Investigation of the double-double for the dimensioning of composite cryogenic tank skin.

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Abstract

This article aims to analyze a design method for composite structures (Double-Double). It first presents the two types of laminates which are the Double-Double and the QUAD (properties, advantages and design rules), before addressing the presentation and analysis of the failure criteria used to size the laminates. the following is used the failure criteria that have been numerically validated to design optimization algorithms for the two types of DD and QUAD laminates in order to size the composite structures subjected to load flows. Finally, the article presents the results obtained in an application case which is a torsion wing box subjected to a force F and an internal fuel pressure. This caisson was dimensioned in several ways and using all the failure criteria that have been validated.

1. Introduction

This article is devoted to the analysis of a new method for sizing composites as part of a 2nd year research internship at isae-supaero.During this internship we used several articles and documents to make an in-depth analysis of laminates and to propose perspectives.

We started with the document [8] which presents the laminates in a general way: the classic theory of the laminates, the laws of behavior of the composites, the mixing laws to find the properties of the plies. The author of this document presents approaches to calculate the properties of the plies in a laminate after failure according to the mode of failure (fiber or matrix). With this he proposes a PFA approach to achieve last ply failure in a laminate. We have implemented this approach in the rest of this document to size the composites in LPF (Last ply Failure).

The article [2] presents a new approach based on invariants to describe the elastic properties and the failure of composite ply and laminates is proposed. The approach is based on the trace of the plane stress stiffness matrix as a material property, which can be used to reduce the number of trials and simplify the design of laminates. Strain failure omni envelopes are proposed as the minimum internal failure envelope in the deformation space, which defines the failure of a given composite material for all ply orientations. The proposed approach is demonstrated using various carbon/epoxy composites and offers radically new scaling to improve design and fabrication.

Papers [2] and [5] propose an invariant-based design procedure using a normalized plane stress stiffness matrix and a unit circle. the failure criterion of carbon fiber reinforced polymer (CFRP) is presented and compared to traditional design approaches. Using the invariant-based design approach, the optimal stiffness-based lamination solution is material-independent and therefore valid for any CFRP. Then, the trace of the plane stress stiffness matrix is the only material property needed for strain scaling. The results show that the invariant-based design approach greatly simplifies the design procedure of CFRP Component structures.

The article [6] presents a new family of composite laminates (Double-Double) which could revolutionize composite structures by making them lighter, stronger, easier to understand and design, and faster and less expensive to manufacture. This new family of laminates called double-double (DD), based on two pairs of angular plies, can rather redirect the trend towards simplicity and rationality. Advantages enabled by DD include homogenization and tapering to save weight.

In the rest of this article it is a question of using this bibliographic research to firstly present the DD and QUAD laminates, then to present and analyze the failure criteria of the composites in FPF and LPF, after proposing algorithms for the optimization of the structures and finally to make a comparison with the existing methods on an application case and to propose alternatives.

2. QUAD LAMINATES

Quad laminates are based on a collection of discrete 0, 45, 90-degree plies. The Quad starts with four plies. If orthotropy is desired, plies should be added. With a high ply count, optimization becomes impossible, and design and manufacturing become so complex that they are not well understood. DD is totally different with a more sophisticated field of two sets of corner folds in [±θ/±Ψ]. The building block is 1/10 as thick as the quad and can easily be homogenized to allow for design and fabrication as simple as, if not simpler than, metals.

3. DOUBLE-DOUBLE LAMINATES

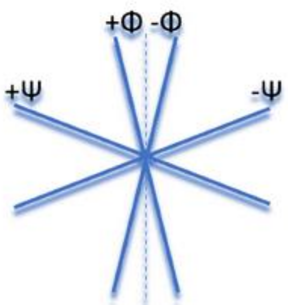


Figure 1: Double-Double

The emergence of double-double as [±Φ/±Ψ] to replace the traditional quad as [0, ±45, 90] is based on a number of innovative steps in modeling composite laminates.DD is a laminate in the general form of [± Φ / ± Ψ] n. Φ and Ψ are laminate orientations from 0° to 90° and continuously cover the entire possible spectrum of stiffness and strength. The underlayment is very simple and always the same throughout the structure. Manufacturing is simple. The variation from one point to another will only be on the thickness which is the repeated n. This taper solution is similar to what is done on metal parts. Homogenization is made possible with only 10 quadruple laminate building blocks. Homogenized double-double laminates are naturally symmetrical, and ply fall can be in singles, rather than symmetrical pairs for the quad (**Figure 2**).

Source : https://doi.org/10.2514/1.J060659

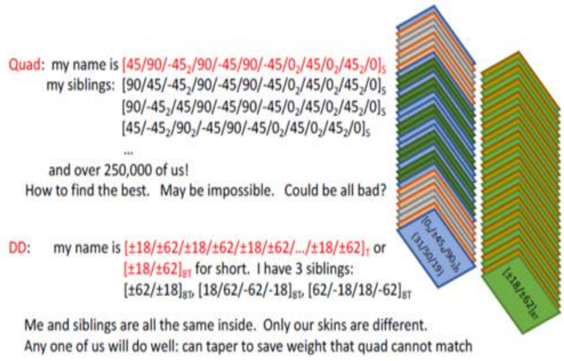


Figure 2 : QUAD Vs DD

The stacking sequence of Φ and Ψ has no considerable effect on the properties where for QUAD the number of permutations is so high by thousands that optimization is impossible. DD-laminate family is unique, which has two continuous plies angles.

We recall that the classical theory of laminates also applies to DD laminates. The advantage with the DD is that the calculation of the stiffness matrices for a DD is simpler. Thus, for a DD [± Φ / ± Ψ] 2N, one can easily calculate its stiffness matrices by the following formulas:

$$A_{ij} = 2Ne(Q_{ij}^{+\phi} + Q_{ij}^{-\phi} + Q_{ij}^{+\psi} + Q_{ij}^{-\psi})$$

$$C_{ij} = D_{ij} = a * Q_{ij}^{+\phi} + b * Q_{ij}^{-\phi} + b * Q_{ij}^{+\psi} + a * Q_{ij}^{-\psi}$$

$$a=\sum_{i=1}^{N} \frac{e^3}{3*4^3}[(4i)^3 - (4i-1)^3 + (4i-3)^3 - (4i-4)^3 \ ]$$

$$b=\sum_{i=1}^{N} \frac{e^3}{3*4^3}[(4i)^3 - (4i-1)^3 - (4i-3)^3 \ ]$$

With e=thickness of a ply.

4. FAILURE CRITERIA USED TO SIZE

4.1 FPF (First Ply Failure)

In this work we have used the several failure criteria of composites (DD and QUAD).

TSAI-Hill Criterion

It is a 2D and quadratic stress criterion, it is based on the calculation of the stresses in each ply and expressed in the local reference of the ply. it must be verified for all the layers of the laminate, it is given by:

$\boldsymbol{H_{ij}\sigma_i\ \sigma_j=1}$ / i, j=1,2,6

The matrix coefficients [H] depend on the properties of the material. This matrix is worth:

$$[H]=\begin{bmatrix} \frac{1}{Xc/t^2} & -\frac{1}{2*Xc/t^2} & 0 \\ -\frac{1}{2*Xc/t^2} & \frac{1}{Yc/t^2} & 0 \\ 0 & 0 & \frac{1}{S^2} \end{bmatrix}$$

Where
$$\sigma_1 > 0 \Rightarrow X_{C/T} = X_T \ldots \sigma_1 < 0 \Rightarrow X_{C/T} = X_C$$
$$\sigma_2 > 0 \Rightarrow Y_{C/T} = Y_T \ldots \sigma_2 < 0 \Rightarrow Y_{C/T} = Y_C$$

Criterion of TSAI-Wu in strain

It is a 2D criterion, quadratic and linear in deformation, it is based on the calculation of the deformations in each ply and expressed in the local coordinate system of the ply. it should be checked for all layers of the laminate.

It is expressed by: $\boldsymbol{G_{ij}\varepsilon_i\varepsilon_j + G_i\varepsilon_i = 1}$. $[G]$ and $\{G\}$ depend on the material and are defined by:

$$[G] = Q * [F]\ ,\{G\} = Q * \{F\} * Q$$

With

$$F_1 = \left(\frac{1}{X_1^T} - \frac{1}{X_1^C}\right), F_2 = \left(\frac{1}{X_2^T} - \frac{1}{X_2^C}\right), F_{12} = -\frac{1}{2}\sqrt{\frac{1}{X_1^T * X_1^C} * \frac{1}{X_2^T * X_2^C}}\ ,$$

$$F_{11} = \frac{1}{X_1^T X_1^C}\ , F_{22} = \frac{1}{X_2^T X_2^C}, F_6 = \left(\frac{1}{X_{12}^T} - \frac{1}{X_{12}^C}\right), F_{66} = \frac{1}{X_{12}{}^T * X_{12}{}^C}$$

Use of the Omni rupture envelope in strain for sizing in FPF (First Ply Failure) ([4])

The rupture criterion seen previously is implemented to be used ply by ply inside the laminate. However, when the number of layers of the laminate increases or is very large, the calculation time becomes very large, and the precision of the results is lost. For these reasons other approaches to predict first ply failure in a laminate are used.

The omni envelope is a failure envelope in strain space, this envelope depends only on the material used and is independent of the orientation of the plies which are in the laminate. To obtain it, one superimposes the envelopes of ruptures of all the possible orientations according to the criterion of rupture of TSAI-Wu in strain space ($\boldsymbol{G_{ij}\varepsilon_i\varepsilon_j + G_i\varepsilon_i = 1}$), then one extracts the minimal envelope after intersections. The following **figure 3** shows the ply failure envelope at 0° and 90° for a material in strain space using the above criterion.

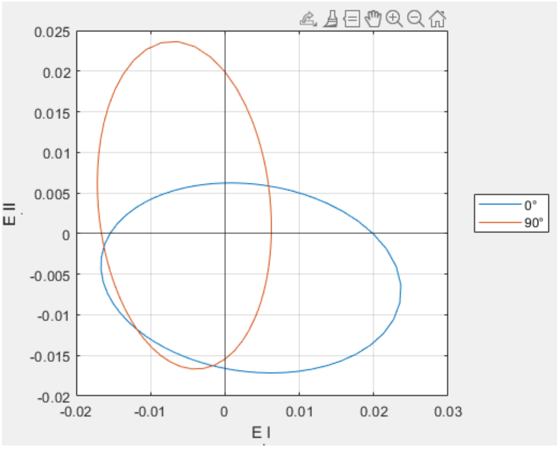


Figure 3:Ply failure enveloppe for 0 and 90

By doing the same for the other possible orientations, we obtain **the figure 11** which shows the envelope of Omni based on the failure criterion of TSAI-WU in deformation for two materials.

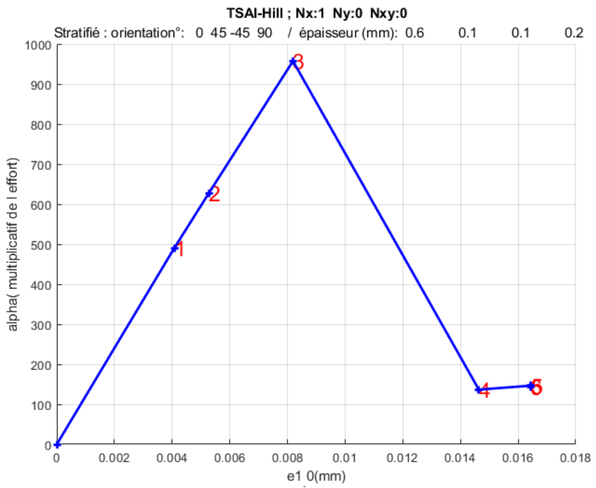
it can be noted that with this approach, all the data of a laminate can be displayed on the same graph in deformation space, which is a very practical tool for visualizing the failure of a material.

4.2 Failure criteria used to size in LPF

Progressive Failure Analysis (PFA) [8]

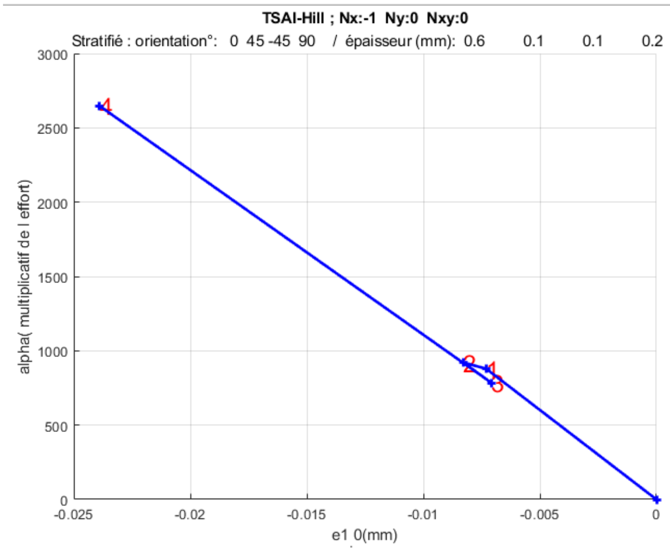
A progressive failure analysis methodology has been developed to predict the nonlinear response and failure of laminated composite structures. Progressive failure analysis is based on classical lamination theory to calculate in-plane stresses. Several failure criteria, including the maximum strain criterion, Hashin's criterion and Christensen's criterion, are used to predict failure mechanisms. The failure model studied here is the one proposed in [8] and the criterion used is the TSAI-Wu criterion in stain space. This model consists of a ply-by-ply strength analysis for post-FPF strength prediction. A flowchart for the traditional criterion and its extension to include degradation is shown in **Figure 12**. Ultimate strength is achieved after progressive degradation of all plies. **Figures 4** and **5** show the results of PFA on QUAD (with P0=0.6, P45=

0.1 and thickness=1mm) in simple tension and compression.



'Points'	'0'	'45'	'-45'	'90'
'1'	'2.0071'	'1.2974'	'1.2974'	'1'
'2'	'1.5463'	'1'	'1'	'2.7881'
'3'	'1'	'2.0267'	'2.0267'	'1.7712'
'4'	'55.6708'	'1.1237'	'1.1237'	'1'
'5'	'49.562'	'1'	'1'	'Inf'
'6'	'49.5802'	'Inf'	'1'	'Inf'

Figure 4: PFA for a Quad in simple traction with RF history



'Points'	'0'	'45'	'-45'	'90'
'1'	'1.1348'	'1'	'1'	'2.9047'
'2'	'1'	'38.6119'	'38.6119'	'2.8687'
'3'	'1'	'46.5699'	'46.5699'	'3.3746'
'4'	'Inf'	'13.8123'	'13.8123'	'1'

Figure 5: PFA for a QUAD laminate in simple compression with RF history

the historics of degradation for these two cases are respectively shown in **figures 7** and **8**.

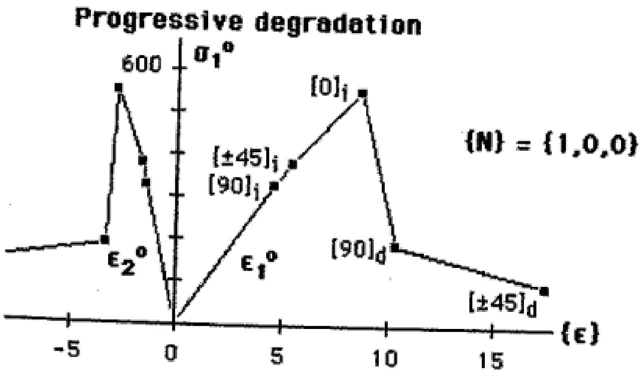


Figure 6: PFA shows by TSAI in [8]

The results obtained by this PFA in simple traction for the two criteria are similar and are very close to the result proposed by TSAI in [8] (**figure 6**). But on the other hand, the results in simple compression are not Very satisfactory.

Indeed, for the two criteria (TSAI-Hill and TSAI-Wu) in simple compression one realizes that after the rupture of the properties of the matrix of the plies, the laminate supports less load, in other cases after the rupture properties of the fibers of the plies the laminate supports more load which should not be the case (**figure 5**). The material used in this case has the following properties: Xc=1500Mpa and Yc=245 MPA. The PFA of **figure 5** shows us that the laminate can withstand up to 2800 MPA which is practically not possible.

OMNI LPF

Construction of the omni-strain last ply failure envelope (LPF) follows the same procedure as described for the omni-strain FPF [4]. Based on a given failure criterion, such as Tsai-Wu or maximum strain, failure envelopes are generated in the strain space for a laminate with all ply orientations, from 0 to 90. Whereas for the omni failure envelopes strain FPF envelopes are achieved using intact ply properties, omni strain LPF envelopes are defined using degraded ply properties.

Degraded ply properties are a widely acceptable approach to account for decreased matrix-dominated stiffness components and increased fracture stresses, due to the presence of micro-cracks.

'Points'	'0'	'45'	'-45'	'90'
'1'	'Intact'	'Intact'	'Intact'	'Matrice dégradée'
'2'	'Intact'	'Matrice dégradée'	'Matrice dégradée'	'Matrice dégradée'
'3'	'Fibre dégradée'	'Matrice dégradée'	'Matrice dégradée'	'Matrice dégradée'
'4'	'Fibre dégradée'	'Matrice dégradée'	'Matrice dégradée'	'Matrice et Fibbre dégradées'
'5'	'Fibre dégradée'	'Matrice et Fibbre dégradées'	'Matrice dégradée'	'Matrice et Fibbre dégradées'
'6'	'Fibre dégradée'	'Matrice et Fibbre dégradées'	'Matrice et Fibbre dégradées'	'Matrice et Fibbre dégradées'

Figure 7:Degradation history for figure4

'Points'	'0'	'45'	'-45'	'90'
'1'	'Intact'	'Fibre dégradée'	'Fibre dégradée'	'Intact'
'2'	'Matrice dégradée'	'Fibre dégradée'	'Fibre dégradée'	'Intact'
'3'	'Matrice et Fibbre dégradées'	'Fibre dégradée'	'Fibre dégradée'	'Intact'
'4'	'Matrice et Fibbre dégradées'	'Fibre dégradée'	'Fibre dégradée'	'Fibre dégradée'

Figure 8:Degradation hostory for figure 5

Figure 10 shows the omni LPF deformation envelope for T700/2508. In this case, the failure envelopes for the individual plies were generated using the Tsai-Wu failure criterion with a normalized interaction term Fxy*=1/2 and matrix degradation factor Em*=0.15. Simultaneously the degradation

of the folds was considered with degraded material properties calculated according to the relations presented in the previous part (PFA).

Using Unit circle [4]

The article [4] presents an approach for the construction of the unit circle. This article shows us that from 4 anchor points obtained with the properties of the non-degraded material we obtain an envelope which is inside the OMNI LPF envelope. The OMNI LPF envelope is obtained from the properties of the gradient material. We drew (**figure 9**) these two envelopes (Unit circle from the anchor points and the OMNI LPF envelope. But the envelope obtained from the unit circle is not included in the omni LPF. Indeed, this is because the anchor points are obtained with the properties of the material not degraded and the OMNI LPF envelope is obtained from the properties of the degraded material Sizing by optimization in FPF and LPF

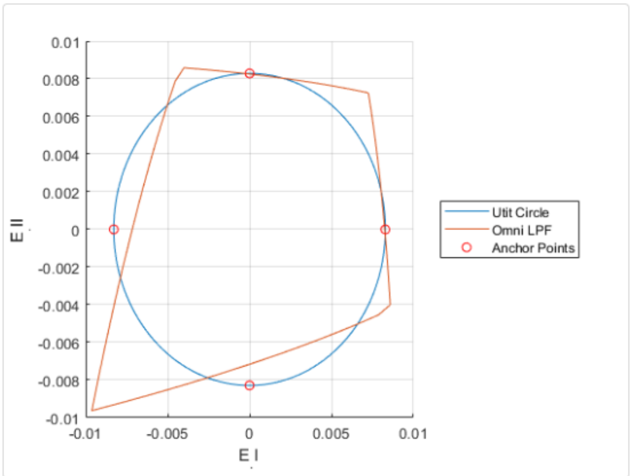


Figure 9:Unit circle and Omni LPF for T300/5208

SIZING BY OPTIMIZATION IN FPF AND LPF

We used optimization algorithms to size the composite panels under several load cases. For each failure criterion, we used Matlab's "fmincon" function for local optimization and "GlobalSearch" for global optimization. To make a comparison we designed these algorithms for DD and QUAD.

To design a QUAD laminate, we need the following three parameters: P0° (percentage of ply at 0°), P45° (percentage of ply at 45°), The total thickness of the laminate. Knowing that (-45) °=p45° and p90°=1-p0°-2*p45°. The goal of optimization for a QUAD is to determine for a given loading flow the P0° and P45° which allow the lowest thickness of the laminate. However, for DD laminates we need the following three parameters: Φ, Ψ, The total thickness of the laminate (e). The proportions of the orientations in the laminate being known 0.25%, the optimization of DD laminates consists in determining for a loading flow given the angles Φ and Ψ which make it possible to have the smallest thickness of the laminate. The optimization algorithms will be appended.

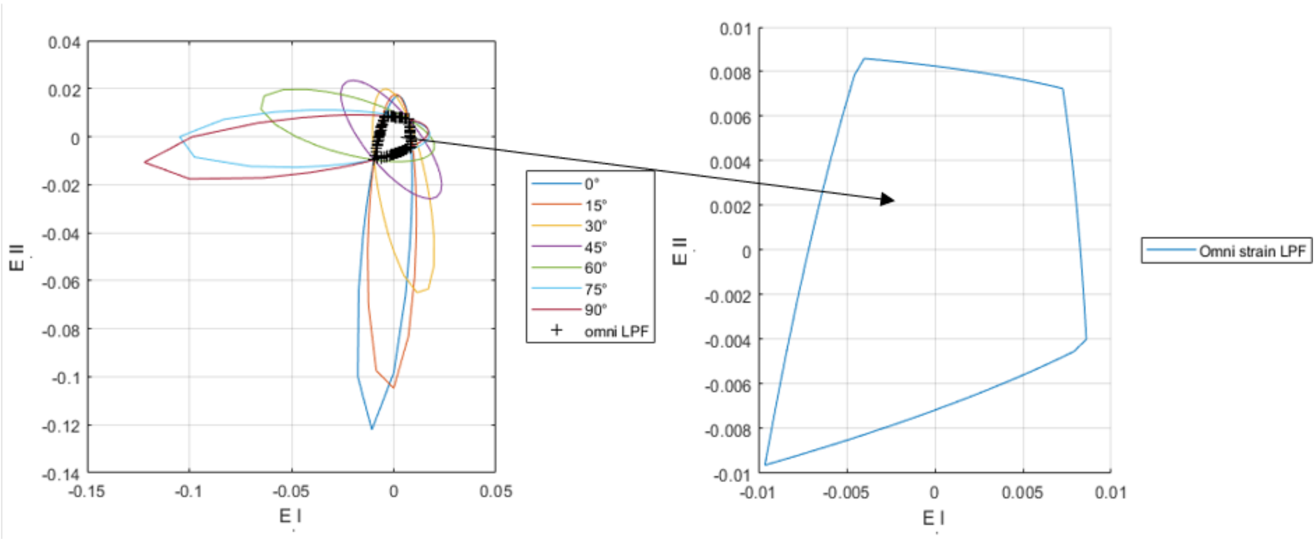


Figure 10:Omni Strain LPF for T700/2508

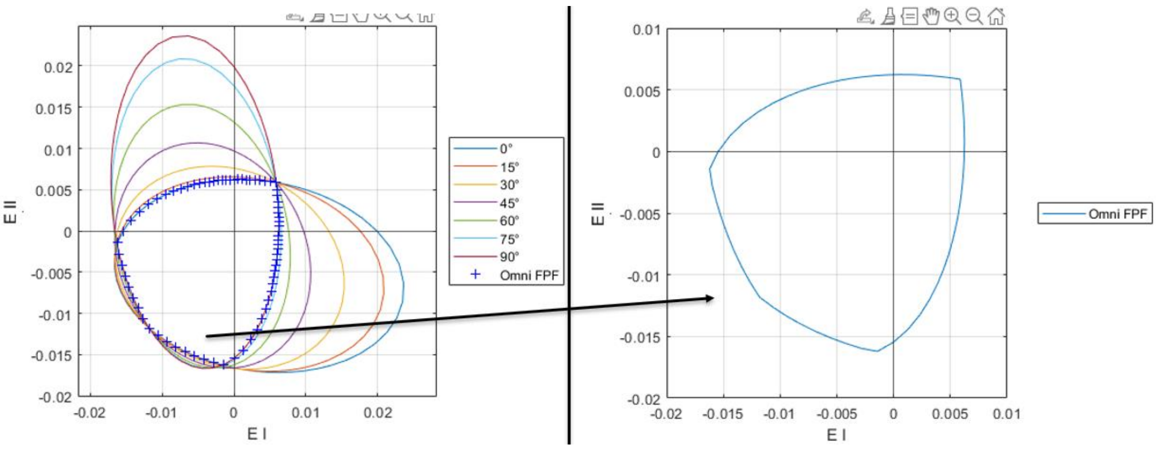


Figure 11: Omni FPF for T800/Cytec

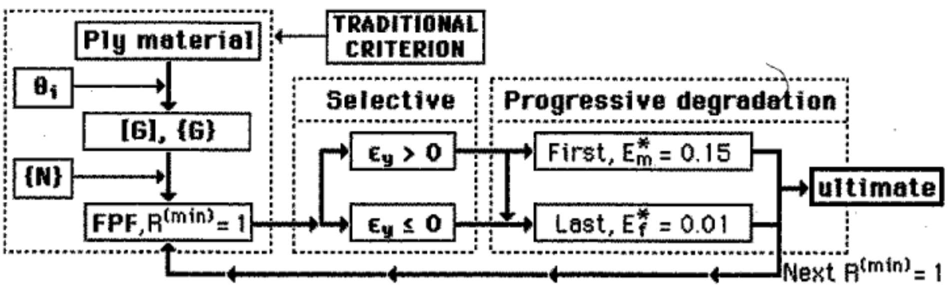


Figure 12:PFA model proposed by TSAI in [8]

5. RESULTS AND COMPARISONS

The objective is to arrive at the final pre-design of a torsion wing box (**Figure 13**) made of panels of composite materials. The overall dimensions of the box are given in the sketch below. This box is fully embedded on the left side, while its free right side is subjected to a concentrated vertical (along y) force F = 10000 N applied to point A. The dimensioning of this box will be done under two load cases: The first case (CASE 1) considering just the force F=10000N. And the second case (CASE 2) in addition to the force F=10000N, we will consider the internal fuel pressure of P=2 bars (0.2 N/mm2) which will generate Nyy forces in all the panels of the box.

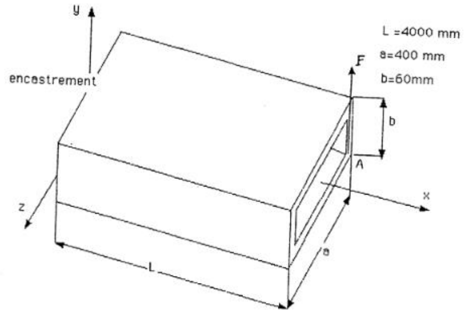


Figure 13:Torsion wing-box

Using a factor of safety of 2 on the stresses, we had the following stresses in the structure:

	σ_{xxMax}(N/mm)	τ_1(N/mm)	σ_{yyMax}(N/mm)
Upper Panel	-3333.33	250	12
Lower panel	3333.33	-250	12
Vertical panel(z >0)	0	83.33	80
Vertical panel (z<0)	0	250	80

The material used to size in FPF has the following properties:

El = 140 GPa Et = 5 GPa νlt = .35 Glt=5Gpa
Xt = 1200 MPa Xc = 1000 MPa
Yt = 50 MPa Xc = 120 MPa S = 65 MPa

5.1 Results in FPF

First, we will size the panels keeping the thickness constant on each panel and we will consider a ply thickness (PT) = 0.125 mm.

- Horizontal panels

CASE 1 (*Nx=3333.33 N/mm; Nxy=-250 N/mm; Ny=0 N/mm*)

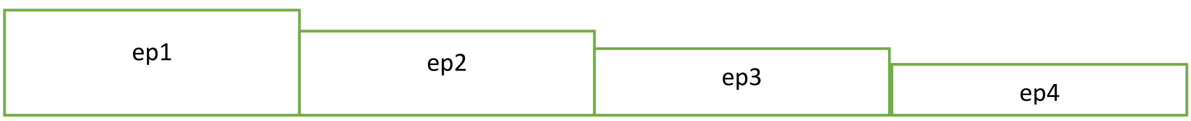
Criteria	DD			QUAD (pli= 0.125mm)	
	thickness (mm)		Orientation	[Thickness (mm) P0 P45]	One of the possible sequences
	PT=0.125 mm	PT=0.01 mm			
TSAI-Hill	5	4.56	[±0/±12.7]	[5 0.7 0.1]	$[0_2/-45/0_4/45/\ 0_4/-45/\ 0_4/45/90_2]_{s.}$
TSAI-WU	5.5	5.04	[±6.12/ ±7.12]	[5 0.7 0.1]	$[0_2/-45/0_4/45/\ 0_4/-45/\ 0_4/45/90_2]_{s.}$
Omni FPF	5.5	5.32	[±0/±10]	[5 0.7 0.1]	$[0_2/-45/0_4/45/\ 0_4/-45/\ 0_4/45/90_2]_{s.}$

- CASE 2 (*Nx=3333.33 N/mm ; Nxy=-250 N/mm ; Ny=12 N/mm*)

Criteria	DD			QUAD (pli= 0.125mm)	
	thickness (mm)		Orientation	[Thickness (mm) P0 P45]	One of the possible sequences
	PT=0.125 mm	PT=0.01 mm			
TSAI-Hill	5	4.64	[±0/±12.2]	[5 0.7 0.1]	$[0_2/-45/0_4/45/\ 0_4/-45/\ 0_4/45/90_2]_{s.}$
TSAI-WU	5.5	5.16	[±6/±7]	[5 0.7 0.1]	$[0_2/-45/0_4/45/\ 0_4/-45/\ 0_4/45/90_2]_{s.}$
Omni FPF	5.5	5.44	[±0/±10.5]	[5 0.7 0.1]	$[0_2/-45/0_4/45/\ 0_4/-45/\ 0_4/45/90_2]_{s.}$

The thickness of the horizontal panels being large (for the DD and the QUAD), we have sequenced these panels into 4 sub-panels. The forces supported by the panels will be different and this makes it possible to gain in thickness. We will therefore have for each part (**PT = 0.125 mm**) :

N= [-3333.33 ;12 ;250] [-2500 ;12 ;250] [-1666.7;12 ;250] [- 833.33 ;12 ;250]



The results of the optimization criteria being close, we used the Omni FPF envelope for this dimensioning by part.

First, we calculate the equivalent DD for each part using the OMNI FPF optimization algorithm separately and we obtain:

[5.5 mm, 0°, 10.8°] | [4.5mm, 0°, 13.54°] | [3.5 mm, 0°, 59.8°] | [2.5 mm, 0°, 52°]

With this strategy we gain a lot in thickness and therefore in mass, but on the other hand, the angles being different over the whole panel, there will be a discontinuity of the layers on the panel which can cause a problem of transmission of forces in the panel.

To solve this problem of discontinuity, we kept the same orientations of DD on the panel while minimizing H=ep1+ep2+ep3+ep4. For this we have designed an optimization algorithm having for but to minimize H= ep1+ep2+ep3+ep4 by using the Omni FPF envelope to save computation time.

After calculation we obtained with a ply thickness=0.125 mm:

- DD :

6.5 mm | 5 mm | 3.5 mm | 2.5 mm

[±0/±62.2]

With this strategy on the snapshot H=ep1+ep2+ep3+ep4 =17.5 against 16. But on the snapshot a panel which is much more homogeneous than the preceding one.

- QUAD: Her we will give [Thickness(mm) nombre_pli_0 nombre_pli_45 nombre_pli_90]

[5mm 28 4 4] | [4.5mm 24 4 4] | [3.5mm 16 4 4] | [2.5mm 10 4 2]

With this approach we obtain a panel that supports the initial efforts but with less mass. This makes it possible to make a huge gain in mass.

➢ Vertical panels
  - CASE 1 (*Nx=0 N/mm; Nxy=250 N/mm; Ny=0 N/mm*)

Criteria	**DD**			**QUAD (pli= 0.125mm)**	
	thickness (mm)		Orientation	[Thickness (mm) P0 P45]	One of the possible sequences
	PT=0.125 mm	PT=0.01 mm			
TSAI-Hill	1	0.56	[±44.5/±45.5]	[1.5 0.1 0.4]	$[-45_2/90/45/0/45]_{s.}$
TSAI-WU	1	0.64	[±44.5/±45.5]	[1.5 0.1 0.4]	$[-45_2/90/45/0/45]_{s.}$

Omni FPF	1	0.68	[±44.5/±45.5]	[1.5 0.1 0.4]	[-45$_2$/90/45/ 0/45]$_{s.}$

- CASE 2 (*Nx=0 N/mm ; Nxy=250 N/mm ; Ny=80 N/mm*)

Criteria	DD			QUAD (pli= 0.125mm)	
	thickness (mm)		Orientation	[Thickness (mm) P0 P45]	One of the possible sequences
	PT=0.125 mm	PT=0.01 mm			
TSAI-Hill	1	0.72	[±37.5/±58.3]	[1.5 0.1 0.4]	[-45$_2$/90/45/ 0/45]$_{s.}$
TSAI-WU	1	0.8	[±38.7/±58.5]	[1.5 0.1 0.4]	[-45$_2$/90/45/ 0/45]$_{s.}$
Omni FPF	1	0.84	[±40/±59.5]	[1.5 0.1 0.4]	[-45$_2$/90/45/ 0/45]$_{s.}$

5.2 Résults in LPF

To study the LPF, we needed to degrade the material properties. For this we needed to have more detail on the properties of the materials (property of the matrix and the fiber of the materials). We only had this data available to us for a single material, which is T300/5208, and it was this material that was used to size it in LPF.

Data[3] :

```
%    Ex     Ey    Nuxy  Gxy  Xt     Xc    Yt     Yc     S     en GPA
mat=[181  10.3 0.28  7.17 1.5   1.5  0.040 0.246 0.068];    % T300/5208

The matrix and fiber properties of this material are:

%        Ex  vf    Nuxy   Efx    Em   ny     Efy   ns     Gfx    Gxy
mat_m_f=[181 0.70 0.28   258.57 3.40 0.5161 18.69 0.3162 19.68  7.17] ;%
T300/52
```

- Horizontal panels
  - CASE 1 (*Nx=-3333.33 N/mm ; Nxy=250 N/mm ; Ny=0 N/mm*)

Criteria	DD			QUAD (pli= 0.125mm)	
	thickness (mm)		Orientation	[Thickness (mm) P0 P45]	One of the possible sequences
	PT=0.125 mm	PT=0.01 mm			
Omni LPF	4	3.96	[±0/±13.6]	[4.5 0.7 0.1]	[90/-45/0$_4$/45/90/-45/ 0$_4$/45/ 0$_4$]$_{s.}$

- CAS 2 (*Nx=3333.33 N/mm ; Nxy=-250 N/mm ; Ny=12 N/mm*)

Criteria	**DD**			**QUAD (pli= 0.125mm)**	
	thickness (mm)		Orientation	[Thickness (mm) P0 P45]	One of the possible sequences
	PT=0.125 mm	PT=0.01 mm			
Omni LPF	4	4	[±0/±13.3]	[4.5 0.7 0.1]	$[90/-45/0_4/45/90/-45/0_4/45/0_4]_s$.

- Vertical panels

- CASE 1 (*Nx=0 N/mm ; Nxy=250 N/mm ; Ny=0 N/mm*)

Criteria	**DD**			**QUAD (pli= 0.125mm)**	
	thickness (mm)		Orientation	[Thickness (mm) P0 P45]	One of the possible sequences
	PT=0.125 mm	PT=0.01 mm			
Omni LPF	0.5	0.52	[±44.4/±45.5]	[1 0.1 0.4]	$[90/-45/0/45]_s$.

- CASE 2 (*Nx=0 N/mm ; Nxy=250 N/mm ; Ny=80 N/mm*)

Criteria	**DD**			**QUAD (pli= 0.125mm)**	
	thickness (mm)		Orientation	[Thickness (mm) P0 P45]	One of the possible sequences
	PT=0.125 mm	PT=0.01 mm			
Omni LPF	1	0.6	[±34.6/±55.6]	[1 0.1 0.4]	$[90/-45/0/45]_s$.

5.3 Interpretation

The previous results in FPF show that the results of the sizing criteria are similar. But the calculation times of the criteria are different.

Indeed, the times of calculation of the criteria of TSAI-HILL and TSAI-WU are equal but that of the envelope OMNI FPF is well reduced because with this envelope one does not need to make the calculations of the stresses and the strains of all the folds of the laminate. It is enough just to have the strains of the average plan and with that one directly finds the thickness necessary to support the flow of load given. This greatly reduces computation time and reduces optimization parameters.

In LPF for OMNI LPF we have the same conclusion as in OMNI FPF because the calculation procedure is the same for these two criteria.

Regarding DD and QUAD, when using the folds at 125 mm on the place of the QUAD. The use of 0.01 mm folds on the DD makes it possible to gain thickness on all the panels. With these folds at 0.01 mm on the DD the number of repeat of the block [± Φ / ± Ψ] increases necessary (we leave from 2 repeats on the vertical panels to 21 repeats in OMNI FPF case 2 for example). This very large number of repetitions makes it possible to have homogeneous laminates with thermal coupling stiffnesses which tend towards 0.

Conclusion

Thus, arrived at the end of this research internship report where the objective was to make an analysis of a new method for dimensioning composites by starting a bibliographical research on the classic theory of stratifies and the failure criteria of composites, and after to propose structure optimization algorithms on QUAD and Double-Double using several failure criteria in First Ply Failure and Last Ply Failure. We started by analyzing the sizing criteria proposed for any type of laminate (TSAI-Hill, TSAI-Wu, OMNI FPF, PFA, unit circle and OMNI LPF). The results obtained in FPF with TSAI-Hill, TSAI-WU and omni FPF are quite close, and in LPF we used to size only one criterion (OMNI LPF) because the other criteria in LPF (Unit circle and PFA) n were not valid based on the analysis and numerical tests we performed.

With these criteria we designed optimization algorithms for DD and QUAD which we used to size a case of Wing Box. In general, on the results obtained, we had gains (thickness and therefore the mass) and advantages (homogenization, cancellation of the terms of coupling stiffness and ease of design) by using the DD with very thin ply thicknesses at instead of QUAD. These advantages are mainly due to the fact that with fine folds on DD the number of block repetitions $[\pm \Phi / \pm \Psi]$ is high (>18 in our case). As the preliminary study of the DD (part 2) showed it with this number of repetitions the DD is much more effective than the QUAD.

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