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Buckling behavior of wind turbine blade

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Résumé - *De nos jours, l'utilisation des matériaux composites a pris de l'ampleur vis-à-vis des matériaux traditionnels, dans pratiquement tous les secteurs industriels où nous avons besoin de structures puissantes, légères et rentables, tel que le secteur de l'énergie éolienne. En effet, les pales d'éoliennes représentent un exemple concret de ce type de structures en matériaux composites. Actuellement, les pales d'éoliennes modernes deviennent considérablement grandes avec une longueur dépassant les 60 m. Les pales d'éoliennes sont souvent confrontées à des charges extrêmement complexes en raison des conditions environnementales qu'elles subissent. L'une des charges importantes agissant sur les pales sont ceux de pression, qui peuvent engendrer le fléchissement de la structure. D'autre part, la conséquence de la stratégie de conception optimale, les pales deviennent des structures à parois minces, ce qui augmente le risque de flambement. Par conséquent, la compréhension du comportement de la pale sous ce type de charges est cruciale. Dans ce travail, une étude par éléments finis du comportement de flambement du longeron d'une pale éolienne est présentée. Pour ce faire, un longeron d'une pale avec un profil NACA 634-421 a été choisi. Le longeron est considéré comme étant une coque cylindrique composite multicouche. L'étude porte sur l'effet du choix du matériau, la séquence d'empilement ainsi que le nombre de couches sur la résistance au flambement du longeron. Les résultats obtenus ont montré que la charge critique de flambement est très sensible aux paramètres considérés.*

Abstract - *The use of composite materials is growing up compared to the traditional materials, in basically all the industrial domains, where we need powerful, lightweight and cost effective structures. An example of a challenging lightweight structure made of composite materials are wind turbine blades. Indeed, the modern wind turbine blades are becoming dramatically bigger, and nowadays a length of a standard one is over 60 m. The wind turbine blades are often facing extremely complex loads due to environmental conditions they are working in. One of the main loading acting on the wind turbine bale are pressure load, which can engender flap wise and edgewise bending. On the other hand, the consequence of optimum design strategy, the wind turbine blades are becoming thin-walled structures, which raise the risk of buckling phenomena. Therefore, the understanding of the wind turbine blade behaviour under this kind of aforementioned load is very crucial. In this study, the buckling behaviour of the spar cap of a wind turbine blade using the finite element method is investigated. For so doing, a generic NACA 634-421 airfoil section is considered. The spar cap is taken as a multilayer curved cylindrical shell. A parametric study is made in order to study the effect of material choice, stacking sequence and number of layers on the buckling resistance of the spar cap. The results showed that the buckling load is very sensitive to the considered parameters.*

Keywords: Wind turbine blade - Spar cap - Composite materials - Cylindrical shell - buckling.

1. INTRODUCTION

From the inception of the wind energy industry since the late of 1970s, the size of the wind turbine blades has been increasing dramatically, presenting today blades with more than 60 m length. Driving by the need of higher energy output and meeting the market requirement, the size

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of the blades being developed is still increasing. However, beside the aerodynamic aspect of the blade, structural configuration and materials selection are one of most important aspect involved in the design of wind turbine blades. Indeed, such structures require large stiffness, simplicity of assembling and most of all small weight [1].

Therefore, the engineer must constantly face the difficulty of choosing the material that meets the requirements of its structure. Therefore, the selection of an adequate material does not reside solely in the mechanical properties of the latter, such as strength, rigidity and ductility, but also by considering its physicochemical, aesthetic and economic properties[2]. One of the most promising technological advances in the field of materials today are 'composite materials'.

Nowadays, composite technology has become trendy, it has seen an extraordinary expansion due to the remarkable advantages of these materials, such as high strength, high rigidity, long fatigue resistance, low density, thermal stability and a great adaptability to the functions required by a structure [3]. As a result, their use is becoming increasingly widespread with respect to traditional materials in virtually all industrial fields, namely: aeronautics, aerospace, automotive and naval construction, civil engineering, etc...[4]

Modern wind blades are made of different kinds of materials, typically composite materials in laminated or sandwich configuration. In their manufacturing, various connections solutions are used between different substructures, where each substructure is designed to cope with the load it is supposed to carry [5].

The wind turbine blades are often facing extremely complex loads due to environmental conditions they are working in. The main loads acting on the wind turbine blade are engendered by wind and gravity, where they can induce both flap wise and edgewise bending [6]. On the other hand, the consequence of optimum design strategy, the wind turbine blades are becoming thin-walled structures [5], which raise the risk of buckling phenomena. Therefore, understanding the behavior of wind turbine blade under this kind of loads is very crucial.

The aim of this work is to investigate the buckling behavior of the spar cap of a wind turbine blade using the finite element method. For so doing, a generic NACA 634-421 airfoil section is considered (figure 1). The spar cap is taken as a multilayer curved cylindrical shell. It should be noted that the blade considered in this paper was previously presented by Lund [7]. A parametric study is made in order to analysis the effect of the material choice, stacking sequence and number of layers on the buckling resistance of the spar cap.

2. COMPOSITE SHELL STRUCTURE FORMULATION

In this study, the finite element method is used to perform a linear buckling analysis of the spar cap of a wind turbine blade. As the spar cap is taken as a multilayer cylindrical shell (figure 2), the equivalent single layer approach and the first order shear deformation theory are considered. The displacement field is given as follows:

$$\begin{aligned} u(x,y,z) &= u_0(x,y) + z\,\beta_x(x,y) \\ v(x,y,z) &= v_0(x,y) + z\,\beta_y(x,y)\ y \\ w(x,y,z) &= w_0(x,y) \end{aligned} \tag{1}$$

Where u_0, v_0, w_0 are the in-plane and transverse displacement components of the shell, respectively. β_x and β_y are the rotations of the normal to the mid-surface in two planes $x-z$ and $y-z$, respectively.

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{pmatrix} \dfrac{\partial u}{\partial x} + \dfrac{1}{2}\left(\dfrac{\partial w}{\partial x}\right)^2 \\ \dfrac{\partial v}{\partial y} + \dfrac{1}{2}\left(\dfrac{\partial w}{\partial y}\right)^2 \\ \dfrac{\partial v}{\partial x} + \dfrac{\partial u}{\partial y} + \dfrac{\partial w}{\partial x}\dfrac{\partial w}{\partial y} \end{pmatrix} + z \begin{Bmatrix} \dfrac{\partial \beta_x}{\partial x} \\ \dfrac{\partial \beta_y}{\partial y} \\ \dfrac{\partial \beta_x}{\partial y} + \dfrac{\partial \beta_y}{\partial x} \end{Bmatrix} = \underbrace{\{\varepsilon_L + \varepsilon_{NL}\}}_{\{\varepsilon\}} + z\{\kappa\} \tag{2}$$

$$\{\gamma\} = \begin{Bmatrix} \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix} = \begin{Bmatrix} \beta_x + \dfrac{\partial w}{\partial x} \\ \beta_y + \dfrac{\partial w}{\partial y} \end{Bmatrix}$$

Where $\{\varepsilon\}$, $\{\kappa\}$ and $\{\gamma\}$ are the mid-plane strain, shell curvature and transverse shear strain, respectively. The stress-strain relation of the composite multilayer shell is given by:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix}_k = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{21} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{31} & \overline{Q}_{32} & \overline{Q}_{36} \end{bmatrix}_k \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{bmatrix}_k \tag{3}$$

$$\begin{Bmatrix} \tau_{xz} \\ \tau_{yz} \end{Bmatrix}_k = \begin{bmatrix} K_{11}\overline{Q}_{44} & K_{12}\overline{Q}_{45} \\ K_{21}\overline{Q}_{54} & K_{22}\overline{Q}_{55} \end{bmatrix}_k \begin{bmatrix} \gamma_{xz} \\ \gamma_{yz} \end{bmatrix} \tag{4}$$

Where, $\overline{Q}_{ij}$ are the transformed reduced stiffness and K_{ij} are the shear correction factors.

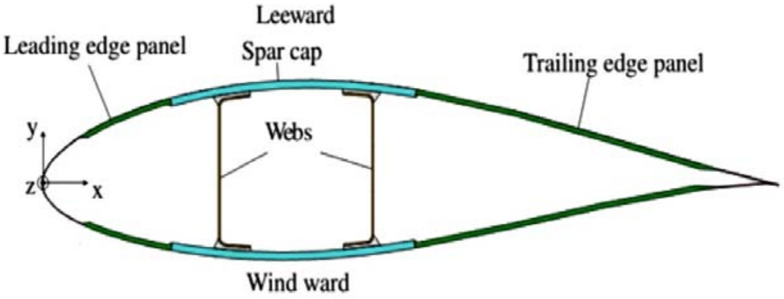

Fig. 1: Cross section of NACA 634 - 421 wind turbine blade test section [9]

The forces and the moments resultants are related to the mid-surface strains and to the curvatures by:

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} [A] & [B] \\ [B] & [D] \end{bmatrix} \begin{bmatrix} \varepsilon^0 \\ \kappa \end{bmatrix} \ ; \ [T] = [C][\gamma] \tag{5}$$

with $[A]$, $[B]$, $[D]$ and $[A]$ the extensional, coupling and bending rigidity matrix, respectively. Those can be defined by:

$$A_{ij} = \int_{h/2}^{h/2} \left[\overline{Q}_{ij}\right]_k dz \ , \ B_{ij} = \int_{h/2}^{h/2} \left[\overline{Q}_{ij}\right]_k z dz \tag{6}$$

$$D_{ij} = \int_{h/2}^{h/2} \left[\overline{Q}_{ij}\right]_k z^2 dz \ , \ C_{ij} = \int_{h/2}^{h/2} \left[\overline{Q}\right]_k dz \tag{7}$$

The total potential of multilayer shell subjected to axial forces can be given by:

$$\Pi = \frac{1}{2}\int\int_{-1}^{1}\Big(\{\varepsilon_L^0\}^T [A]\{\varepsilon_L^0\} + \{\varepsilon_L^0\}^T [B]\{\kappa\} + \{\kappa\}^T [B]\{\varepsilon_L^0\} + \{\kappa\}^T [D]\{\kappa\}\Big) \\ \Big(-2\{\varepsilon_L^0\}^T [N] + \{\kappa\}^T [M]\Big) + \Big(\{\varepsilon_L^0\}[N]\Big) dx\, dy \tag{8}$$

After assembling the finite element stiffness's and load vectors and setting the second, variation of the strain energy to zero, the standard eigen value problem is obtained:

$$[K]\{X\}+\lambda\lfloor K^{G}\rfloor\{X\}=0 \tag{9}$$

where $[K]$, $\{X\}$, $\lfloor K^{G}\rfloor$ are the global stiffness matrix, the global displacement vector and the global geometry matrix, respectively. In the case of bruckling analysis, λ is the buckling load factor.

3. RESULTS AND DISCUSSIONS

In this study, the buckling behavior of the spar cap of a wind turbine blade using the finite element method is investigated. A generic NACA 634-421 airfoil section is considered as shown in figure 1. The spar cap is taken as a multilayer curved cylindrical shell (figure 2). A four nodded iso parametric shell finite element with reduced integration is used. In all the study cases that will be discussed, the spar cap is considered to be simply supported as shown in figure 3. **Table 1** lists the materials and their properties used in this study.

Table 1: Material properties

	Materials	E_1(GPa)	E_2	V_{12}	G_{12}	G_{13}	G_{23}	ρ (km/m^3)
Skin	E-Glass/Epoxy	30.6	8.7	0.29	3.24	3.24	2.9	1910
	Carbon/Epoxy	121	8.6	0.27	4.7	4.7	3.1	1490
Core	Wood-carbon/Epoxy	57.5	0.62	0.45	1.2	1.2	1.1	1560
	SAN Foam	0.6	-	0.3	-	-	-	81
	PVC	0.7	-	0.3	-	-	-	60
	Balsa	0.4	0.4	0.2	0.025	0.1	0.1	155

Figure 4 shows the effect of the core material and stacking sequence on the critical buckling load. It should be noted that in this case the E-glass/Epoxy was considered as the skin material.

It can be seen, for all the considered stacking sequences, that the Wood-Carbon/Epoxy gives the higher critical buckling load. This can be explained by the presence of carbon, which increases the bending stiffness of the core layer. On the other hand, the PVC, BALSA and SAN materials gave close critical buckling loads, which can be explained by the similar mechanical proprieties.

Regarding the stacking sequence effect, it can be seen that it has a negligible effect on the critical buckling loads with the PVC, BALSA and SAN materials. This is probably due to the isotropic character of these materials.

Concerning the Wood-Carbon/Epoxy, it is noticed that the critical buckling load is considerably affected by the stacking sequence, which can be explained by the high anisotropy ratio E1/E2 of the Wood-Carbon/Epoxy.

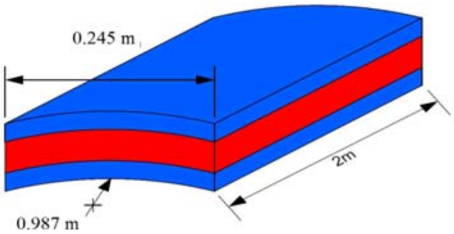

Fig. 2: Geometrical proprieties of the spar cap

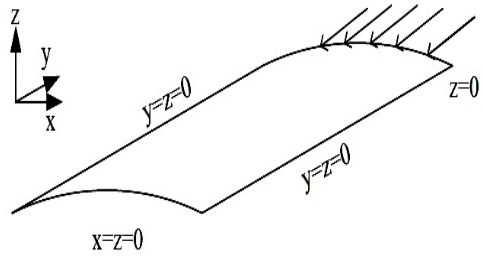

Fig. 3: Schematic representation of the Simply-Supported boundary condition 0zyx

Figure 5 shows the effect of the skin material the and stacking sequence on the critical buckling load. In this case the Wood-Carbon/Epoxy was considered as the core material.

Four skin materials were considered, namely: E-glass / Epoxy, Carbon / Epoxy and two hybrid stacking sequence configurations [G/C/W-C]s and [C/G/W-C]s, where C, G and W-C stand for Carbon/epoxy, E-glass/Epoxy and Wood-Carbon/Epoxy, respectively.

As expected, the Carbon/Epoxy gives the higher critical buckling loads for all the considered stacking sequences, where the E-glass/Epoxy gives the lowest. Regarding the hybrid configurations, they give very close critical buckling loads except for the case of [90/45/0]s.

It can be seen, for the latter stratification, that the [C/G/W-C]s gives higher critical buckling load than the [G/C/W-C]s. this can be explained by the higher bending rigidity developed by the [C/G/W-C]s.

The effect of the core thickness and the stacking sequence on the critical buckling load is presented in figure 6. In this case the E-glass/Epoxy and Wood-Carbon/Epoxy were considered as the skin and the core materials, respectively.

It is noticed that the critical buckling loads decrease as the thickness of the core decreases. It can be explained by the reducing in bending stiffness of the multilayer shell.

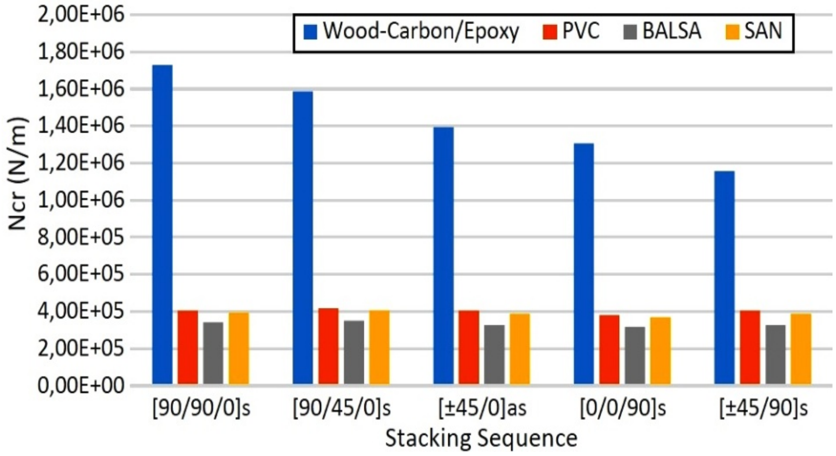

Fig. 4: Effect of the core material and stacking
sequence on the critical buckling load

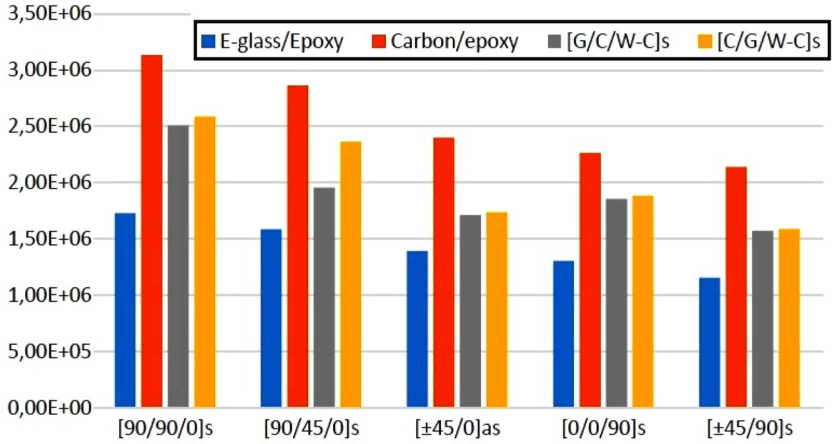

Fig. 5: Effect of the skin material and
stacking sequence on the critical buckling load

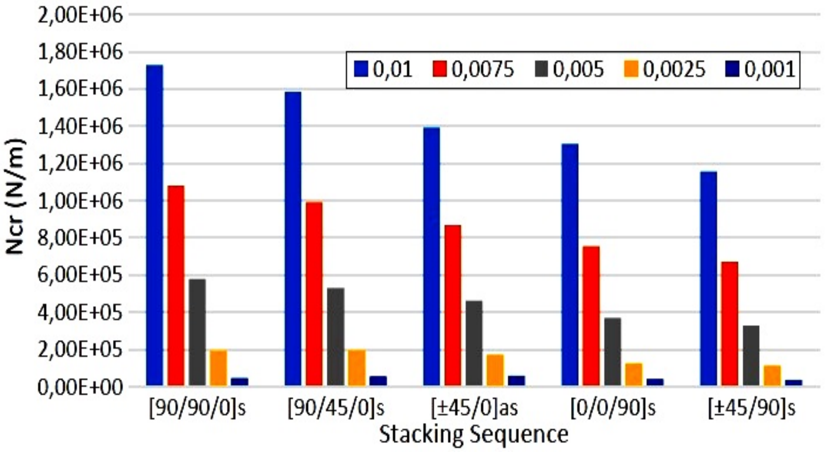

Fig. 6: Effect of the core thickness and
stacking sequence on the critical buckling load

Figure 7 shows the effect of the number of layers and the orientation angle on the critical buckling load. In this case, the E-glass/Epoxy and Wood-Carbon/Epoxy were considered as the skin and the core materials, respectively. The skins are considered to have an angle-ply lamination [±θ/core/±θ].

From the figure, it can be seen that the number of layers has a negligible effect on the critical buckling load. The latter can be explained by the very thin thickness of the skins. Moreover, According to [2, 8].

The orthotropic solution is approached as the number of layers is increased, which reduces the coupling effect. On the other hand, it can be noticed that the variation of the angle of orientation has a significant effect on the critical buckling load.

4. CONCLUSION

In this study, the buckling behavior of the spar cap of a wind turbine blade using the finite element method was investigated. A generic NACA 634-421 airfoil section was considered. A parametric study is made in order to analysis the effect of material choice, stacking sequence and number of layers on the buckling resistance of the spar cap. The results showed that the buckling load is very sensitive to the considered parameters. The study allowed to conclude that:

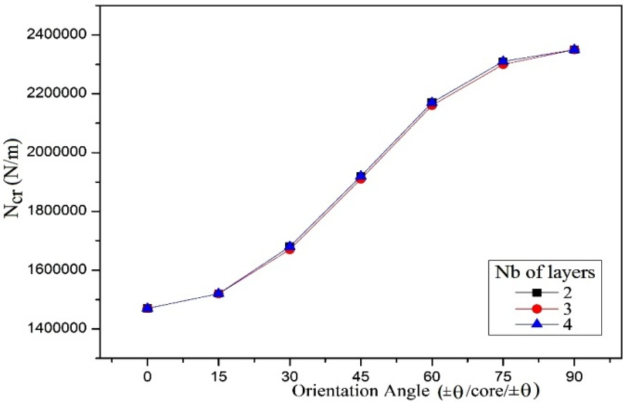

Fig. 7: Effect of the number of layers and orientation angle on the critical buckling load

- The Wood-Carbon/Epoxy and Carbon/Epoxy taken as core and skin materials, respectively, with a $[90_2/0]_s$ as stacking sequence give a higher buckling resistance of the spar cap comparing with the other considered materials and stacking sequences,
- The Hybrid composite materials can be good candidate for wind turbine blade spar cap,
- The critical buckling load is significantly affected by the thickness of the core.

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