Carbon fibre/PVC foam sandwich composite modelization for MAVs & long range drones structures

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ABSTRACT

This paper deals with the characterization, modelization and simulation of a composite structure used for MAV or generally for drones design. Composite structures are extremely difficult to simulate due to the anisotropic behaviour. The first part of the article is focused on carbon fiber/PVC foam (AIREX) sandwich composite characterization with the design of experiments method on tensile tests. This method gives equations, which describe the material mechanical behaviour (Young's modulus, tensile strength) depending on factors values. The second part of the article deals with the improvement of mechanical simulation of an anisotropic material with the goal to get an accurate model and to generalised properties to an entire structure. Then, the macroscopic mechanical properties of the most performing sandwich will be obtained with the global composite behaviour matrix 6x6, in order to be integrated into a Finite Element Analysis software (CREO / Simulate) to simulate a fixed wing behaviour. Finally, comparisons between experiment and numerical simulation on the wing will give promising results, and simulations will reveal substantial differences between tension & compression in a flexural solicitation.

1 INTRODUCTION

The design of experiments method (Or Taguchi method) is used to study various combinations of sandwich composite. Commonly used in aeronautic design, this method can be implemented in drones design because drones become more and more competitive. This method provides many advantages for drones' design, such as lean sizing and extra weight avoidance to increase drones' performances and reduce manufacturing cost [4].

This approach permits to investigate the effect of each factor on mechanical properties, and offers a way to choose the best sandwich material in order to follow the specifications. Design of experiments finally gives equations that take design factors into account. INSA STRASBOURG team CIGOGNE (https://www.facebook.com/equipecigogne/; https://fondation.unistra.fr/projet/imav2018/) uses this method in the design process of the ELCOD project INTERREG in cooperation with German and French universities. The objective is to design a low-cost long endurance drone. By choosing the correct carbon fibre sandwich for the structure and knowing the correct mechanical behaviour of the material, the objective is to choose the best factors combination that optimizes cost and high strength of the drone.

2 The design of experiments

The design of experiments used is a three factors general full factorial design.

- The first qualitative factor is carbon fibre type (Four levels: A, B, C and D)
- The second quantitative factor is fibre orientation (Two levels: 0° and 45°)

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- The third quantitative factor is PVC foam (AIREX© sheet C70.75 – R&G composite) thickness (Three levels: 1.2mm, 2mm and 5mm)

Thus, for this experiments plan, 24 combinations were tested with tensile tests. Furthermore, for each combination, three experiments were made to test the repeatability of the measure and to have a convincing average response. Those experiments were also made on an article for the IMAV 2015 where the tensile norm and experiments process are clearly explained [1].
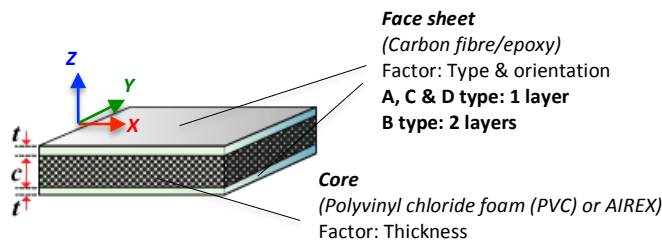

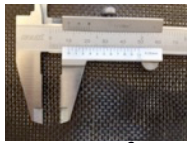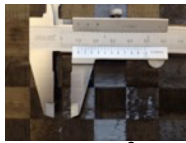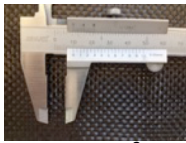**Figure 1 - Sandwich composite structure**

Carbon fibre type

A	C	D
65 g/m^2	**80 g/m^2**	**160 g/m^2**
Plain weave (60 tex)	Spread tow fabric TeXtrem (800 tex)	Plain weave (200 tex)

Table 1 - Carbon fibre type

- *The B type is made with two layers of carbon fibre 65g/m^2 (A type) for the face shee...*
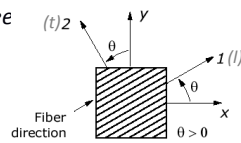- *0° is the XX direction:*

Figure 2 - Fibre orientation

F0	F1 (θ)	F2 (c)		
Carbon fibre type	**Orientation**	**Foam thickness [mm]**		
A	0°	1,2	2	5
	45°	1,2	2	5
B	0°	1,2	2	5
	45°	1,2	2	5
C	0°	1,2	2	5
	45°	1,2	2	5
D	0°	1,2	2	5
	45°	1,2	2	5

Table 2 - Design of experiments; factors' values

3 Results

3.1 Effect of factors

Tensile tests results are analysed to study each effect of factors on mechanical properties: Tensile strength and Young's modulus are the responses studied.
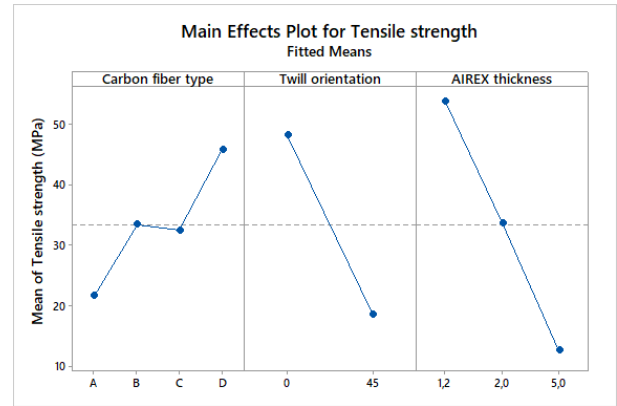

Figure 3 - Effect of each factors on average tensile strength
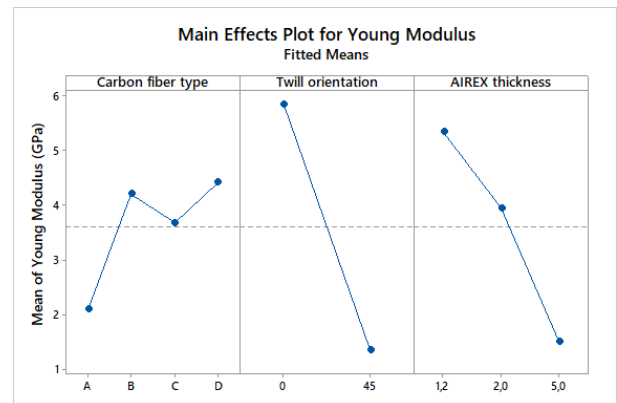

Figure 4 - Effect of each factors on average Young's modulus

When PVC foam thickness increases, average mechanical properties decrease, because sandwich properties converge to foam properties. That is adequately explained with the sandwich rule of mixture [3]. Off-axis orientation decreases also mechanical properties [2, 5].

With this method, a selection can be done:
- A type hasn't got enough mechanical strength
- B type is too expensive in a low-cost design (the carbon fibre surface is doubled compare to the other types)
- 80g/m^2 and 160g/m^2 carbon (C & D type) have to be preferably considered in terms of mechanical properties. In the following, a complete analysis will be done.

3.2 Composite behaviour equations

3D plots give visual results on the best sandwich material composition. The comparison between sandwich C and D is done on the Figures 5 & 6. Behaviour equations are given on the Equation 1 & 2.
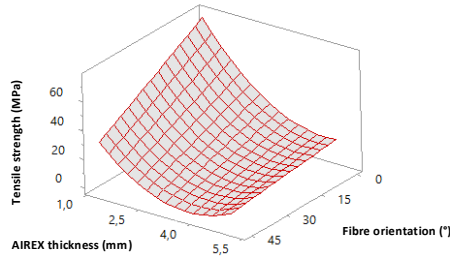
Figure 5 - Carbon fibre C type; factors 3D plot

Figure 6 - Carbon fibre D type; factors 3D plot
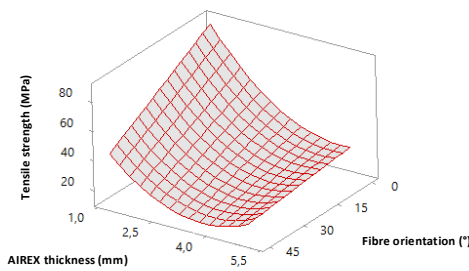
Sandwich C
$\sigma_{max} = 122,1 - 1,23{\times}F1 - 45,0{\times}F2$ $+4,76{\times}F2^2 + 0,21{\times}F1F{\times}2\ (eq.1)$
Sandwich D
$\sigma_{max} = 135,5 - 1,23{\times}F1 - 45,0{\times}F2$ $+4,76{\times}F2^2 + 0,21{\times}F1{\times}F2\ (eq.2)$

Table 3 - Composite behaviour equations (R²=81,04%)
F1: Orientation (θ) - F2: Foam thickness (c)

Equation 1 & 2 gives theoretical tensile strength for this factors combination. It is an important time saving in the design step.

Example: For the carbon fibre C, with θ=0° and foam thickness=3mm:

$$\sigma_{max} = 122,1 - 1,23{\times}0 - 45{\times}3 + 4,76{\times}3^2$$
$$+ 0,21{\times}0{\times}3 = \mathbf{40,94MPa}$$

Design experiments method can be use for structure sizing. By choosing factors values for the composite, it is possible to evaluate the theoretical Young's modulus and tensile strength.

4 Flexural models

The objective is to determine the most adequate flexural model to use in the following study. A 3-points bending test will be done to study flexural behaviour. As sample, a 2mm thickness sandwich beam C type will be tested.

4.1 Castigliano model

Equations 3 & 5 give the deflection Δ [mm] of a composite sandwich beam for a 3-point bending test under a load F [N]:

- $\Delta = \dfrac{Fl^3}{48(EI)_{éq}} + \dfrac{Fl}{4}\dfrac{k}{(GS)}$ (eq. 3) [2]

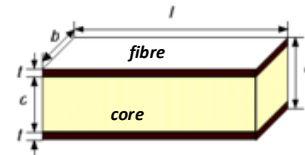With $(EI)_{eq} = \dfrac{E_f bt^3}{6} + \dfrac{E_c bc^3}{12} + \dfrac{E_f btd^2}{2}$ (eq. 4) [6]

Figure 7 - Sandwich composite thickness data

This model takes the separate layers and the shear contribution (second term of Equation 3) into account.

For the bending test, properties of the sample are:
- $E_f = 49$ and $E_c = 0,066$ [GPa]
- $b = 50$, $l = 600$, $c = 2$ and $t = 0,22$ [mm]
- $k = 1$

Note: E_f and E_c are determined with suppliers' data and rule of mixture for E_f with epoxy resin. The error is quantified to +/-5%.

4.2 Homogeneous beam model (Voigt model)

- $\Delta = \dfrac{Fl^3}{48(EI)_{global}}$ (eq. 5)

The term $(EI)_{global}$ is determined with the tensile test from the design of experiments.
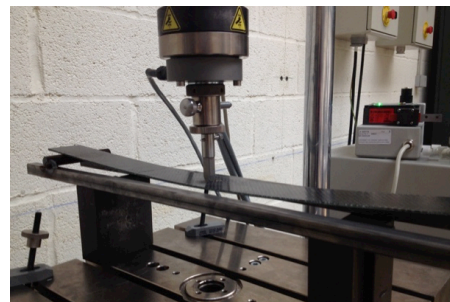
4.3 Experimental 3-points bending test

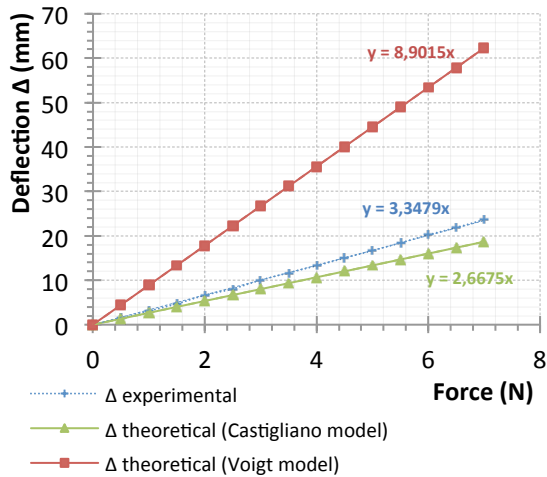Figure 8 - 3-point bending test on sandwich sample (C type)

Figure 9 - Beam comparison between flexural models

Model	Relative error
Castigliano	20%
Voigt	166%

Table 4 - Relative error comparison between flexural models

In flexural solicitation, it's more adequate to use the Castigliano model (Sandwich model): To take the distinct layers into account with the $(EI)_{éq}$ term. The theoretical result will be closer to the reality with this model. For tensile, the macroscopic model can be used; it is by definition the behaviour of a composite with the rule of mixture. However, for flexural solicitation a more elaborate bending theory is needed [2, 7]. This accurate theory takes behaviour of heterogenic layers and the shear contribution into account. That is why the relative error is less important.

5 Best factor combination

Low foam thickness means high tensile strength and high Young's modulus. And high foam thickness means high rigidity (high second moment of inertia). The objective is to find a compromise between high tensile strength and high rigidity.

Thanks to the experiments, the optimization process gives a thickness between **1.8mm and 2,5mm** (white area on the Figure 10) with the carbon fibre C and 0° orientation to insure best

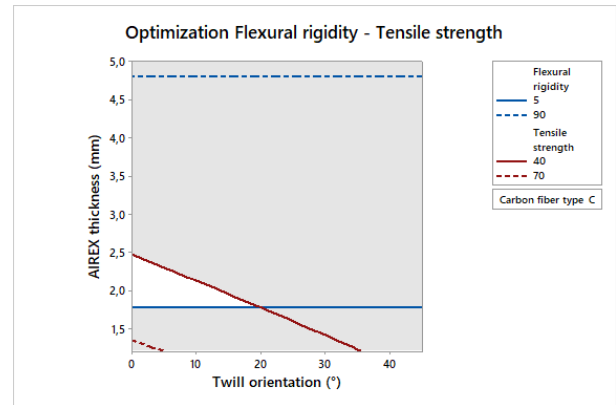compromise between high bending stiffness and high tensile strength:

Figure 10 - Composite thickness optimization

In the following parts, a comparison will be done between a real bending test and a numerical simulation on a C type carbon fibre sandwich wing (NACA MH 32 wing profile) with a carbon fibre sandwich spar. The objective is to study the accuracy of a numerical simulation on complex fixed wing geometry. Thanks to the previous results, the choice of a 2mm foam, Carbon fibre C type is done for the analysis. The multi-layers model will be used to increase the accuracy of the simulation.
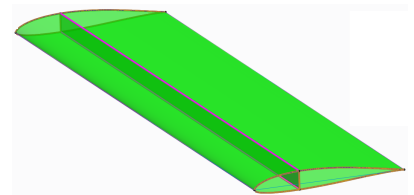

Figure 11 - Experimental wing MH32 + spar Composite sandwich structure C

6 Sandwich mechanical behaviour

The following equations are used for input all material data on CREO Simulate.

$$\begin{cases} E_x(\theta) = \dfrac{1}{\frac{c^4}{E_l}+\frac{s^4}{E_t}+c^2s^2\left(\frac{1}{G_{lt}}-2\frac{\nu_{tl}}{E_t}\right)} \\[3mm] E_y(\theta) = \dfrac{1}{\frac{s^4}{E_l}+\frac{c^4}{E_t}+c^2s^2\left(\frac{1}{G_{lt}}-2\frac{\nu_{tl}}{E_t}\right)} \\[3mm] G_{xy}(\theta) = \dfrac{1}{4c^2s^2\left(\frac{1}{E_l}+\frac{1}{E_t}+2\frac{\nu_{tl}}{E_t}\right)+\frac{(c^2-s^2)^2}{G_{lt}}} \end{cases} \quad \text{(eq. 6)} \quad [2]$$

Equations 6 can give G_{lt} thanks to the tests at $\theta = 45°$. Thus, all coefficients of stiffness matrix $[Q]$ can be determined for each layer:

$$[Q]_{Facesheet} = \begin{bmatrix} 58,47 & 14,03 & 0 \\ 14,03 & 58,47 & 0 \\ 0 & 0 & 30,47 \end{bmatrix}_{0°/90°}$$

$$[Q]_{Foam} = \begin{bmatrix} 0,073 & 0,022 & 0 \\ 0,022 & 0,073 & 0 \\ 0 & 0 & 0,028 \end{bmatrix}$$

(Units in GPa)

Distinct layers have to be integrated into the behaviour matrix 6x6, in order to get macroscopic sandwich composite behaviour:

$$[N] = \begin{bmatrix} A_{11} & A_{12} & 0 & B_{11} & B_{12} & 0 \\ A_{12} & A_{22} & 0 & | & B_{12} & B_{22} & 0 \\ 0 & 0 & A_{66} & & 0 & 0 & B_{66} \\ & — & & & — & \\ B_{11} & B_{12} & 0 & D_{11} & D_{12} & 0 \\ B_{12} & B_{22} & 0 & | & D_{12} & D_{22} & 0 \\ 0 & 0 & B_{66} & & 0 & 0 & D_{66} \end{bmatrix} \text{(eq. 7)}$$

With:

$$A_{ij} = \sum_{k=1}^{n} Q_{ij}{}^{k} e_{k} \text{ (8)}$$

$$B_{ij} = \frac{1}{2}\sum_{k=1}^{n} Q_{ij}{}^{k}\left(h_{k}^{2} - h_{k-1}^{2}\right) \text{ (9)}$$

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n} Q_{ij}{}^{k}\left(h_{k}^{3} - h_{k-1}^{3}\right) \text{ (10)}$$

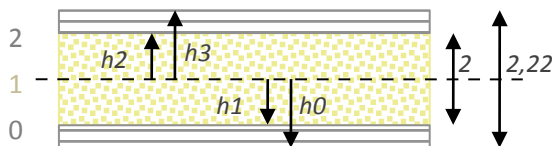*Note: For a symmetric composite: $B = 0$*

Figure 12 - Sandwich composite layers thickness

Finally, the carbon fibre/foam 2mm sandwich composite macroscopic behaviour can be expressed with this matrix:

$$[N] = \begin{bmatrix} 13009 & 3131 & 0 & & & \\ 3131 & 13009 & 0 & | & & 0 \\ 0 & 0 & 6759 & & & \\ & — & & 14379 & 3453 & 0 \\ & 0 & & | & 3453 & 14379 & 0 \\ & & & & 0 & 0 & 7486 \end{bmatrix}$$

(A matrix in N/mm; D matrix in N.mm)

7 Sandwich simulations

After computing matrix behaviour data (Equation 7) into CREO Simulate, flow stress and beam is calculated with a 10N load at the edge of the tested wing:
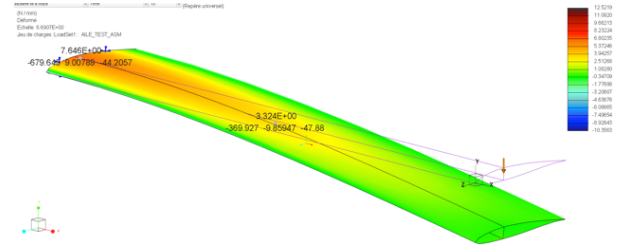

Figure 13 – Flow stress XX (N/mm) simulation on sandwich composite C; wing + spar   (Display beam scale: 10%)

The upper side of the wing is in tension and the lower side in compression. The maximum stress is reach in the spar of the wing. It is this part on the wing which takes up efforts.

8 Sandwich experimental test

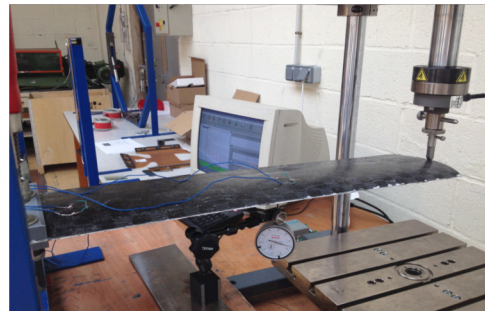The objective is to compare simulation with an experimental bending test:

Figure 14 - Experimental Zwick Roell bending test bench

Strain is measured in three points with strain gauges:

Pt1: Upper side, close to rigid link

Pt2: Lower side, close to rigid link
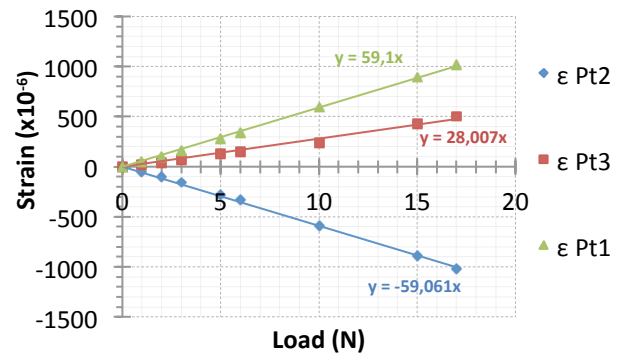
Pt3: Upper side, middle of the wing

Figure 15 - Experimental wing strain on 3 points

In the experimental test, the tensile stress on the upper side of the wing is the same than the compressive stress on the lower side of the wing.

For compression the relative error is more important because it is difficult to predict compressive behaviour for fibre due to crushing, buckling and fibre delamination. Those results are showed in the Table 5.

	Numerical	Experimental	
	Stress XX (MPa)		Error
Pt1	3,83	3,95	3,1%
Pt2	-3,15	-3,94	25%
Pt3	1,66	1,63	1,8%
	Beam UY (mm)		Error
Max	10,31	13,62	25%

Table 5 - Relative error on stress and beam comparison

9 CONCLUSION

Design of experiments has made possible the choice the best sandwich composite for the corresponding application and gives equations to correctly design the composite structure. This method has to be used to design drones; it is an important time saving to compare structures and to choose the best factors' values.

After choosing the adequate sandwich composite, numerical simulations show that composite behaviour is not the same in tension or compression for high deformations. Even if the model with distinct layers is more accurate than the homogeneous model, investigation can be done to improve this theory. Buckling and fibre delamination can occur for compression, and a more exhaustive theory that takes layers slippage and plastic deformation into account has to be used. The flexural behaviour is non-linear for high compressive deformations [7]; and for the experiment of the present article, increasing the load to produce higher deformations could permit to study a more accurate non-linear compressive behaviour and reveal buckling [7, 8]. To go further with simulation, Tsai-Wu failure criterion can be used to study the limit of the composite, plus observation on sample have to be done to investigate damage and failure [8]. For numerical simulation, it is possible to be confident with tension, because the behaviour is linear-brittle

and error is under 5%. However, it is highly recommended to be careful when local compression appears. Indeed, the current model is neither accurate nor optimal and simulation error is higher than 25% because of buckling.

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