	-7,18E+04	7,18E+04	7,86E-10	-1,44E+05	0,627	1,595	59,491
1	3	3	Top	Laminate	Maximum Stress	-6,15E+04	-6,15E+04	6,15E+04	6,98E-10	-1,23E+05	0,537	1,861	86,073
...													
1	9	9	Bottom	Laminate	Maximum Stress	4,10E+04	4,10E+04	-4,10E+04	8,20E+04	8,73E-11	0,508	1,967	96,717
1	9	9	Middle	Laminate	Maximum Stress	5,13E+04	5,13E+04	-5,13E+04	1,03E+05	-5,82E-11	0,635	1,574	57,374
1	9	9	Top	Laminate	Maximum Stress	6,15E+04	6,15E+04	-6,15E+04	1,23E+05	-5,82E-11	0,763	1,311	31,145
1	10	10	Bottom	Laminate	Maximum Stress	6,15E+04	6,15E+04	-6,15E+04	1,23E+05	-5,82E-11	0,763	1,311	31,145
1	10	10	Middle	Laminate	Maximum Stress	7,18E+04	7,18E+04	-7,18E+04	1,44E+05	-1,16E-10	0,890	1,124	12,410
1	10	10	Top	Laminate	Maximum Stress	8,20E+04	8,20E+04	-8,20E+04	1,64E+05	-2,04E-10	1,017	0,984	-1,642
1	11	11	Bottom	Laminate	Maximum Stress	8,20E+04	8,20E+04	-8,20E+04	1,64E+05	-2,04E-10	1,017	0,984	-1,642
1	11	11	Middle	Laminate	Maximum Stress	9,23E+04	9,23E+04	-9,23E+04	1,85E+05	-2,91E-10	1,144	0,874	-12,570
1	11	11	Top	Laminate	Maximum Stress	1,03E+05	1,03E+05	-1,03E+05	2,05E+05	-3,49E-10	1,271	0,787	-21,313
1	12	12	Bottom	Laminate	Maximum Stress	1,03E+05	1,03E+05	-1,03E+05	2,05E+05	-3,49E-10	1,271	0,787	-21,313
1	12	12	Middle	Laminate	Maximum Stress	1,13E+05	1,13E+05	-1,13E+05	2,26E+05	-2,33E-10	1,398	0,715	-28,467
1	12	12	Top	Laminate	Maximum Stress	1,23E+05	1,23E+05	-1,23E+05	2,46E+05	-4,07E-10	1,525	0,656	-34,428

Figure 3: Sample screen capture of ply results table exported in Excel format (the case of unidirectional off-axis $[45_{12}]_T$ test coupon)

To perform the strength analysis, by clicking on the option Analyze Laminate Strength in the Validation field of Laminate Modeler module, a new dialog box is displayed as shown in Figure 2-b, that is intended to input the applied loads per unit length and also to generate the analysis results (e.g. Ply Results Table, Strength Ratio, etc.) in an Excel spreadsheet format.

The operation of Simcenter 3D Laminate Composites module is based on the First-order Shear Deformation Theory (FSDT) [14]. It accounts for shear effects and, due to that, it can describe in a satisfactory way the kinematic of a generic laminate test coupon under flexure loading. Nevertheless, FSDT considers linear shape functions to describe the in-plane displacements through the laminate thickness, which results in constant shear strains. Moreover, the plane sections perpendicular to the neutral plane are considered to remain plane but no longer perpendicular upon deformation, each ply behaves under plane-stress condition, the plies are ideally glued, and not the last, deformations and displacements are assumed to be small.

The composite stiffness matrix $[ABD]_{6x6}$ is used to compute the strains from the resultant shell stresses and the transverse shear matrix $[S]_{2x2}$ defines the correspondence of composite strain energy to the strain energy associated with the distribution of shear stresses caused by in-plane bending and shear.

According to Wowk et al. [8], the internal torsional load induced in angle-ply laminates subjected to four-point bending can be determined based on the $[ABD]_{6x6}$ stiffness matrix. That is, the term D16 describes how much twisting deformation occurs when an external moment per unit length, m_{xx}, is applied in the fiber direction of laminate, while the term D66 defines the amount of torsional loading required to twist a laminate, or for the present case of four-point bending, it can be seen as the amount of torsional loading required to untwist the laminate back to its initial flat shape. These terms can be effectively used to determine the internal torsional load induced as a result of interaction to the roller restrains of four-point bending test setup. In fact, the same authors described a straightforward methodology intended to study the induced torsional load as a function of the ratio D16/D66, for different angle-ply and quasi-isotropic laminates [8].

3.2. The finite element analysis

In this section, a FE computational model intended to predict the first-ply failure test loads for two distinct layup configurations (i.e. an unidirectional off-axis $[45_{12}]_T$ and a cross-ply $[45_3/\text{-}45_3]_S$ symmetrically balanced laminate) of four point bending testing coupons, according to the above mentioned geometry, material and loading data, performed in Simcenter 3D using SOL101 Linear Statics, is described.

As represented in Figure 4, the boundary conditions in line with the applied loads were prescribed by means of semi-cylindrical supports and loading noses to accurately simulate the mechanical conditions of four point bending test. Essentially, the total applied load of 960 N (see eq. 2) was prescribed in the negative vertical zdirection and equally distributed over the two semi-cylindrical noses, while the other two lower semi-cylindrical supports were constrained for all degrees of freedom.

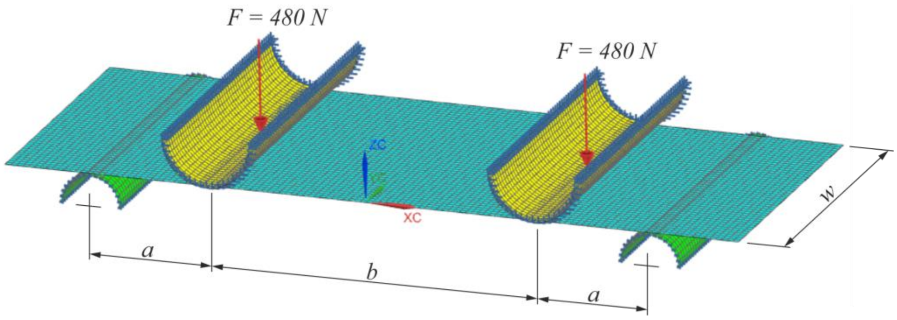


Figure 4: The finite element model (Simcenter 3D)

The contacts between the lower semi-cylindrical supports and coupon as well as between the upper semi-cylindrical loading noses and coupon were defined through the option "Surface-to-Surface-Contact" with the consideration of a static friction coefficient equal to 0,4. An "Initial Penetration" set to zero was taken to establish that the possible gaps or penetrations are treated as touching. The normal and tangential component of penalty contact functions are both set to minimum in order to ensure a uniform smooth distribution instead of a locally increased contact pressure. The shell thickness offset contact parameter was used to account for the thickness of shell elements so that the contact is achieved at half-thickness distance. The geometry of the entire assembly was meshed using linear quadrilateral shell elements. Mesh sensitivity was considered within a carefully convergence study, to ensure that the model is appropriate to compute the deformations, ply stresses and the associated Strength Ratios. Consequently, an average size of finite elements equal to 1 mm was found to give well-converged results.

4. RESULTS AND COMMENTS

In Table 2, the predicted values of bending moment that cause the first-ply failure of a symmetrically balanced cross-ply laminate $[45_3/\text{-}45_3]_S$ test coupon in line with an unidirectional off-axis $[45_{12}]_T$ flexure test coupon, using the shorthand laminate strength analysis in Simcenter 3D, are compared against the average values of experimentally bending moment, as reported by Koc and al. [12].

Table 2: Experimental data [12] and the predicted bending moment based on shorthand laminate strength analysis in Simcenter 3D

Stacking sequence	Experimental Bending Moment in *Nmm/mm*, acc. to [12]	Failure criterion	Predicted Bending Moment in *Nmm/mm*, based on laminate strength analysis	Min. SR (laminate strength analysis)	Error (%)
$[45_3/\text{-}45_3]_S$	166 COV = 10.5%	Max. stress	186,07	0,93	12,1 (↑)
		Max. strain	186,07	0,93	12,1 (↑)
		Hoffman	151,55	0,76	-8,7 (↓)
		Hill	162,26	0,81	-2,3 (↓)
		Tsai-Wu	151,45	0,76	-8,8 (↓)
$[45_{12}]_T$	130 COV = 9%	Max. stress	131,15	0,66	0,90 (↑)
		Max. strain	134,20	0,67	3,20 (↑)
		Hoffman	102,27	0,51	-21,3 (↓)
		Hill	107,19	0,54	-17,5 (↓)
		Tsai-Wu	102,19	0,51	-21,4 (↓)
***Note**: Minimum Strength Ratio (SR) is calculated relative to an applied bending moment per unit length of 200 Nmm/mm as highlighted in eq. (1).*					

Regarding the data reported within the above table, it can be seen that in case of symmetrically balanced cross-ply $[45_3/\text{-}45_3]_S$ test coupon, the results of shorthand strength analysis by means of Maximum stress and Maximum strain criteria, predict a level of first-ply failure test loads which is slightly greater relative to the experimental values, while the results obtained based on Hoffman, Hill and Tsai-Wu failure criteria, are

somewhat conservative. However, provided that the average errors are about 12% and 9% respectively and considering the actual scatter of experimental data (e.g. COV equal to 10,5%), one may conclude that the differences between the estimated and the statistics of experimentally values are not significant.
As concern the unidirectional off-axis $[45_{12}]_T$ test coupon (see also Table 2), it is apparent that the shorthand strength analysis results based on Maximum stress and Maximum strain failure criteria are predicting well the experimental data. Moreover, one may also observe that the shorthand strength-based predictions of Hoffman, Hill and Tsai-Wu criteria underestimate the first-ply failure bending with an average error of 20%. In fact, for all considered failure criteria, an overall decrease of 10% average error is obtained with respect to the previous results of symmetrically balanced cross-ply $[45_3/\text{-}45_3]_S$ test coupon. These differences may be attributed to different flexural-twisting coupled responses of the laminate test coupons under investigation in the present work. Indeed, as reported in Table 3, the ratios D16/D66 appear to be quite different. Thus, provided that such an analytical assessment does not account for the complex interactions between the involved flexural-twisting deformation on one side and the structural roller supports of physical bending test setup on the other side, the results obtained based on the shorthand laminate strength analysis might be accepted as they are on the safe side.

Table 3: The terms of compliance D matrix obtained based on the laminate strength assessment in Simcenter 3D

Stacking sequence	The compliance D matrix	D16	D66	$\frac{D16}{D66}$
$[45_3/\text{-}45_3]_S$	$10^6\begin{bmatrix}38.764 & 29.255 & 21.213\\ 29.255 & 38.764 & 21.213\\ 21.213 & 21.213 & 31.233\end{bmatrix}$	$21.213\cdot10^6$	$31.233\cdot10^6$	0.679
$[45_{12}]_T$	$10^6\begin{bmatrix}38.764 & 29.255 & 28.284\\ 29.255 & 38.764 & 28.284\\ 28.284 & 28.284 & 31.233\end{bmatrix}$	$28.284\cdot10^6$	$31.233\cdot10^6$	0.906

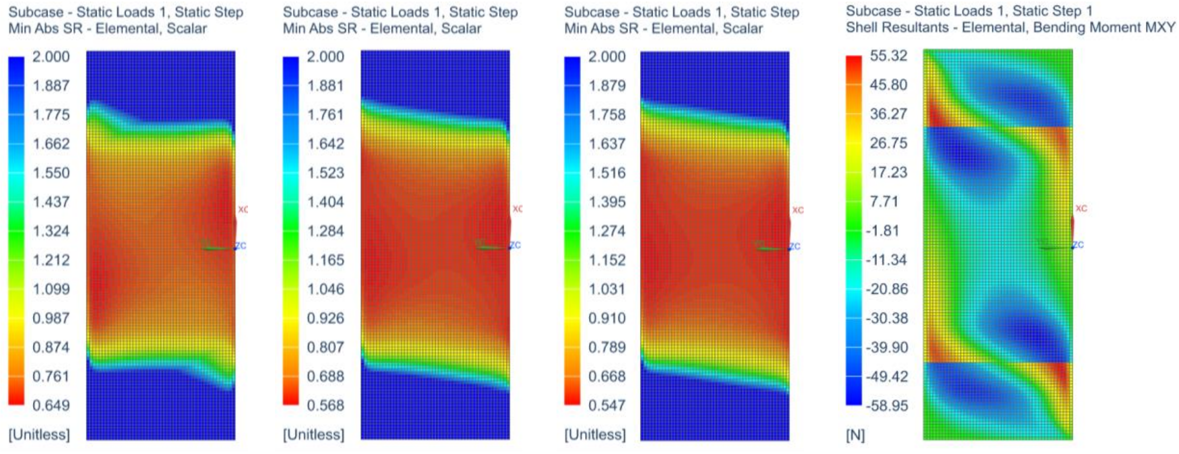
In Table 4, the predicted values of bending moment that cause the first-ply failure of both test coupons (i.e. the unidirectional off-axis $[45_{12}]_T$ as well as the cross-ply $[45_3/\text{-}45_3]_S$ symmetrically balanced), subjected to four-point bending by means of Finite Element Analysis in Simcenter 3D, with layered shell elements and appropriate boundary conditions, are compared to the statistics of experimental results reported by Koc and al. [12]. In fact, the use of FEA is supposed to overcome the aforementioned lack of interaction between the coupled flexural-twisting behavior and the structural roller supports, in the analytical assessment.

Table 4: Experimental data [12] and the predicted bending moment based on Finite Element Analysis results using layered shell elements

Stacking sequence	Experimental Bending Moment in *Nmm/mm*, acc. to [12]	Failure criterion	Predicted Bending Moment in *Nmm/mm*, based on actual FEA	Min. SR (based on actual FEA)	Error (%)
$[45_3/\text{-}45_3]_S$	166 COV = 10.5%	Max. stress	211,80	1,06	27,6 (↑)
		Max. strain	211,80	1,06	27,6 (↑)
		Hoffman	171,60	0,86	3,4 (↑)
		Hill	184,00	0,92	10,8 (↑)
		Tsai-Wu	171,40	0,86	3,3 (↑)
$[45_{12}]_T$	130 COV = 9%	Max. stress	129,60	0,65	-0,3 (↓)
		Max. strain	131,60	0,66	1,2 (↑)
		Hoffman	109,40	0,55	-15,8 (↓)
		Hill	113,60	0,57	-12,6 (↓)
		Tsai-Wu	109,40	0,55	-15,8 (↓)

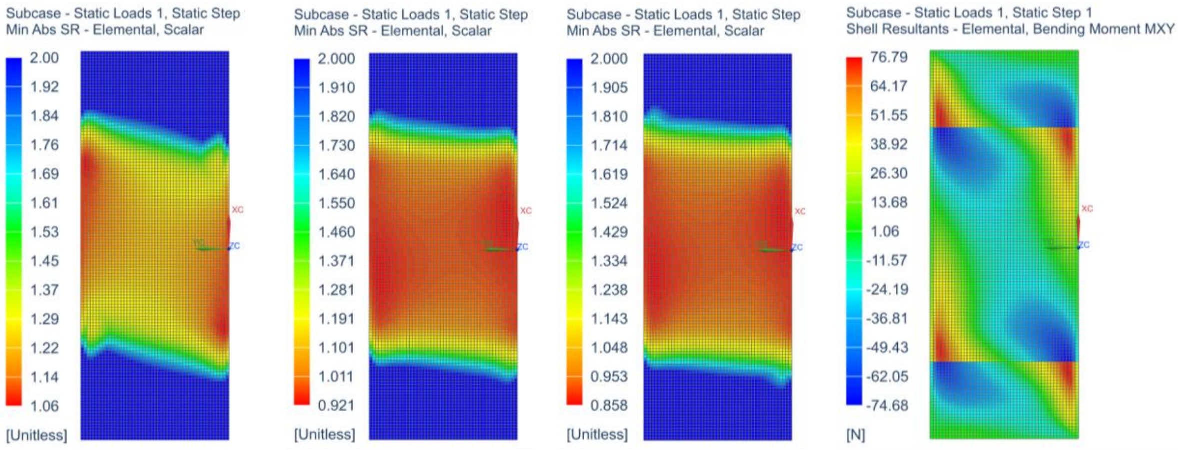
***Note**: Minimum Strength Ratio (SR) is calculated relative to an applied bending moment per unit length of 200 Nmm/mm, see eq. (1).*

As far as the cross-ply $[45_3/\text{-}45_3]_S$ laminate flexural coupon is concerned, one may easily observe that FEA results overestimate the experimental data for both independent and interactive failure criteria considered in the present study. On the contrary, in case of unidirectional off-axis test coupon $[45_{12}]_T$, the predicted values of bending moment are matching about the same pattern of results as those obtained based on the shorthand strength assessment, but slightly less conservative, which is however quite satisfactory. This is mainly because Finite Element Analysis (FEA) only outputs the mid-ply results for shell elements. Therefore, as long as the bending moment is dominant as is the present case of four-point bending flexural test, relying on the shell element mid-ply results is not as conservative as the more accurate predictions obtained by extracting the Top and Bottom ply results by means of Laminate Modeler module built-in Simcenter 3D (see back to Figure 3).



a) Max. Stress b) Hill c) Tsai-Wu d) m_{xy}

Figure 5: Minimum absolute values for SR (unidirectional off-axis $[45_{12}]_T$), relative to the fringe plot of internal twisting shell moment (m_{xy}) - FEA-based



a) Max. Stress b) Hill c) Tsai-Wu d) m_{xy}

Figure 6: Minimum absolute values for SR (cross-ply laminate $[45_3/\text{-}45_3]_S$), relative to the fringe plot of internal twisting shell moment (m_{xy}) - FEA-based

Figure 5 and Figure 6 present the typical fringe plots of minimum representative values of Strength Ratios and the corresponding failure criteria, for both layup configurations of flexural test coupons considered in the present study (i.e. the unidirectional off-axis $[45_{12}]_T$ and the cross-ply $[45_3/\text{-}45_3]_S$ symmetrically balanced laminate). In addition, for comparative purposes, each of two figures above also depict the related magnitude and distribution of the induced internal torsional moment per unit length (m_{xy}), obtained by means of FEA with layered shell elements and the appropriate boundary conditions.

5. CONCLUSIONS

The first-ply failure analyses of four-point bending composite coupons made of unidirectional off-axis $[45_{12}]_T$ and a cross-ply $[45_3/\text{-}45_3]_S$ symmetrically balanced laminate, have been conducted and the results are reported in this paper. A shorthand strength assessment, based on the FSDT results extracted from Laminate Modeler module in Simcenter 3D, together with finite element analyses performed un shell-based models with appropriate boundary conditions were employed in the computation. Several failure theories, i.e., the Maximum stress, Maximum Strain, Hoffman, Hill and Tsai–Wu, are used in the prediction of the first-ply failure load and the results are validated against existing experimental data reported in literature.

In particular, in case of symmetrically balanced cross-ply $[45_3/-45_3]_S$ test coupon, the results of shorthand strength analysis by means of Maximum stress and Maximum strain criteria, predict a level of first-ply failure test loads which is slightly greater relative to the experimental values, while the results obtained based on Hoffman, Hill and Tsai-Wu failure criteria, are somewhat conservative. As concern the unidirectional off-axis $[45_{12}]_T$ test coupon, it was found that the shorthand strength analysis results based on Maximum stress and Maximum strain failure criteria are predicting well the experimental data, while the interactive failure criteria (i.e. Hoffman, Hill and Tsai-Wu) underestimate the first-ply failure bending with an average error of 20%. This difference may be attributed to different flexural-twisting coupled responses of unidirectional off-axis and cross-ply laminates when subjected to four-point bending.

Numerical computations based on FEA predict more or less the same first-ply failure loads compared to the experimental data. Nevertheless, further analyses employing solid layered elements are required to study deep in detail the effects of different off-axis and angle-ply orientations.

REFERENCES

[1] ASTM D7264/D7264M-15. (2015). Standard test method for flexural properties of polymer matrix composite materials.

[2] ISO Committee. ISO 14125: 1998, Fibre-Reinforced Plastic Composites–Determination of Flexural Properties, ISO Committee, Geneva, 2013.

[3] Grediac, M. (1993). Four-point bending tests on off-axis composites. Composite structures, 24(2), 89-98.

[4] Van Paepegem, W., De Geyter, K., Vanhooymissen, P., & Degrieck, J. (2006). Effect of friction on the hysteresis loops from three-point bending fatigue tests of fibre-reinforced composites. Composite Structures, 72(2), 212-217.

[5] Mujika, F. (2006). On the difference between flexural moduli obtained by three-point and four-point bending tests. Polymer Testing, 25(2), 214-220.

[6] Vargas, G., & Mujika, F. (2011). Determination of in-plane shear properties by three-point flexure test of±45° anti-symmetric laminates. Polymer testing, 30(2), 204-215.

[7] Benbelaid, S., Bezzazi, B., & Bezazi, A. (2012). Cross-ply laminates under static three-point bending: a numerical development model. In Key Engineering Materials (Vol. 498, pp. 42-54). Trans Tech Publications Ltd.

[8] Wowk, D., Marsden, C. C., & Thibaudeau, D. Interpreting data from four-point bending tests of thin angle play laminates–test set-up, edge and width effects. ECCM16 – 16th European Conference on Composite Materials, Seville, Spain, 22-26 June 2014.

[9] Hara, E., Yokozeki, T., Hatta, H., Iwahori, Y., & Ishikawa, T. (2015). Out-of-plane tensile modulus of CFRP laminates by 3-point bending test. Advanced Composite Materials, 24(3), 221-237.

[10] Meng, M., Le, H. R., Rizvi, M. J., & Grove, S. M. (2015). 3D FEA modelling of laminated composites in bending and their failure mechanisms. Composite Structures, 119, 693-708.

[11] Klasztorny, M., Nycz, D., & Labuda, R. (2018). Modelling, simulation and experimental validation of bend tests on GFRP laminate beam and plate specimens. Composite Structures, 184, 604-612.

[12] Koc, M., Sonmez, F. O., Ersoy, N., & Cinar, K. (2016). Failure behavior of composite laminates under four-point bending. Journal of Composite Materials, 50(26), 3679-3697.

[13] Kim, J. S., Lee, S. Y., & Roh, J. H. (2020). Failure analysis of laminated composites subjected to flexural loadings. Advanced Composite Materials, 29(3), 301-316.

[14] Goncharov, P., Artamonov, I., & Khalitov, T. (2014). Engineering analysis with NX advanced simulation. Lulu Press, Inc.

[15] https://www.hexcel.com/user_area/content_media/raw/HexPly_8552_eu_DataSheet.pdf

[16] https://docs.plm.automation.siemens.com/tdoc/nx/12/nx_help/#uid:index