FIBER WAVINESS CHARACTERIZATION AND NUMERICAL ANALYSIS OF CURVED STRUCTURAL PROFILES FOR AIRCRAFT APPLICATIONS

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Abstract. *Fiber-reinforced composite materials have become an attractive alternative to traditional metallic materials for several aircraft components due to their high specific properties. The current challenge for the aircraft industry is to employ these materials in the fuselage and wing structures of aircrafts. For this, it is mandatory to design materials, components and manufacturing processes carefully in order to achieve the desired properties and safety factors. In this context the pultrusion process can lead an important role for this industry, because straight and curved structural profiles can be fabricated by reasonable costs and high production rates in the future. Nevertheless, some fiber waviness was reported in curved profiles. Considering the fiber waviness as an inherent deviation of the manufaturing process, it is important to understand the effects of this imperfection on the mechanical properties. In order to characterize the material, several image analyses were performed with different techniques for micro and macro scale pictures. With these results, the loss of the mechanical properties was predicted by mathematical relations. Finally, a numerical model was built to evaluate the mechanical behavior of the composite profile, in terms of stiffness and critical buckling load. Therefore, it is possible to predict the influence of the fiber waviness in a fuselage design context.*

Keywords*: Composite structures, Fiber waviness, Curved profiles, Pultrusion, Finite elements method.*

1. INTRODUCTION

It is widely known the importance of the composite materials for the aircraft industry, notably the carbon-epoxy layup. Big companies like Airbus and Boeing are continuously investing their efforts to increase the amount of this material in the structure of aircrafts in order to reduce weight and fuel consumption. Thus, operating costs and gas emissions can be reduced due to optimized and high specific properties of the laminated composite materials.

Many components of the aircrafts already use composite materials technology to reduce the mass. However, the current challenge for these industries is to employ this material in the fuselage and wing structures. To attend the aircraft industry it is necessary to reach not only the component requirements of the project, but the manufacturing process also. Therefore, productive manufacturing processes are very important to achieve the adequate production rates and reasonable costs. In this context, the pultrusion manufacturing process can lead an important role for aircraft industry.

Nevertheless, during the manufacturing process some fiber waviness was reported in curved composite T-profiles for stringer-stiffened panels. Hence, the purpose of this work is to evaluate the effects of out-of-plane fiber waviness on the mechanical properties by analytical and numerical methods.

Firstly, a comprehensive characterization of the fiber waviness was performed in order to describe the phenomenon. With this information, the mechanical properties can be predicted by mathematical modeling, based on the theory of elasticity and mechanics of laminated composite materials. Finally, a structural analysis of curved composite profiles for aircraft applications was conducted with numerical methods in order to evaluate the mechanical behavior. In an aircraft structural design context, it is fundamental to predict how these imperfections can influence the mechanical behavior of the component.

2. PULTRUSION

Developed in the early 1950's, pultrusion is a continuous and automated manufacturing process that is cost effective for high volume production of composite profiles. Due to uniformity of the geometry and fiber distribution and alignment, structural profiles can be fabricated by this process. These pultruded products can compete directly with traditional metal profiles and finally replace them in the future because of their excellent mechanical properties and durability, especially in corrosive environments.

Many research programs on manufacturing processes of composite materials are conducted in Faserinstitut, because it is known that the development of automatic production technologies is indispensable for cost-effective breakthrough of CFRP (Carbon Fiber Reinforced Plastics) components in aircraft structures. So, the development of the pultrusion process is considered a key factor for this area, since high quality structural profiles can be fabricated with reasonable costs and high production rates.

2.1. Manufacturing process of curved profiles

The standard pultrusion process can be adapted to produce curved composite profiles. Basically, the pulling device operates and the curvatures arise rearward the pullers. The radius of the profile becomes a function of the slope angle and other process parameters, like temperature and velocity. In addition, if some parameters were controlled (pulling speed and die configuration) the pultrusion process could also produce profiles with non uniform curvature. Figure 1 explains the operation of pultrusion machine for curved profiles.

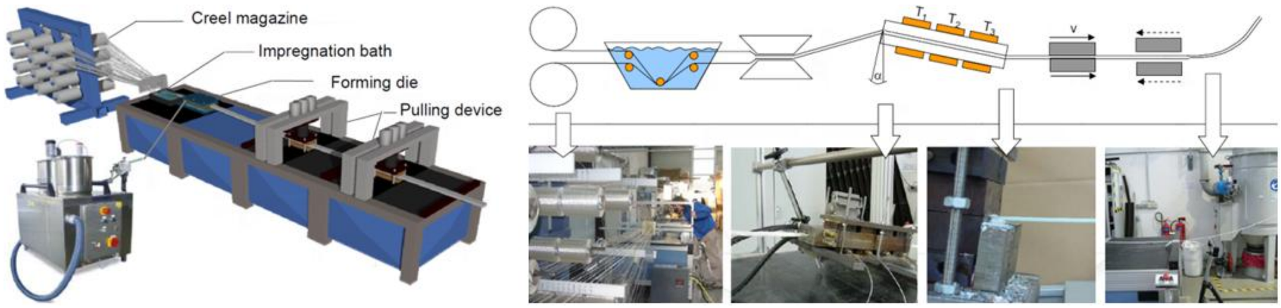

Figure 1. Pultrusion equipment of Faserinstitut and Curved pultrusion process (Purol and Dommes, 2008)

2.2. Curved profiles and aircraft applications

Composite curved profiles are very important for aircraft applications. The development of pultrusion is the first step of the continuous production of curved profiles in order to substitute current RTM (Resin Transfer Molding) and autoclave processes. Typically, the fuselage structures are curved with radii between 2 m (frames) and 8 m (stringers).

3. FIBER WAVINESS

In the case of curved stringers with radii about 8000 mm, manufactured by the pultrusion process, some out-of-plane waviness was reported on the inner surface of the profile (Fig. 2). This imperfection was related only because of the bending process, since the straight ones were virtually perfect. It is important to describe how these phenomena can affect the properties of the component, because some waviness is inherent to the manufacturing process. So, the component designer must be careful to include these imperfections in the project.

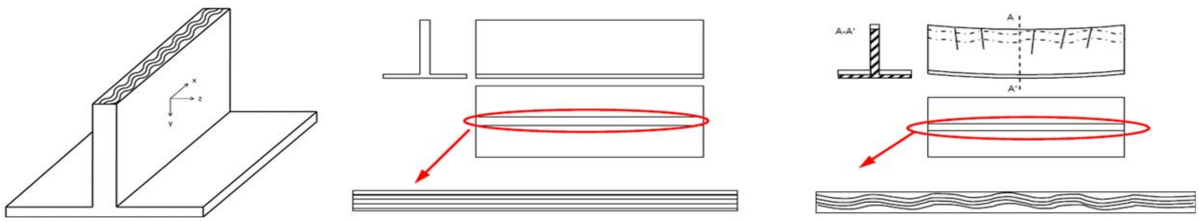

Figure 2. Fiber waviness description

It is known that reinforcing fibers have to be optimally elongated in a structure to achieve the maximum fiber characterized material properties in terms of stiffness and strength. In any case, the observed fiber waviness significantly reduces the material and product characteristics. The use of such qualitative partially degraded stringers to stiffen a thin curved CFRP fuselage panel may be reliable if the influences of the fiber waviness to the overall structural stability behavior could be analyzed and further quantified.

Several papers (Hsiao and Daniel, 1996; Chun *et al.*, 2001; and Soutis, 2000) relate the loss of mechanical properties of composite parts due to fiber waviness, mostly under compressive loadings. In the case of longitudinal compression, the loss of the strength is related to the micro buckling mechanism. Therefore, with the increasing use of thick composite structures under compressive loadings, the effect of fiber waviness becomes a significant subject. Piggott (1995) also discuss fatigue problems related to fiber waviness.

Quality norms of composite parts specify a tolerance of fiber waviness. General requirements establish that the maximum angle must satisfy the following condition: $-5 \leq \theta_{max} \leq +5$.

In addition, previous work reported a relation between the fiber waviness and the height of the web of curved T-profiles produced by pultrusion process. It was shown that the waviness decreases along the height of the web from top to bottom (Fig. 3). The gradient of waviness in the profile is related to angle deviation and amount of data out of tolerances.

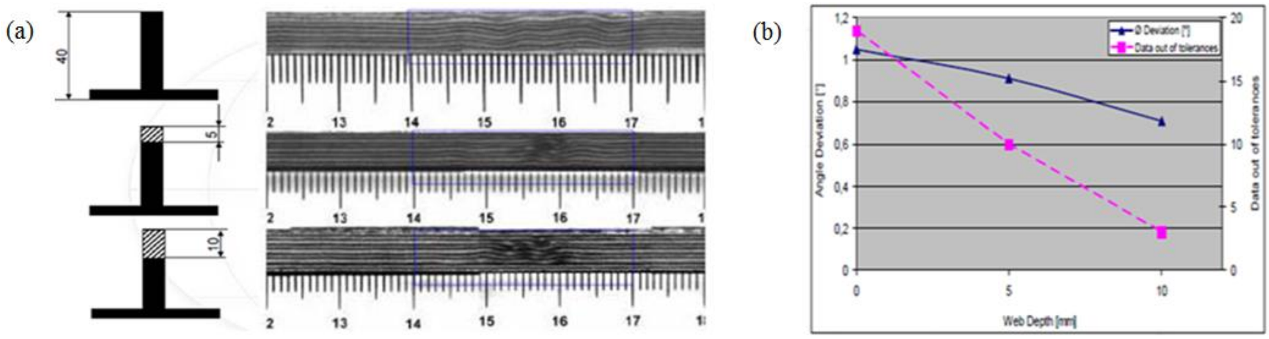

Figure 3. Waviness (a) and Gradient of waviness along the height (b) (Purol and Dommes, 2008)

4. IMAGE ANALYSIS

Different image analysis techniques were employed to characterize the curved profiles. The information obtained by these procedures is essential to perform the calculations concerning the structural analysis of the component. The mechanical behavior of composite materials is highly dependent of the configuration of the layers, fiber orientation, thickness, fiber content and defects. Firstly, a micro scale analysis was performed to describe the material, and then a macro scale analysis was conducted to characterize the fiber waviness.

4.1. Micro scale

The purpose of the micro scale analysis is to characterize the layers of the laminate, evaluating the fiber orientation and thickness of each layer, by optical microscopic techniques. Hence, preparation of the samples by metallographic procedures was needed to evaluate properly the tops of the web and the flange of the profile. The thickness was measured by an average value of three measurements (Fig. 4).

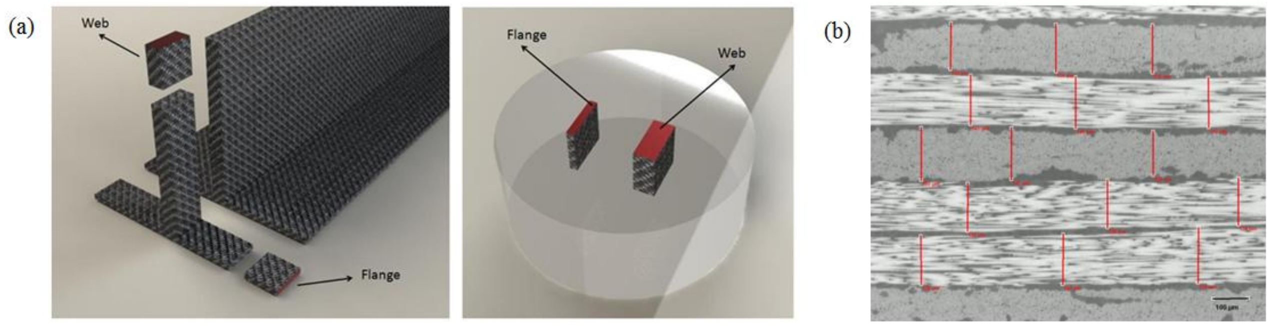

Figure 4. Preparation of samples (a) and Thickness measurement, 50x (b)

The fiber orientations were identified based on the fact that carbon fiber tends to be very reflective (or to show a high degree of contrast) compared to thermoset resins. However, it was difficult to distinguish 90° configuration from 45° based only by the pictures, because they have similar cross-sections. Moreover, it depends on the reference plane (cutting plane) of the sample. The results of this analysis will be used during the finite element procedures.

4.2. Macro scale

Macro scale pictures were taken to analyze specifically the fiber waviness on the top of web along the length. Quantitative information about angle, wavelength, amplitude and distribution are expected. The aim of this image analysis software is to find the borderlines between the different layers of the composite material, which show different colors (grey and dark grey stripes) within the image. The computational tool avoids the long time consuming of a manual analysis, performing all the following procedures in a matter of seconds: image preparation, finding lines, finding waves in the lines, filter criteria and data treatment.

The identified waves are shown through detailed tables and pictures with highlighted lines and important points of the waves (Fig. 5a). The meaning of the colored lines and points are explained in Fig. 5b.

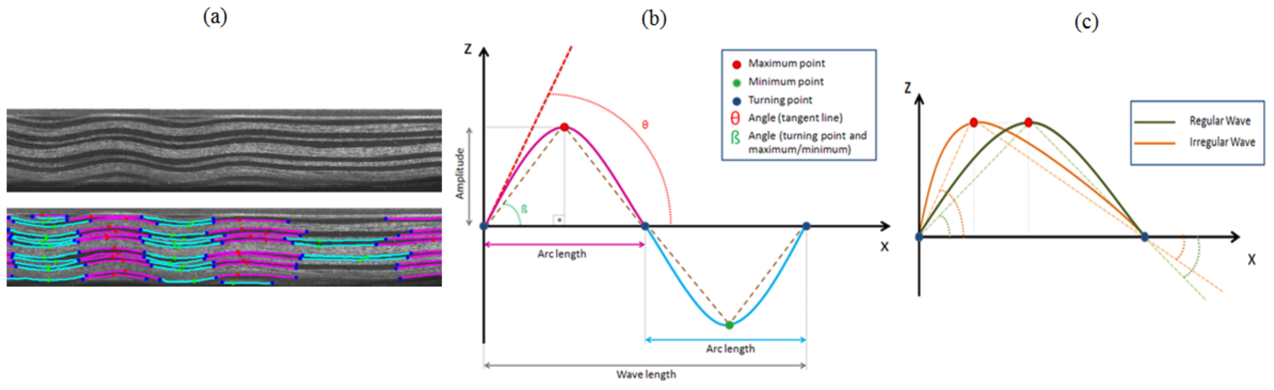

Figure 5. Results (a), Representation of fiber waviness (b) and ß values (measured and calculated) (c)

In order to improve the waviness characterization, more details were obtained based on mathematical relations. Data of result table were organized to obtain more information indirectly. It is possible to describe mathematically the fiber waviness based on the general sinusoidal function, as shown in Eq. (1).

$$z = A\sin\left(\frac{2\pi x}{L}\right) \tag{1}$$

where A is the amplitude and L is the wavelength (Fig. 5b).

Applying simple differential operations, the maximum angle, denoted by θ_{max}, is finally found.

$$\frac{dz(0)}{dx} = \tan(\theta_{max}) = 2\pi\left(\frac{A}{L}\right) \tag{2}$$

θ_{max} can also be written in terms of the arc length, L_A, idealized as half wave length.

$$\theta_{max} = \tan^{-1}\left(\frac{2\pi A}{L}\right) = \tan^{-1}\left(\frac{\pi A}{L_A}\right) \tag{3}$$

The angle found directly by the image analysis software was measured through the lines between the turning point and maximum/minimum and the horizontal. This angle can be estimated mathematically by trigonometric relations, similarly to θ_{max}, as depicted as follows.

$$\tan(ß) = \frac{4A}{L} \tag{4}$$

$$ß = \tan^{-1}\left(\frac{4A}{L}\right) = \tan^{-1}\left(\frac{2A}{L_A}\right) \tag{5}$$

It is very important to underline that all these equations consider a regular wave form, described by Eq. (1). Therefore, some different results are expected between the measured and calculated values. It is expected that measured ß angles show bigger values than calculated ß, because each measured angle is a mean value of Angle 1 and Angle 2. So, this difference is basically related to the horizontal displacement of the extreme point between the turning points due to the irregularity of the wave, as shown in Fig. 5c. In any case, this comparison is interesting to consolidate the analysis and the characterization method.

Table 1 contains the tolerance values of image analysis software. For the second analysis, another filter criterion was further used to refine the results based on the maximum angle criteria ($\theta_{max} \geq 5°$).

Table 1. Tolerance values of filter criterion

Analysis	**Angle ($ß_{measured}$) (°)**	**Height (pixel)**	**Width (pixel)**	**Waviness (pixel/pixel)**
First (all lines)	0.0°	0.0	0.0	1.0
Second (wavy lines)	3.0°	1.0	5.0	1.0

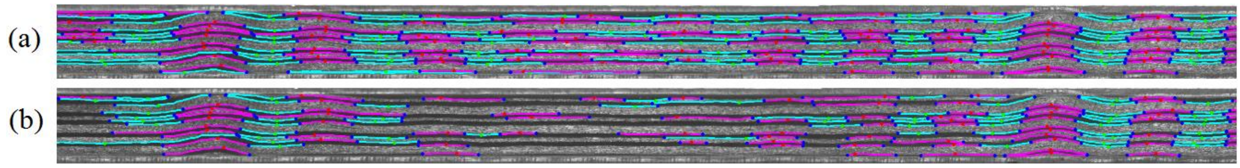

Figure 6. Image analysis results: All lines (a) and Wavy lines (b)

Additionally, in order to evaluate the waviness along the length of the profile, the element was divided in 50 mm sections. The average values of the angles of each part were reunited, as shown below. The average value of all the lines for each case was also included in the same graph.

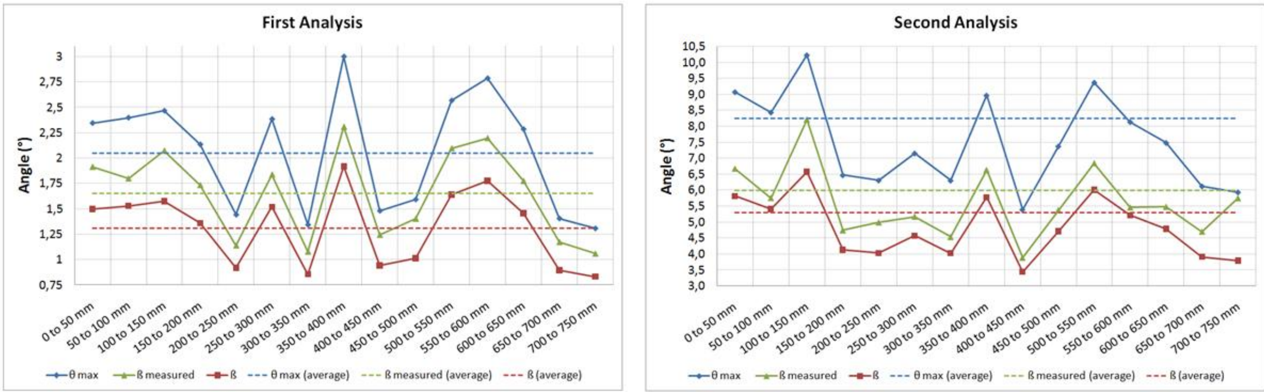

Figure 7. Results: First analysis ($\boldsymbol{\theta_{max}} \geq \mathbf{0}°$) and Second analysis ($\boldsymbol{\theta_{max}} \geq \mathbf{5}°$)

In all profiles, the behavior of the angle results was always $\theta_{max} > \beta_{measured} > \beta$. Therefore, there is a good agreement between theory and results. Moreover, both analysis results show a random distribution of waviness along the length of the profile in terms of amount and intensity. This fact was really expected because the samples were produced by a continuous process.

5. MATHEMATICAL MODELING

Mathematical relations were employed to correlate the fiber waviness characteristics and the mechanical properties of the composite material. It was assumed a linear elastic behavior for the material.

5.1. Prediction of the loss of mechanical properties

The relation between strains and stresses are calculated through the general compliance matrix of orthotropic materials, presented in Eq. 6.

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{Bmatrix} = \begin{bmatrix} 1/E_1 & -\nu_{21}/E_2 & -\nu_{31}/E_3 & 0 & 0 & 0 \\ -\nu_{12}/E_1 & 1/E_2 & -\nu_{32}/E_3 & 0 & 0 & 0 \\ -\nu_{13}/E_1 & -\nu_{23}/E_2 & 1/E_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{12} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{Bmatrix} \tag{6}$$

The mechanical properties were predicted for the case of regular and uniform fiber waviness (Hsiao and Daniel, 1996). For that, the average strain was calculated by the general definition of the average value of any function.

$$\overline{\varepsilon_x} = \left\{\frac{1}{L}\int_0^L S_{xx}\, dx\right\}\overline{\sigma_x} \tag{7}$$

$$\overline{\varepsilon_x} = [S_{11}I_1 + (2S_{12} + S_{66})I_3 + S_{22}I_5]\overline{\sigma_x} \tag{8}$$

Where S_{ij} is the compliance matrix term and I_n is a constant involving the fiber waviness characteristics.

So, considering a plane stress assumption for the material, the required elastic properties for the structural analysis are obtained as follows.

$$I_1 = \frac{1+\alpha^2/2}{(1+\alpha^2)^{3/2}} \tag{9}$$

$$I_3 = \frac{\alpha^2/2}{(1+\alpha^2)^{3/2}} \tag{10}$$

$$I_5 = 1 - \frac{1+3\alpha^2/2}{(1+\alpha^2)^{3/2}} \tag{11}$$

$$I_6 = \frac{1}{(1+\alpha^2)^{1/2}} \tag{12}$$

$$I_8 = 1 - \frac{1}{(1+\alpha^2)^{1/2}} \tag{13}$$

$$\alpha = 2\pi \frac{A}{L} = \pi \frac{A}{L_A} = tan\, \theta_{max} \tag{14}$$

$$E'_1 = \frac{1}{S_{11}I_1+(2S_{12}+S_{66})I_3+S_{22}I_5} \tag{15}$$

$$E'_2 = \frac{1}{S_{22}} \tag{16}$$

$$\nu'_{12} = -\frac{S_{12}I_6+S_{23}I_8}{S_{11}I_1+(2S_{12}+S_{66})I_3+S_{22}I_5} \tag{17}$$

$$G'_{12} = \frac{1}{2(S_{22}-S_{23})I_8+S_{66}I_6} \tag{18}$$

$$G'_{13} = \frac{1}{4(S_{11}+S_{22}-2S_{12})I_3+S_{66}(I_1-2I_3+I_5)} \tag{19}$$

$$G'_{23} = \frac{1}{2(S_{22}-S_{23})I_6+S_{66}I_8} \tag{20}$$

Based on these relations, Fig. 8 shows the influence of the fiber waviness on the elastic properties of the material. It was found a good agreement when compared to the paper of Rai *et al.* (2007).

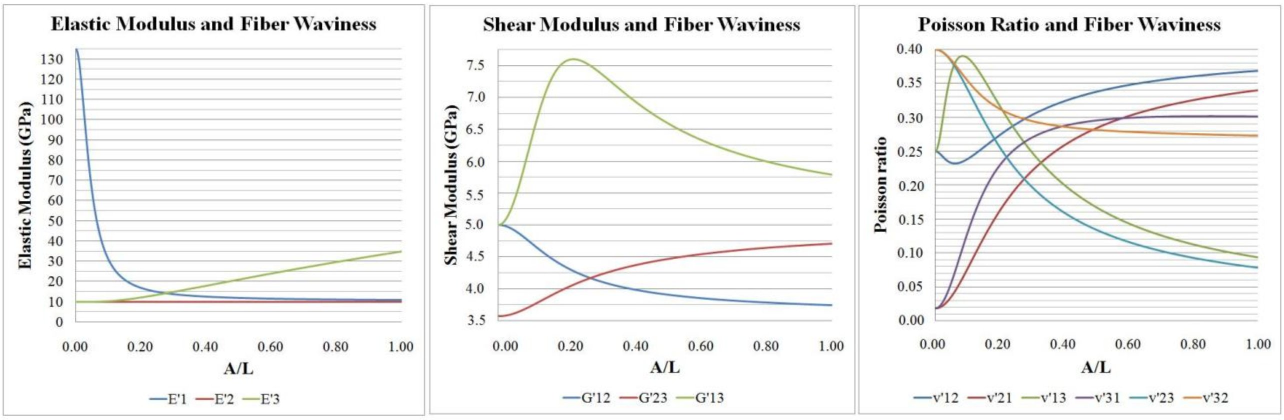

Figure 8. Elastic material properties and fiber waviness

5.2. Mechanics of laminated composite materials

The obtained elastic properties are employed in the classical theory of laminated composite materials, which works inside the FEM software. The properties are introduced in extensional and flexural stiffness terms of the matrix. The general equation is presented as follows.

$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{21} & A_{22} & A_{26} & B_{21} & B_{22} & B_{26} \\ A_{61} & A_{62} & A_{66} & B_{61} & B_{62} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{21} & B_{22} & B_{26} & D_{21} & D_{22} & D_{26} \\ B_{61} & B_{62} & B_{66} & D_{61} & D_{62} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix} \tag{21}$$

$$A_{ij} = \sum_{k=1}^{n} \left(Q_{ij}\right)_k (h_k - h_{k-1}) \tag{22}$$

$$B_{ij} = \sum_{k=1}^{n} \left(Q_{ij}\right)_k \frac{(h_k^2 - h_{k-1}^2)}{2} \tag{23}$$

$$D_{ij} = \sum_{k=1}^{n} \left(Q_{ij}\right)_k \frac{(h_k^3 - h_{k-1}^3)}{3} \tag{24}$$

6. FEM MODEL

A finite element model was build to evaluate the influence of the predicted loss of mechanical properties on the component. All the previous data about the fiber waviness were reunited in this numerical model. Therefore, information about stiffness and critical buckling load for the component with and without waviness can be properly evaluated and compared. It is expected that critical buckling load presents lower values, since it is dependent on the elastic modulus, as denoted by Euler column's equation:

$$P_{cr} = \frac{n^2\pi^2 EI}{L^2} \tag{25}$$

Where: E is the elastic modulus, I is the moment of inertia of the cross-section and L is the length of the bar. Since the first mode is being investigated, it is assumed that $n = 1$.

6.1. Geometry

The FEM analysis investigated a stiffened fuselage panel, composed by the following parts: skin and T-profile (web and flange). All parts were merged, so there are no interactions among them. Three geometries of panels were analyzed and then compared: flat, cylindrical and spherical. They were modeled as surfaces in order to discretize the composite material as shell elements. The thickness of each region is introduced during the shell formulation, depending on the composite layup. In order to compare the results, same mesh size was used for all the analysis.

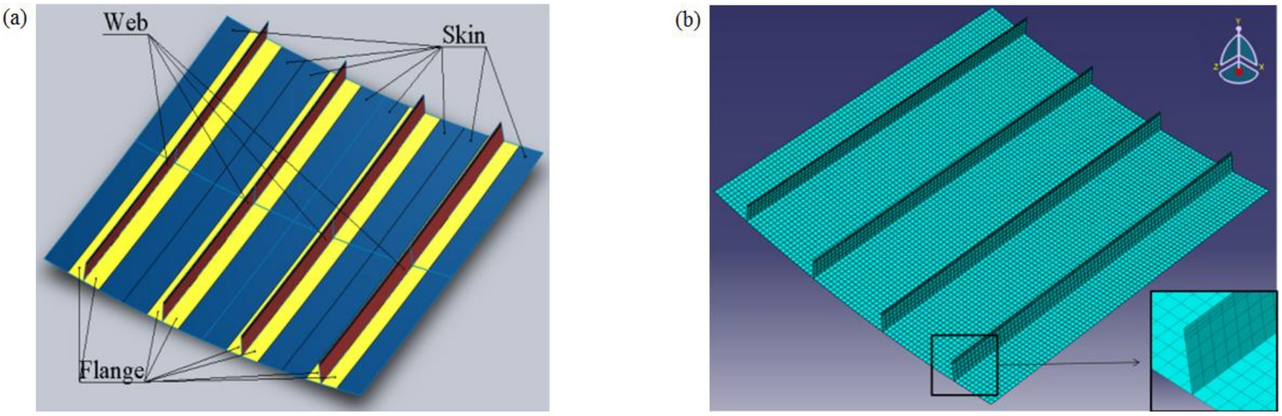

Figure 9. Parts of fuselage panel (a) and Structured 8-node shell elements (b)

As observed in Fig. 10b, the web of T-profile was divided in regions, because different material properties were assigned to each part of web, depending on the fiber waviness. The top of the web is the most affected region of the profile (Fig. 3a). A linear gradient of properties was considered between regions with and without fiber waviness, as observed in Fig. 3b. Table 2 shows the angles of each region for three waviness conditions.

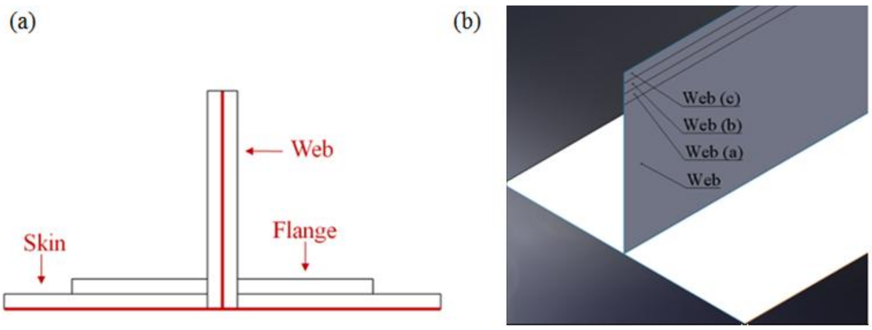

Table 2. Waviness values

Region	$\boldsymbol{\theta_{max}}$ **(°)**		
Web (c)	5	10	15
Web (b)	3.33	6.66	10
Web (a)	1.66	3.33	5
Web	0	0	0

Figure 10. Shell offset (a) and Sub regions (2.5 mm) (b)

6.2. Material properties

All parts were made of CFRP and the elastic properties of affected regions were predicted by Eq. (9) to Eq. (20) and then organized in the table below. The intermediate properties of web (Fig. 10b) were predicted by the same equations assuming a linear decrease of fiber waviness along the height (Tab. 2). For CRFP Fabric, the elastic modulus is the same for longitudinal and transverse directions. Moreover, it should be noted that 90° layers of web are not affected by fiber waviness, considering the reference angle coincident with length direction of the profile.

Table 3. Main elastic properties

Material	θ_{max} (°)	E_1 (GPa)	E_2 (GPa)	ν_{12}	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)
CFRP Uni [(a)]	0	135.00	10.00	0.250	5.000	5.000	3.846
CFRP Fab [(b)]		57.00	57.00	0.320	3.800	3.800	21.923
CFRP Uni (5)	5	123.40	10.00	0.242	4.994	5.034	3.850
CFRP Fab (5)		54.43	54.43	0.305	3.812	3.849	21.528
CFRP Uni (10)	10	98.79	10.00	0.225	4.977	5.135	3.860
CFRP Fab (10)		48.19	48.19	0.270	3.848	3.995	20.448
CFRP Uni (15)	15	73.90	10.00	0.209	4.949	5.310	3.877
CFRP Fab (15)		40.54	40.54	0.227	3.912	4.261	18.817

[(a)]: Unidirectional fibers, [(b)]: Fabric 0°/90°

These material properties were employed and properly oriented in the composite layup. It should be noted that the shear moduli G_{13} and G_{23} are included because they may be required for transverse shear calculations in a shell. A general composite layup for stiffened structures was considered. The symmetric layup avoids some coupling terms of stiffness matrix of the laminate (Eq. 21). This is very helpful to prevent defects during the manufacturing process.

6.3. Loadings

Compressive loadings were applied with standard boundary conditions for stiffened panels, as described by Zimmermann *et al.* (2006). An axial load of 10 kN was distributed along the width of the panel, as shown in Fig. 11a. Coupling constraints were employed to distribute the loadings and boundary conditions along the edges of panel.

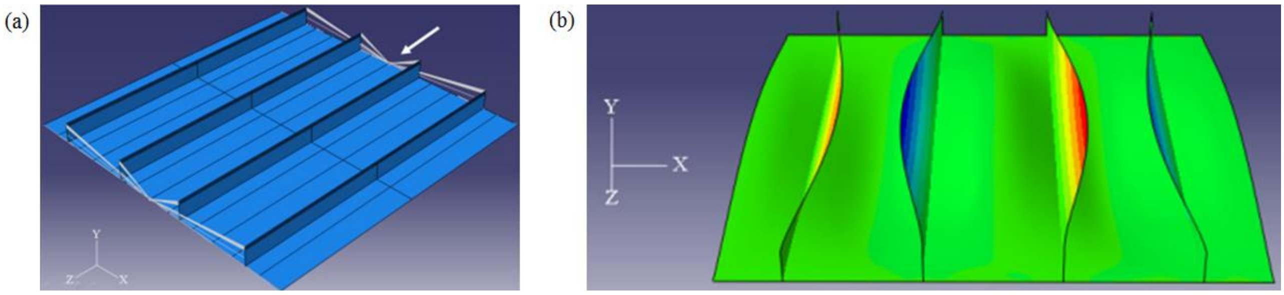

Figure 11. Compressive loading (a) and Deformed shape in X direction (b)

6.4. Results

The numerical results of linear buckling and static analysis were organized in the table below. Qualitatively, it was found a good agreement in the results, once as the fiber waviness increases, the eigenvalue buckling decreases. The deformed shape of buckling analysis in X direction shows the influence of the loss of the stiffness in the top of web due to the fiber waviness (Fig. 11b).

Table 4. Results: eigenvalue buckling prediction and static analysis

Geometry	**Flat**				**Cylindrical**				**Spherical**			
Waviness (θ_{max})	–	5°	10°	15°	–	5°	10°	15°	–	5°	10°	15°
Eigenvalue Buckling [(1)]	8.756	8.737	8.692	8.642	24.27	24.21	24.09	23.95	26.64	26.56	26.40	26.20
Z direction (10^{-2} mm) [(2)]	4.170	4.181	4.206	4.233	4.332	4.344	4.370	4.400	4.563	4.581	4.621	4.669
X direction (10^{-3} mm) [(2)]	1.931	1.938	1.953	1.971	18.34	18.38	18.47	18.58	2.258	2.261	2.267	2.273
Y direction (10^{-2} mm) [(2)]	1.649	1.653	1.664	1.675	3.229	3.236	3.252	3.270	8.001	7.956	7.855	7.727

[(1)]: Linear Buckling analysis, [(2)]: Static analysis – Maximum displacements

For each geometry the deformed shape of the first mode was the same. Figure 12 shows the likely failure mode of the structure. There is no information about the magnitude of deformation at critical load because the buckling mode shapes are normalized vectors.

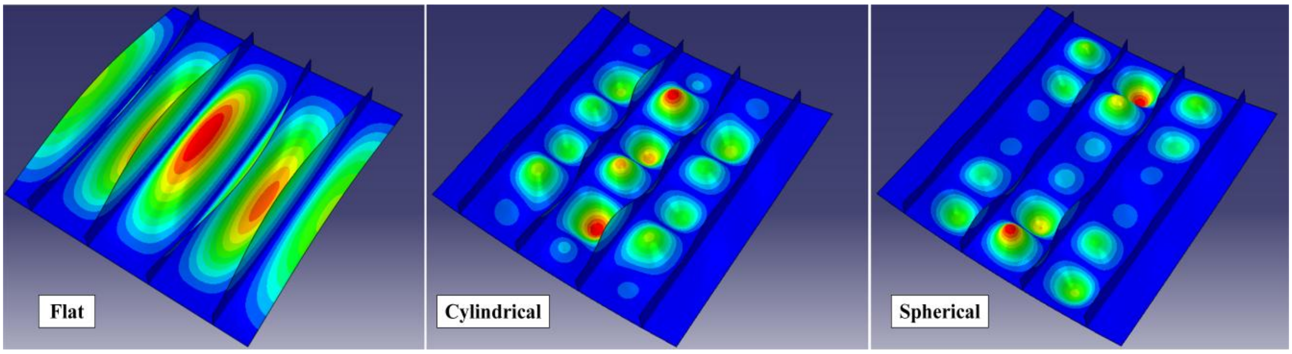

Figure 12. Eigenvalue buckling prediction. Deformed shape of first mode.

The loss of stiffness can also be realized in terms of displacement in a linear elastic analysis. All displacement components were slightly affected, as observed in Tab. 4. Figure 13 shows the results of static analysis in terms of displacements.

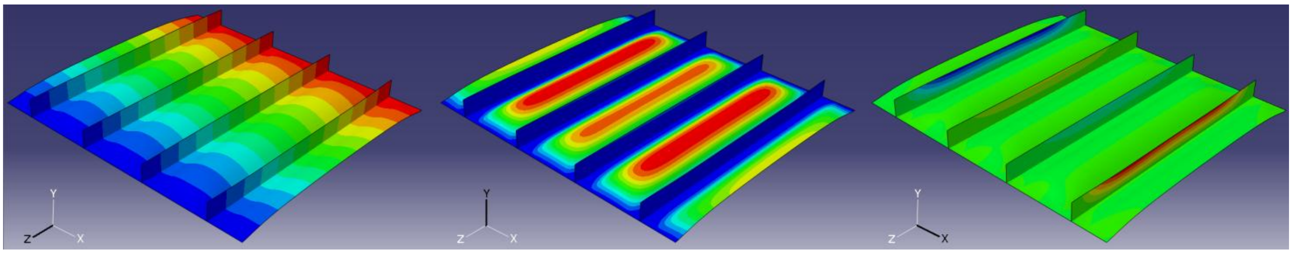

Figure 13. Displacements of static analysis. Flat geometry

7. CONCLUSIONS

Research involving the fiber waviness is important to achieve a continuous manufacturing process for curved composite profiles and then reduce the manufacturing costs. That would consolidate the applications of pultrusion process and laminated composite materials for aircraft industry. Numerical methods are useful to analyze and predict the mechanical behavior of components, including unexpected failures in structures due to small imperfections.

This work was a first step for the evaluation of fiber waviness in curved profiles. Image analysis techniques and structural analyses were employed to estimate the effects of this deviation on the mechanical behavior of the component. It was found a small influence of fiber waviness on the mechanical behavior, in terms of linear buckling and linear elastic analysis.

Obviously, further work must consider experimental data with the stiffened panel (buckling test) or even small samples in order to verify the magnitude of the values. In addition, supplementary simulations, like nonlinear and post-buckling analyses, are also important to evaluate this kind of structure. As a reference, Almeida *et al.* (2009) performed numerical and experimental post-buckling analyses. Additionally, the positive effects of fiber waviness can be analyzed mainly in terms of interlaminar shear stresses. The changing of fiber direction can be beneficial to this aspect.

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