

A METHOD BASED ON CLASSICAL LAMINATION THEORY TO CALCULATE STIFFNESS PROPERTIES OF CLOSED COMPOSITE SECTIONS

Akgün KALKAN*

Prof. Dr. Zahit MECİTOĞLU

INORES, Kayışdağı Cad. No:3 Kat:20/2002,
Ataşehir, İstanbul, Turkey,
akgun.kalkan@inores.com

İTÜ Faculty of Aeronautics and Astronautics,
Reşitpaşa, 34467 Sarıyer, İstanbul, Turkey,
mecit@itu.edu.tr

Received: 1st May 2016, Accepted: 1st December 2016

ABSTRACT

Structural deformation of composite wind turbine blades affect the aerodynamic performance of the rotor. To design better blades in terms of efficiency, aerodynamic performance and load mitigation, it is crucial to understand how blades act under operational loads. An interdisciplinary research should be conducted including composite structures and aerodynamics to analyze this interaction. This article focuses on the structural part and explains an easy to apply method to define sectional properties of a closed composite section. The method is based on Classical Lamination Theory (CLT) and it is assumed that the blade is a thin walled structure. Stress concentration and warping effects are ignored. During preliminary design phase, this method is useful to calculate bending and torsional stiffness values based on different lamination parameters and materials, it can also be used to investigate bending-torsion coupling effects. This article also includes parametric studies on NACA profiles using the method explained. This is the first phase of a study investigating aero-structure interaction in wind turbine blades and its effects on rotor performance.

Keywords: wind turbine blade, composite section, blade section stiffness, coupling.

KAPALI KOMPOZİT KESİTLERİN KATILIK ÖZELLİKLERİNİ KLASİK LAMİNASYON TEORİSİ YARDIMIYLA HESAPLAYAN BİR YÖNTEM

ÖZET

Kompozit rüzgar türbini kanatlarının deformasyonları rotor aerodinamik performansını etkilemektedir. Kanatlarda daha yüksek verimlilik, iyi aerodinamik performans ve mekanik yüklerin azaltılması için operasyonel yükler altında kanat davranışının anlaşılması önem arz etmektedir. Bu etkileşimi anlayabilmek için kompozit yapılar ve aerodinamik alanlarında disiplinler arası bir çalışma yapılması gereklidir. Bu makale yapısal tarafa odaklanmıştır ve kapalı kompozit bir kesitin katılık özelliklerinin hesabı için uygulaması kolay bir yöntem gösterilmiştir. Yöntem, Klasik Laminasyon Teorisi (KLT) tabanlıdır ve kesitin ince cidarlı olduğu kabul edilmiştir, gerilme yığılmaları ve çarpılma ihmal edilmiştir. Ön tasarım aşamasında farklı laminasyonlar ve malzemeler ile eğilme ve burulma katılıkları hesaplanabildiği gibi eğilme-burulma etkileşimi de incelenabilmektedir. Makalede bir NACA profili üzerinde bahsedilen yöntemle çeşitli çalışmalar yapılmıştır. Bu makale türbin kanatlarında hava-yapı etkileşimi ve rotor performansına etkilerini irdeleyen bir çalışmanın ilk fazını kapsamaktadır.

Anahtar Kelimeler: rüzgar türbini kanadı, kompozit kesit, kanat kesit katılığı, etkileşim.

* Corresponding Author

1. INTRODUCTION

There is a rapid growth in wind energy investments for the last decades. Along with this growth wind turbine engineering has an increasing importance and popularity. Wind turbines work under harsh operational conditions and design of the machine needs interdisciplinary analysis including structural mechanics, composites, aerodynamics, control and other disciplines. Performance of a rotor which is directly related to aerodynamic performance of the blade, is a key parameter to define the general efficiency of a wind turbine. To create torque from wind, airfoils are used to define the skin geometry of composite blades in modern wind turbines. A key design aspect of wind turbine blades is determining the right twist angle along the blade where airfoils operate with maximum lift to drag ratios to optimize the blade aerodynamic efficiency. The twist angle is directly related to effective angle of attack of airfoils in desired operating conditions and variation in effective angle of attack influence the aerodynamic performance of airfoil, blade and naturally rotor. In this regard, the designer should also take into account the induced twist by structural deformation of the blade under operational loads composed of aerodynamic loading, gravity, inertial effects and control. So it is important to understand the structural behavior of composite wind turbine blades, to design them to operate in highest efficiency under targeted operating conditions. Such an analysis needs an interaction between composite mechanics and aerodynamics. Fluid structure interaction schemes in 3D including CFD and FE modeling is an option, however it is a time consuming process and not flexible enough to make rapid studies in the early design phases. An alternative method is to use so-called reduced models for both structural and aerodynamics parts to let the designer to have a systematic overview and understand the general behavior of the blade. This article focuses on the structural side, demonstrating a simple and fast method based on CLT and thin walled structures theory. It provides the base for a tool that can be used in early design phases to conduct parametric studies, choose material and lamination parameters.

Turbine blades are long, slender structures similar to a beam, so it is a good approach to model their structural behavior by defining main sectional properties along the blade like bending and torsion characteristics. Two main theories are used for this approach, first one is CLT which is the base for calculating main structural parameters of the composite structure, second one is thin walled structures theory which helps to define the sectional properties by relating airfoil geometry and CLT. CLT is a well documented subject and there are books by Jones [1], Kaw [2], Daniel and Ishai [3], Kollar and Springer [4] and Vasiliev and Morozov [5] defining

the theory thoroughly. It is also used to analyze problems in different industries where composites are used as load bearing structures, consequently there are many articles in the literature related to usage of this theory. Similarly, anisotropic thin walled structures theory has many applications in the literature including the book by Librescu [6] which focuses to composite beam structures. One of the first application in wind turbine blades is by Karaolis et al. [7], their study examines effect of lamination on bending-torsion coupling in blade sections and proposes internal pressurization as an alternative to control induced twist. Armanios and Badir [8] developed a similar but more sophisticated model introducing out of plane warping effects. Chandra and Chopra [9] developed a method based on Vlasov theory and verified their results in terms of torsional and bending characteristics with tests on a composite turbine blade. Lee and Flay [10] investigated bending-torsion coupling in blade sections, to apply passive control on a 50 kW turbine. Lobitz and Veers [11] worked on effects of extension-torsion and bending-torsion coupling on blade deformations and stability. Ong and Tsai [12] conducted numerical and experimental studies regarding bending torsion coupling on the main spar of a turbine blade aiming to increase blade performance and mitigate loads. Volovoi and Hodges [13] used variational asymptotic method to model anisotropic thin walled beams with open and closed [14] sections. Volovoi et al. [15] investigated the theories used for composite rotor blade modeling, concluding that aside from some certain applications theories give similar results, however a large set of experiments is needed to conduct a detailed comparison and verification. Maheri et al. [16] developed a software to calculate the performance of horizontal axis wind turbines, the software is a combination of an aerodynamic code, an adaptive mesher and finite element code, it is emphasized that for realistic performance calculations, aeroelastic interactions on the blade have to be taken into account. Maheri has published other articles [17-19] on the subject, focusing on bending-torsion coupling and other applications. Chen et al. [20] has compared several software used for the calculation of section mechanical properties, favoring VABS which is developed for the helicopter industry as the most reliable tool. Park et al. [21] developed a software based on CLT and St. Venant principle to calculate the section mechanical properties including bending and torsion stiffness, they have compared their software to finite element results. Tingrui and Yongsheng [22] have studied on vibration and stability of rotor blades modeled as anisotropic thin walled beams, they have used variational asymptotic theory. Jeong et al. [23] has conducted aeroelastic analyses on large turbine blades using nonlinear beam theory and vortex method for aerodynamics, they have emphasized the effects of nonlinearity on stability of large turbine blades. Lee et al. [24] developed an analytical process

taking into account aero-structure interactions in turbine blades; blade element momentum theory is used for aerodynamic calculations, whereas finite element software is used for structural calculations, concluding that ignoring interactions can lead to performance loss of up to 17%.

In following chapters, mechanical properties of various composite skin geometries based on NACA profiles are calculated. The calculations use CLT and thin walled structure theory. This basic approach can help the designer to conduct fast parametric studies on different aspects including dimensioning, material selection and profile decision. Based on this approach parametric studies show that thickness ratio of profiles effect stiffness properties considerably, also higher anisotropy and application of hybrid materials increase coupling.

2. ASSUMPTIONS AND DETERMINATION OF SECTION STIFFNESS

As mentioned above, the blade section will be treated as a thin walled composite beam structure, where $t \ll c$, meaning thickness of the skin is much smaller than the chord length. This means that the distance between the plies and skin midplane is negligible, so in-plane bending and coupling effects are also neglected. Only elastic deformations are considered, stress concentrations and related warping effects are ignored.

Under operational loads the blade section will deform in different directions. The centrifugal effect will create a tension force and resulting strain, ε_z^o , whereas the twisting moment will create a twist per unit length, k_{xy} . These and other related parameters can be seen in Figure 1. Strains due to bending can be calculated by multiplying the corresponding curvatures with the related x or y coordinate, and twist can be calculated by multiplying k_{xy} with the length of the corresponding station along the blade.

The first step to determine the stiffness of the section is taking into account a differential element, ds , similar to the one shown in Figure 2. This element can be considered as a laminated panel and it is easy to get the stiffness relations using CLT [1]. The relation for a laminate can be seen in the equation below where N and M represent the forces and moments respectively, both are 3×1 matrices. Here, ε^o is midplane strain and k^o is curvature vector. A_{ij} , B_{ij} and D_{ij} matrices are 3×3 stiffness matrices. A_{ij} relates in plane forces to in plane strains, D_{ij} relates bending moments to curvatures and B_{ij} relates extension loads with out of plane curvatures and vice versa, for this reason it is called as coupling matrix.

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon^o \\ k^o \end{Bmatrix} \quad (1.1)$$

Since skin thickness is negligible compared to chord of the profile, coupling inside the skin is ignored, so $B_{ij}=0$, also bending of the skin element with respect to its midplane will be negligible, so $D_{ij}=0$. After these modifications, skin stiffness matrix becomes:

$$\begin{Bmatrix} N_z \\ N_s \\ N_{zs} \end{Bmatrix} = [A_{ij}] \begin{Bmatrix} \varepsilon_z \\ \varepsilon_s \\ \gamma_{zs} \end{Bmatrix} \quad (1.2)$$

Here, N_z represents the longitudinal load and N_{zs} represents the shear load per unit width. Considering there is no internal pressure N_s will be zero. Assuming the laminate is made of N plies, the stiffness matrix can be written in terms of ply thickness ratio, t being the total laminate thickness, ply thickness ratio is defined as $t'_p = t_p/t$. A prime is used to identify the dimensionless parameters, for example $x' = x/c$ and $A' = A/c^2$.

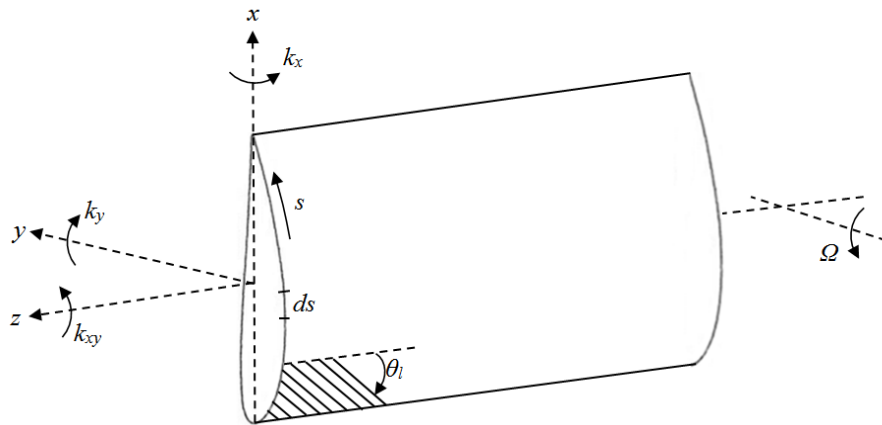


Figure 1. Blade and section parameters.

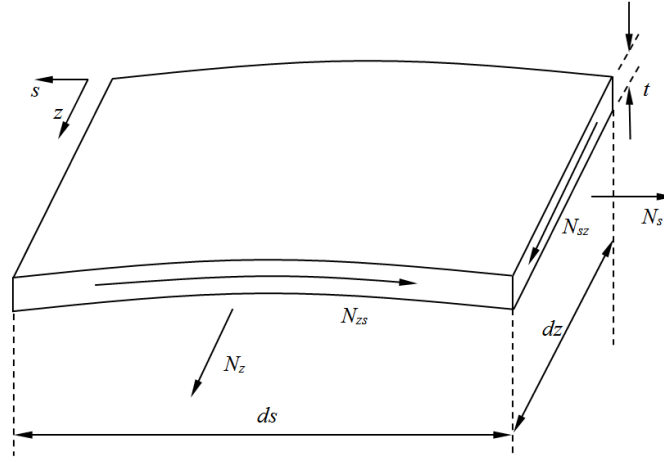


Figure 2. Section skin parameters.

$\bar{Q}_{ij}$ represents elements of the stiffness matrix of the p^{th} ply, it is related to elastic mechanical properties and fiber orientation of the individual plies. The equations to calculate $\bar{Q}_{ij}$ are based on CLT and can be found in the related books [1].

$$A_{ij} = \sum_{p=1}^N (\bar{Q}_{ij})_p t'_p t = A'_{ij} t \quad (1.3)$$

The total axial strain can be described using the formula below, besides its axial component, it also has components coming from the other directions.

$$\varepsilon_z(x, y) = \varepsilon_z^o - xk_y + yk_x \quad (1.4)$$

Considering torsional equilibrium, the below expression can be derived, which is also called Batho-Bredt formula. Here A is the area enclosed by the section.

$$N_{zs} = \frac{M_z}{2A} \quad (1.5)$$

After substituting equations 1.4 and 1.5 to equation 1.2, following expressions can be derived where S_i ($i=1:5$) are called stiffness parameters. S_2 and S_4 are dimensionless, the sign of S_1 and S_3 are always positive and the sign of S_2 and S_5 depend on the sign of fiber orientation.

$$N_z = S_1 t (\varepsilon_z^o - x'ck_y + y'ck_x) - S_2 \frac{M_z}{2A'c^2} \quad (1.6)$$

$$\gamma_{zs} = S_2 (\varepsilon_z^o - x'ck_y + y'ck_x) + \frac{S_3}{t} \frac{M_z}{2A'c^2} \quad (1.7)$$

$$\varepsilon_s = S_4 (\varepsilon_z^o - x'ck_y + y'ck_x) + \frac{S_5}{t} \frac{M_z}{2A'c^2} \quad (1.8)$$

$$S_1 = A'_{11} + \frac{2A'_{12}A'_{13}A'_{23} - (A'_{12})^2 A'_{33} - (A'_{13})^2 A'_{22}}{A'_{22}A'_{33} - (A'_{23})^2} \quad (1.9)$$

$$S_2 = \frac{A'_{12}A'_{23} - A'_{13}A'_{22}}{A'_{22}A'_{33} - (A'_{23})^2} \quad (1.10)$$

$$S_3 = \frac{A'_{22}}{A'_{22}A'_{33} - (A'_{23})^2} \quad (1.11)$$

$$S_4 = \frac{A'_{13}A'_{23} - A'_{12}A'_{33}}{A'_{22}A'_{33} - (A'_{23})^2} \quad (1.12)$$

$$S_5 = \frac{-A'_{23}}{A'_{22}A'_{33} - (A'_{23})^2} \quad (1.13)$$

Equations for the external loads T_z , M_x and M_y may be formulated by integrating the unit force $N_z ds$ with respect to section skin geometry.

$$T_z = c \oint N_z ds' \quad (1.14)$$

$$M_x = c^2 \oint y' N_z ds' \quad (1.15)$$

$$M_y = -c^2 \oint x' N_z ds' \quad (1.16)$$

N_z can be substituted to the above expressions using Equation 1.6 leading to expressions for axial force, bending and edgewise moments. S_2 is kept inside the integrals to take into account the changes in its sign along the path.

$$T_z = \varepsilon_z^o tc S_1 \oint ds' - k_y tc^2 S_1 \oint x' ds' + k_x tc^2 S_1 \oint y' ds' - \frac{M_z}{2A'c} \oint S_2 ds' \quad (1.17)$$

$$M_x = \varepsilon_z^o tc^2 S_1 \oint y' ds' - k_y tc^3 S_1 \oint x'y' ds' + k_x tc^3 S_1 \oint y'^2 ds' - \frac{M_z}{2A'} \oint y' S_2 ds' \quad (1.18)$$

$$M_y = -\varepsilon_z^o tc^2 S_1 \oint x' ds' + k_y tc^3 S_1 \oint x'^2 ds' - k_x tc^3 S_1 \oint x'y' ds' + \frac{M_z}{2A'} \oint x' S_2 ds' \quad (1.19)$$

The shear strain γ_{zs} from equation 1.7 can be used to calculate the torsion per unit length k_{xy} . Also M_z can be written using the resulting equation.

$$k_{xy} = \frac{1}{2A} \oint \gamma_{zs} ds = \frac{1}{2A'} \left[\frac{\varepsilon_z^o}{c} \oint S_2 ds' - k_y \oint x' S_2 ds' \right] + \frac{1}{2A'} \left[k_x \oint y' S_2 ds' + \frac{M_z S_3}{2A'c^3 t} \oint ds' \right] \quad (1.20)$$

$$M_z = \frac{4A'^2 c^3 t k_{xy}}{S_3 \oint ds'} - 2A' tc^2 \varepsilon_z^o \frac{\oint S_2 ds'}{S_3 \oint ds'} + 2A' tc^3 k_y \frac{\oint x' S_2 ds'}{S_3 \oint ds'} - 2A' tc^3 k_x \frac{\oint y' S_2 ds'}{S_3 \oint ds'} \quad (1.21)$$

$$\begin{Bmatrix} T_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} = \begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} \\ H_{12} & H_{22} & H_{23} & H_{24} \\ H_{13} & H_{23} & H_{33} & H_{34} \\ H_{14} & H_{24} & H_{34} & H_{44} \end{bmatrix} \quad (1.22)$$

$$\begin{Bmatrix} T_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} = \begin{bmatrix} H_{11}^* tc & H_{12}^* tc^2 & H_{13}^* tc^2 & H_{14}^* tc^2 \\ H_{12}^* tc^2 & H_{22}^* tc^3 & H_{23}^* tc^3 & H_{24}^* tc^3 \\ H_{13}^* tc^2 & H_{23}^* tc^3 & H_{33}^* tc^3 & H_{34}^* tc^3 \\ H_{14}^* tc^2 & H_{24}^* tc^3 & H_{34}^* tc^3 & H_{44}^* tc^3 \end{bmatrix} \quad (1.23)$$

$$H_{11}^* = S_1 \oint ds' + \frac{\left[\oint S_2 ds' \right]^2}{S_3 \oint ds'} \quad (1.24)$$

$$H_{12}^* = S_1 \oint y' ds' + \frac{\oint S_2 ds' \oint y' S_2 ds'}{S_3 \oint ds'} \quad (1.25)$$

$$H_{13}^* = -S_1 \oint x' ds' - \frac{\oint S_2 ds' \oint x' S_2 ds'}{S_3 \oint ds'} \quad (1.26)$$

$$H_{14}^* = -2A' \frac{\oint S_2 ds'}{S_3 \oint ds'} \quad (1.27)$$

$$H_{22}^* = S_1 \oint y'^2 ds' + \frac{\left[\oint y' S_2 ds' \right]^2}{S_3 \oint ds'} \quad (1.28)$$

$$H_{23}^* = -S_1 \oint y' x' ds' - \frac{\oint y' S_2 ds' \oint x' S_2 ds'}{S_3 \oint ds'} \quad (1.29)$$

$$H_{24}^* = -2A' \frac{\oint y' S_2 ds'}{S_3 \oint ds'} \quad (1.30)$$

$$H_{33}^* = S_1 \oint x'^2 ds' + \frac{\left[\oint x' S_2 ds' \right]^2}{S_3 \oint ds'} \quad (1.31)$$

$$H_{34}^* = 2A' \frac{\oint x' S_2 ds'}{S_3 \oint ds'} \quad (1.32)$$

$$H_{44}^* = \frac{4A'^2}{S_3 \oint ds'} \quad (1.33)$$

The inverse of the stiffness matrix is known as the flexibility matrix $[h_{ij}]$ and it is defined by the following relationship where $[h_{ij}^*] = [H_{ij}^*]^{-1}$.

$$[h_{ij}] = \begin{bmatrix} h_{11}^*/tc & h_{12}^*/tc^2 & h_{13}^*/tc^2 & h_{14}^*/tc^2 \\ h_{12}^*/tc^2 & h_{22}^*/tc^3 & h_{23}^*/tc^3 & h_{24}^*/tc^3 \\ h_{13}^*/tc^2 & h_{23}^*/tc^3 & h_{33}^*/tc^3 & h_{34}^*/tc^3 \\ h_{14}^*/tc^2 & h_{24}^*/tc^3 & h_{34}^*/tc^3 & h_{44}^*/tc^3 \end{bmatrix} \quad (1.34)$$

$$\begin{Bmatrix} \varepsilon_z^o \\ k_x \\ k_y \\ k_{xy} \end{Bmatrix} = [h_{ij}] \begin{Bmatrix} T_z \\ M_x \\ M_y \\ M_z \end{Bmatrix} \quad (1.35)$$

3. COMMENTS ON THE STIFFNESS MATRIX

Elements of the flexibility matrix $[h_{ij}]$ contain information regarding stiffness and coupling parameters of the section. This matrix forms a relation between the applied loads and corresponding displacements. The elements in the diagonal of the matrix relates the displacements to corresponding direct loads, whereas off-diagonal elements indicates coupling and the terms of displacements coming from the coupling are called induced displacements. For example, if there is a non-zero h_{23} element, k_x will not be only determined by M_x , there will be an additional term depending on the value of M_y .

Values of the flexibility matrix elements are determined by several factors including section geometry, fiber orientation, stacking sequence, lay-up, lamination thickness (t) and chord length (c). It can also be observed that diagonal terms are always positive and never zero, however off-diagonal terms depend on the geometry of the section which determines the values of the closed integrals in the stiffness terms. In a mirror lay-up with respect to the section mid-plane which is also called Circumferentially Asymmetric Stiffness (CAS) layup, the opposite sign of the fiber orientation changes the sign of the stiffness parameter S_2 , therefore for a

symmetrical section, S_2 and correspondingly element H_{14} will be zero.

In this phase, it will be valuable to identify individual stiffness and coupling parameters. The flexibility relation in equation 1.35 can be used for this purpose. Assuming that only a flapwise bending moment M_x exists on the section, a definition for bending stiffness can be obtained using the flexibility matrix.

$$EI_f = \frac{tc^3}{h_{22}^*} \quad (1.36)$$

It is possible to remove dependence on the dimensions, this stiffness, EI_f' can be indicated by a prime sign. The actual stiffness can be calculated by multiplying EI_f' by tc^3 .

$$EI_f' = \frac{1}{h_{22}^*} \quad (1.37)$$

Expressions for torsional stiffness can be obtained by a similar approach.

$$GJ = \frac{tc^3}{h_{44}^*} \quad (1.38)$$

$$GJ' = \frac{1}{h_{44}^*} \quad (1.39)$$

Also, coupling level of a section can be defined by a similar approach. If a section is subjected only to a flapwise bending moment M_x , an induced curvature of $h_{24}M_x$ will be realized, the level of coupling is directly related to h_{24} . A parameter, B_m , representing the amount of induced twist per unit flapwise moment (bending-torsion coupling) can be defined by the simple relationship shown below. B_m is independent of t and c , also it does not contain effects of axial strain, to incorporate these effects, curvature k_x may be introduced and using the flexibility matrix it can be possible to define a new coupling parameter B_s which indicates the induced twist per maximum axial strain due to bending. Here $y_m' = y_m/c$, where y_m is the coordinate at the maximum section thickness.

$$B_m = h_{24}^* \quad (1.39)$$

$$B_s = \frac{1}{y_m'} \frac{h_{24}^*}{h_{22}^*} \quad (1.40)$$

4. PARAMETRIC STUDIES

Using the parameters defined above it is possible to analyze bending, torsion and coupling characteristics of sections with different geometries and lamination properties. For this purpose, a code based on the formulations explained above is developed in MATLAB to calculate stiffness matrix of closed composite sections. However without going through parametric studies a comparison will be made between the results by the developed code and PreComp software which is developed by National Renewable Energy Laboratory (NREL) for the similar purpose. For this comparison, two different section geometries, one symmetric, namely NACA 0015 and one cambered, namely NACA 4415 will be used. Layup is symmetric and fiber orientation is 18° degrees, material is glass-epoxy. The results regarding stiffness parameters can be seen in Figure 3. Figure 4 shows the NACA profiles used throughout the article.

According to the results, current study tends to underestimate both bending and torsional stiffness values compared to PreComp, the difference is higher for bending stiffness. Relying on Precomp documentation it can be said that similar theories are used, the reason for difference may be different methods used in contour integration.

coupling with respect to different sections can be seen in Figure 5.

The difference between symmetric section (NACA 0015) and cambered section (NACA 4415) in terms of bending and torsion stiffness is very small, however the increase in thickness ratio (NACA 4421) increases both bending and torsion stiffness significantly. Thin profiles are required to increase bending-torsion coupling, this fact can easily be seen from the coupling parameter calculations and thickest section NACA 4421 shows the lowest coupling ability.

4.2 EFFECT OF MATERIAL PROPERTIES

To investigate the effect of material properties, a NACA 4415 profile is analyzed using the material properties listed in Table 1. A symmetric layup is used and fiber orientations are again $0^\circ / 25^\circ / 45^\circ / -75^\circ$. The stiffness and coupling parameters with respect to different materials can be seen in Figure 6.

Bending and torsion stiffness parameters change in proportion to Young modulus values of the different materials. Simply, higher modulus leads to a higher stiffness. However coupling characteristics show that due to its low ratio of axial to shear stiffness, glass-

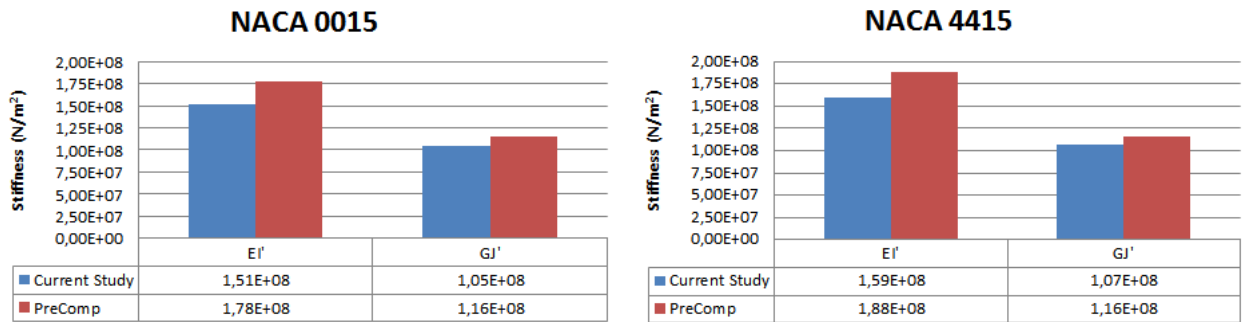


Figure 3. Comparison of current study and PreComp results.

4.1 SECTION GEOMETRY, CAMBER AND THICKNESS RATIO

To analyze the effects of section geometry, three different NACA sections are used, first one is a symmetric profile, NACA 0015 to represent a baseline. The second one is NACA 4415 to see the effects of camber and the third one is NACA 4421 to see the effects of the thickness ratio. A symmetric layup is used and fiber orientations are $0^\circ / 25^\circ / 45^\circ / -75^\circ$, the material is glass-epoxy and its properties can be seen in Table 1. The comparison of stiffness and

epoxy shows the lowest coupling properties, here Kevlar shows the highest coupling ability. Modern blades are mostly made of glass-epoxy and carbon is used partially in some blades, as the blades get longer the usage of carbon will be a necessity due to its high strength.

To have a better understanding of the material effects, a fiber orientation sweep between 0° - 90° has been done on NACA 4415 section using just one layer of material, Figure 7 shows the sweep results.

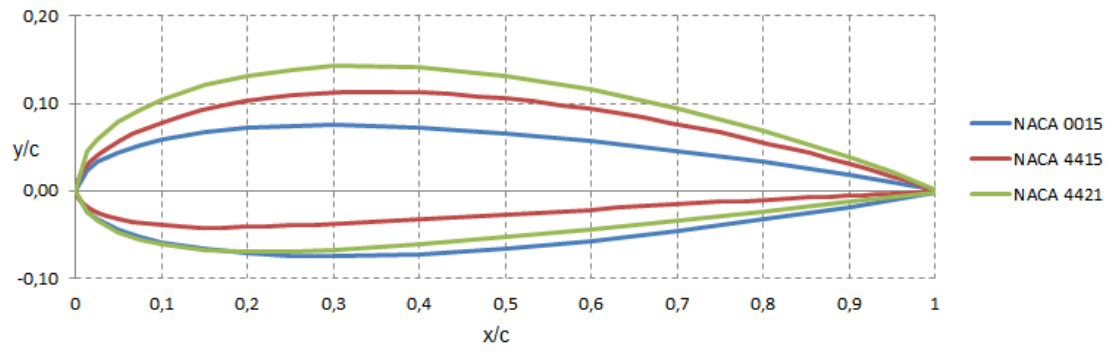


Figure 4. NACA profile geometries used

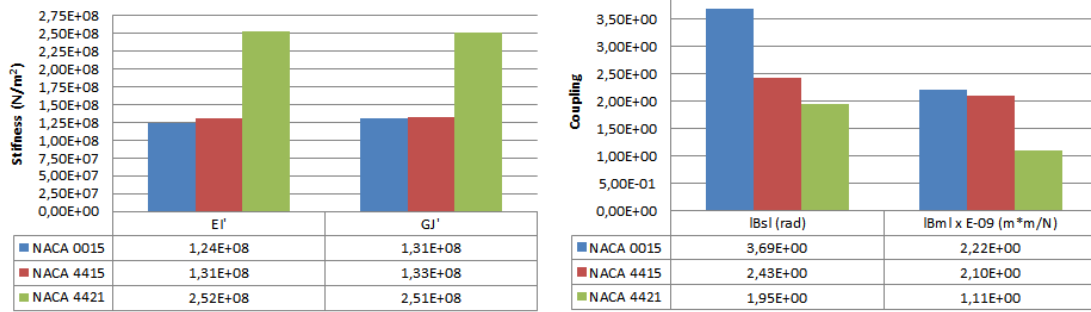


Figure 5. Comparison of section stiffness and coupling for NACA profile geometries used.

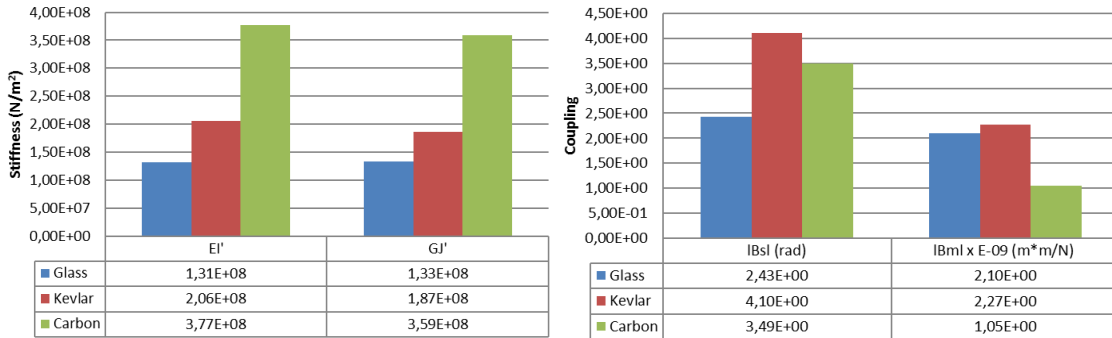


Figure 6. Comparison of section stiffness and coupling for different materials

Table 1. Material Properties

	$E_{11}(\text{GPa})$	$E_{22}(\text{GPa})$	$G_{12}(\text{GPa})$	ν_{12}
Glass-Epoxy	39	8.6	3.8	0.28
Kevlar-Epoxy	87	5.5	2.2	0.34
Carbon-Epoxy	142	10.3	7.2	0.27

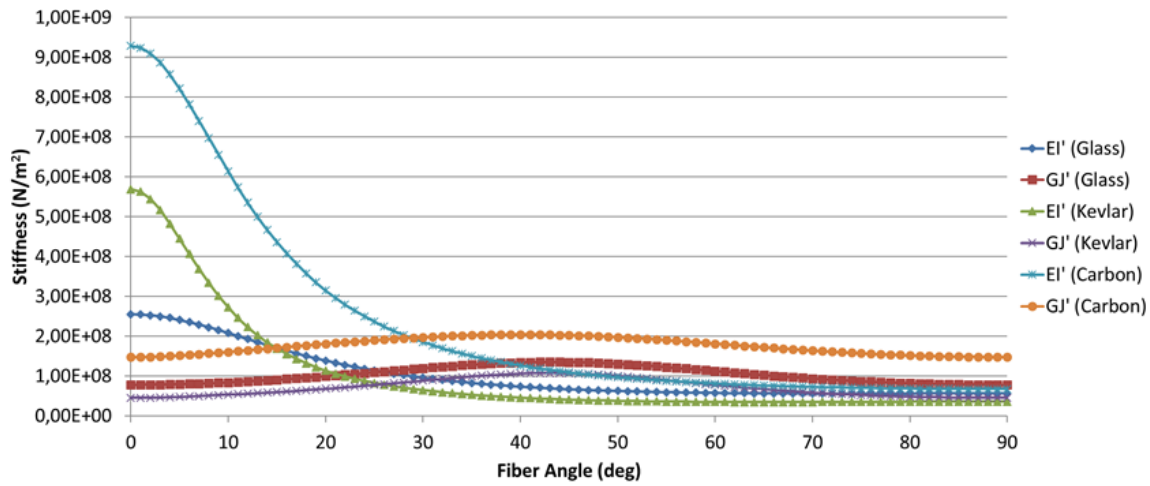


Figure 7. Effect of fiber orientation on stiffness for a single ply of different materials on NACA 4415.

It can be seen that both Kevlar and Carbon bending stiffness show a rapid decrease as the fiber orientation increases, however glass bending stiffness shows a slower change compared to Kevlar and carbon, around 15° bending stiffness of the glass gets the same value as Kevlar's and it has higher values than Kevlar as the orientation angle increases. The bending characteristics also show that Kevlar and carbon are more sensitive to manufacturing misalignments. In terms of torsional stiffness, naturally all the materials have the highest values around 45°, glass shows a higher torsional stiffness compared to Kevlar due to its higher shear stiffness.

In Figure 8, sweep results for coupling can be seen, highest coupling per axial strain occurs at 17°, 9° and 13° for glass, Kevlar and carbon, respectively. On the other hand highest coupling per applied load occurs 29°, 28° and 37° for glass, Kevlar and carbon respectively, in this case a twist value is obtained with a smaller load but higher strain.

Instead of a single ply, if two plies are used with the same thickness and material properties (in this case glass-epoxy), the contour plots shown in Figure 9 can be obtained. As expected the graphs are symmetric along $-\text{Angle } 1 = \text{Angle } 2$ diagonal, here each symmetric ply contributes same amount to the related stiffness parameter. Similar to single ply construction, as the fibers gets closer to 0° the bending stiffness increases and as the fibers gets closer to $\pm 45^\circ$ the torsional stiffness increases. For maximum coupling, 17° was the calculated orientation, along with this value it is clear that we also have maximum coupling regions for 17°/-80° or -17°/80°. Zero coupling is obtained where the fiber orientations are equal but having opposite signs.

If the plies have different thickness or material properties, we will realize that symmetry will disappear. Figure 10, shows the results if a layer is three times thicker than the other layer, it is clear that stiffness and coupling properties are more sensitive to

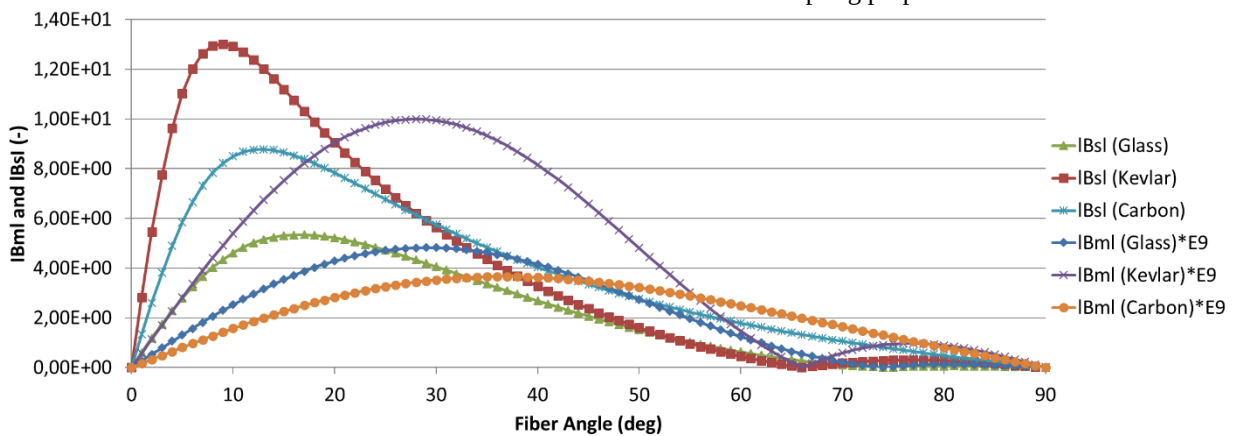


Figure 8. Effect of fiber orientation on coupling for a single ply of different materials on NACA 4415 profile.

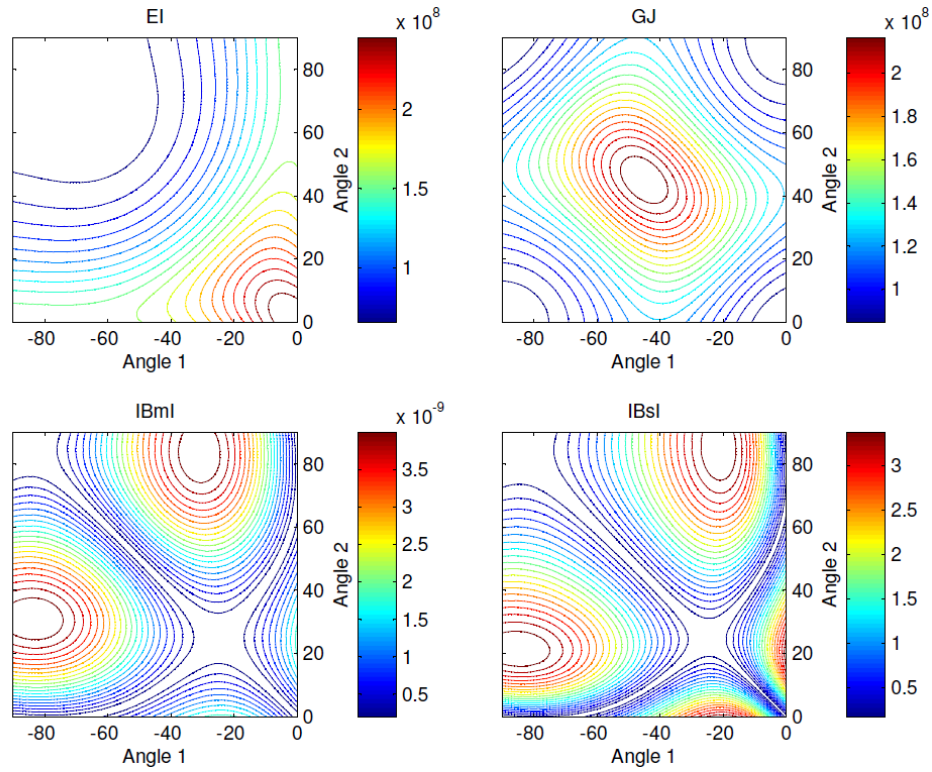


Figure 9. Effect of fiber orientation on stiffness and coupling for two identical plies.

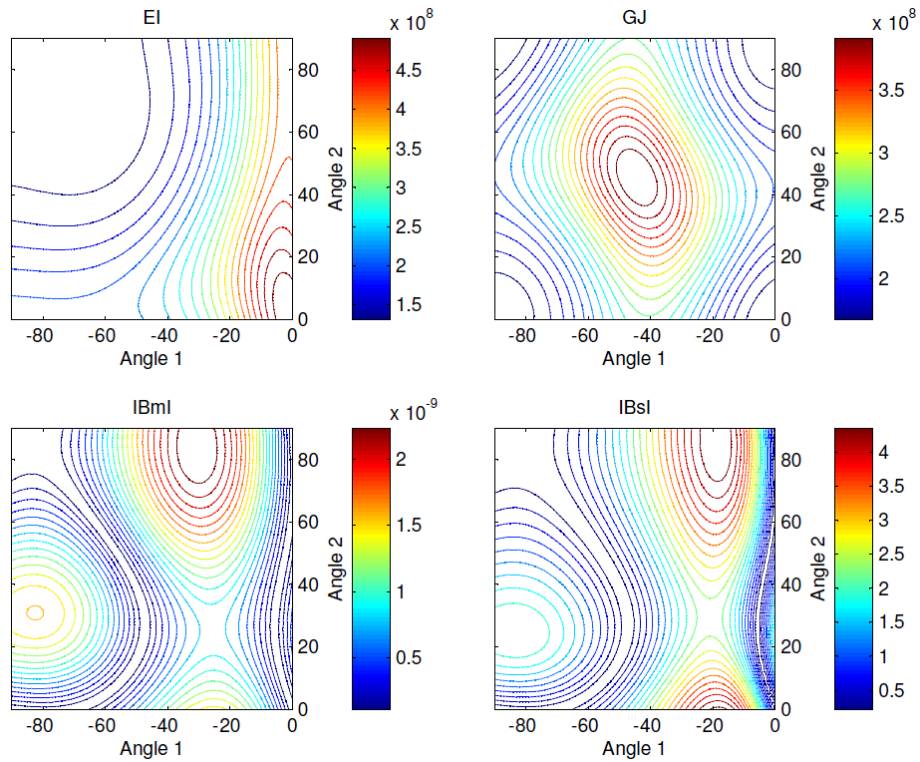


Figure 10. Effect of fiber orientation on stiffness and coupling for two plies having different thickness.

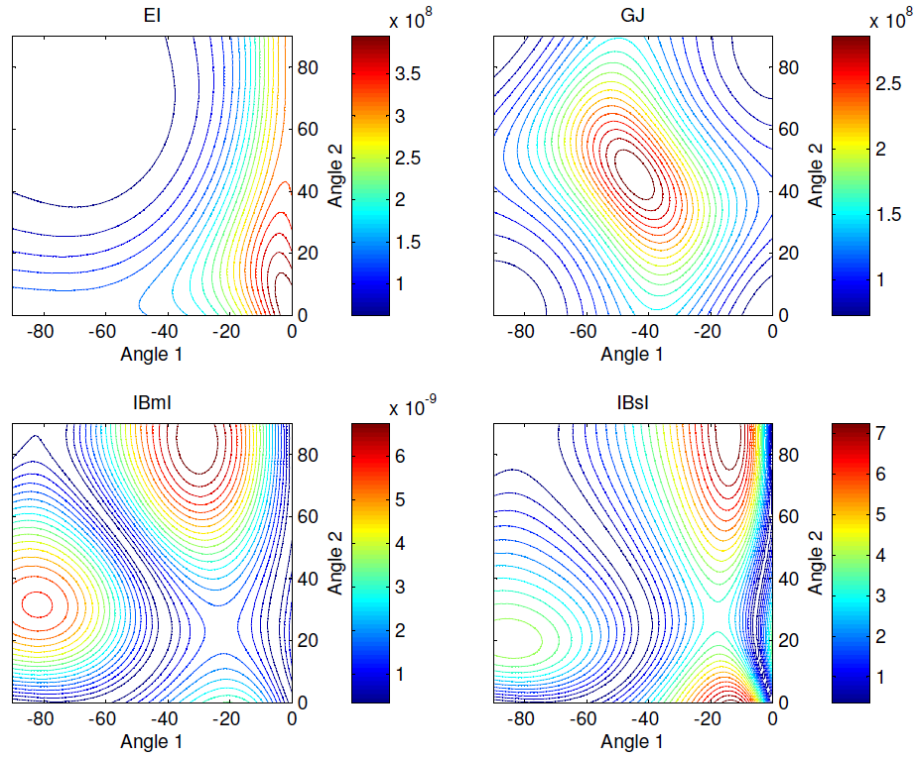


Figure 11. Effect of fiber orientation on stiffness and coupling for glass-kevlar hybrid laminate.

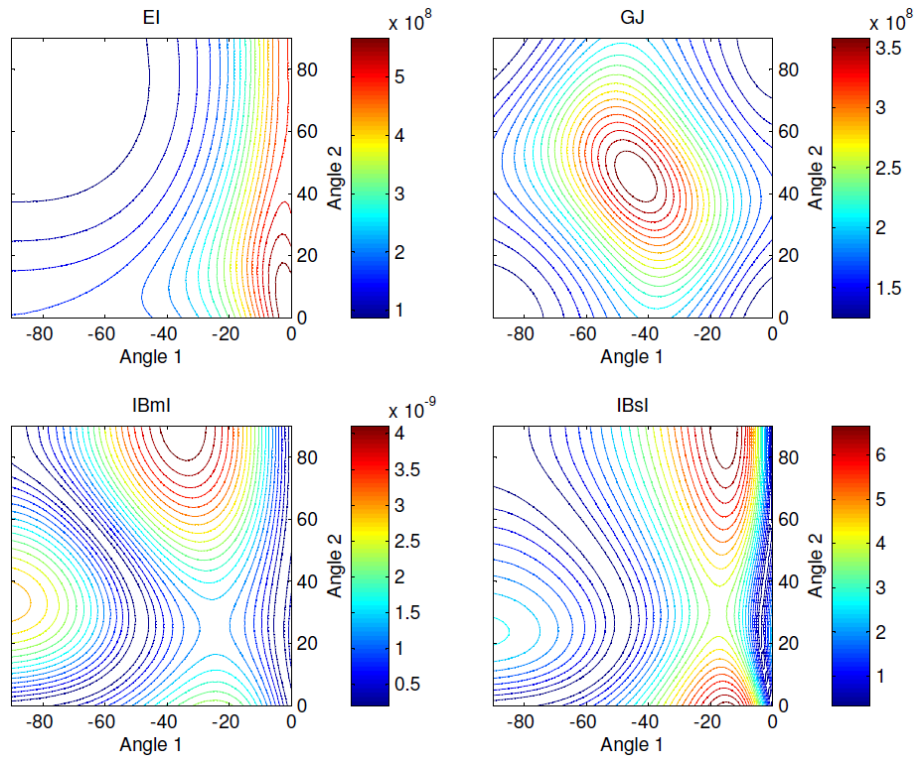


Figure 12. Effect of fiber orientation on stiffness and coupling for glass-carbon hybrid laminate.

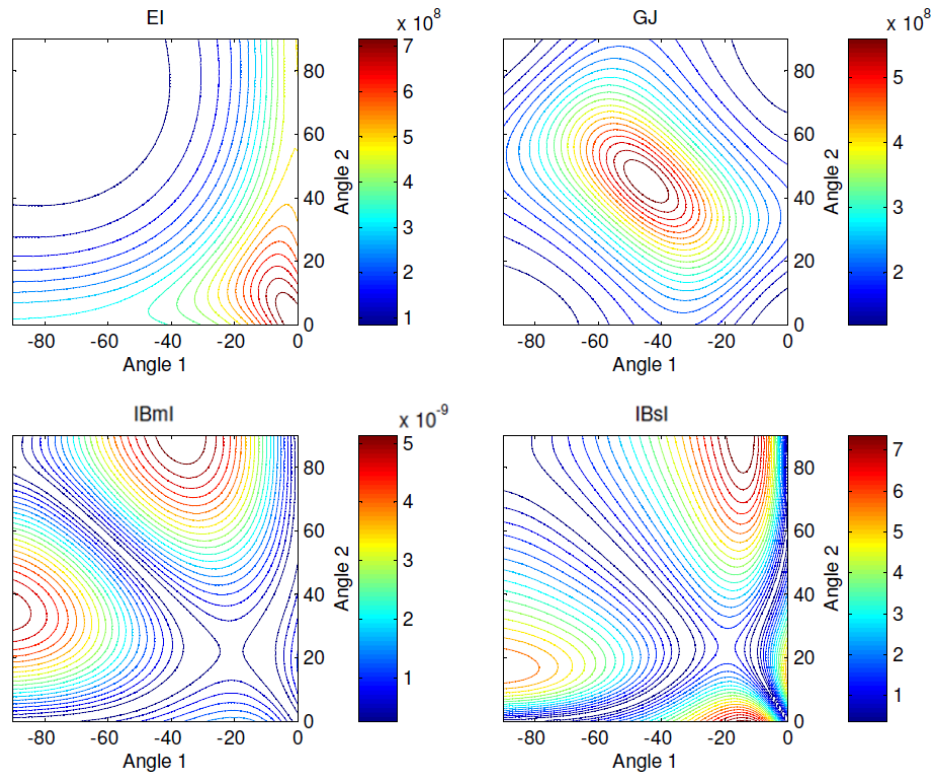


Figure 13. Effect of fiber orientation on stiffness and coupling for kevlar-carbon hybrid laminate.

changes in fiber orientation of the thicker layer. This kind of plots also help to understand the trade-off between torsional and bending stiffness and also trade-off between coupling and stiffness. The plots for different material combinations with the same thickness are also obtained. Combinations of glass-kevlar, glass-carbon and kevlar-carbon are shown in Figures 11-13 respectively. The stiffness and coupling properties change according to the difference between mechanical properties of the materials, it is clear that hybrid laminations have higher coupling ability than glass-glass combinations.

5. CONCLUSIONS AND FUTURE WORK

The work presented in this article shows a method to analyze the mechanical properties of composites skins which are generally used in wind turbine blades. Bending and torsional stiffnesses which are critical for blade design are calculated via presented method, also coupling characteristics can be analyzed which can help the designer to understand the behavior of the blade more precisely and design aeroelastically tailored blades.

The method is simple and can be applied during pre-design phase and helps the designer to complete quick parametric studies which can be useful for dimensioning, decision of profiles and material selection.

Parametric studies show that:

- The thickness ratio of aerodynamic profiles has an important effect on stiffness properties.
- It is seen that higher anisotropy of material properties increases the coupling effects.
- Application of hybrid materials increases the ability of coupling.
- Thinner profiles are required to increase coupling.
- It is calculated that the stiffness properties of the section are proportional to the product tc^3 .
- When more than one material is combined, coupling and stiffness properties are dominated by the material having higher elastic properties.

This study is the first step of a research to investigate aeroelastic effects in blade performance. This article builds a base for the structural part, whereas 3D properties of blade sections are transformed to 1D beam sections. An additional work to include two or three cell sections is planned. Second phase of the study will include aerodynamic effects on blade structure and the setup of aero-structure interaction.

6. REFERENCES

- [1] Jones, R. M., (1998) "Mechanics of composite materials", Taylor & Francis, 2nd Edition.
- [2] Kaw, A. K., (2006) "Mechanics of Composite Materials", Taylor & Francis, 2nd Edition.

- [3] Daniel, I. M. and Ishai, O., (1994) "Engineering Mechanics of Composite Materials", Oxford University Press.
- [4] Kollar, L. P. and Springer, G. S., (2003) "Mechanics of Composite Structures", Cambridge University Press.
- [5] Vasiliev, V.V. and Morozov, E. V., (2001) "Mechanics and Analysis of Composite Materials", Elsevier.
- [6] Librescu, L. and Song, O., (2006) "Thin-walled composite beams: theory and application", Springer.
- [7] Karaolis, N.M., Jeronimidis, G., Musgrove, P. J., (1989) "Composite wind turbine blades: coupling effects and rotor aerodynamic performance", EWEC 1989 Proceedings.
- [8] Armanios, E. A. and Badir, A. M., (1995) "Free Vibration Analysis of Anisotropic thin walled closed section beams", AIAA Journal, Vol. 33, No. 10, pp. 1905-1910.
- [9] Chandra, R. and Chopra, I., (1992) "Structural behavior of two-cell composite rotor blades with elastic couplings", AIAA Journal, Vol. 30, No. 12, pp. 2914-2921.
- [10] Lee, A. ve Flay, R., (1998). "Compliant blades for wind turbines", *IPENZ Transactions*, 1999, Vol. 26, No. 1/EMCh.
- [11] Lobitz. D. W. and Veers, P. S., (1998), "Aeroelastic Behavior of Twist-Coupled Hawt Blades", *Sandia National Laboratories*, Albuquerque, New Mexico 87185-0439.
- [12] Ong, C. H. and Tsai, S. W. (1998), "Elastic Tailoring of a Composite D-Spar", *Sandia National Laboratories*, Report No: SAND98-1750.
- [13] Volovoi V.V. and Hodges D.H., (2000) "Theory of anisotropic thin-walled beams", *J. Applied Mechanics*; 67(3):453-459.
- [14] Volovoi V.V. and Hodges D.H., (2002) "Single and multi-celled composite thin-walled beams", *AIAA J*;40(5):960-6.
- [15] Volovoi, V. V., Hodges, D. H., Cesnik, C. E. S., Popescu, B., (2001). "Assessment of Beam Modeling Methods for Rotor Blade Applications", *Mathematical and Computer Modelling* 33 (2001) 1099-1112.
- [16] Maheri, A., Noroozi, S., Toomer, C., Vinney, J., (2006). "WTAB, a computer program for predicting the performance of horizontal axis wind turbines with adaptive blades", *Renewable Energy* 31 (2006) 1673-168.
- [17] Maheri, A., Noroozi, S., Vinney, J., (2007), "Combined analytical/FEA-based coupled aero structure simulation of a wind turbine with bend-twist adaptive blades", *Renewable Energy* 32 (2007) 916-930, Elsevier.
- [18] Maheri, A., Noroozi, S., Vinney, J., (2007), "Application of combined analytical/FEA coupled aero-structure simulation in design of wind turbine adaptive blades", *Renewable Energy* 32 (2007) 2011-2018.
- [19] Maheri, A., Noroozi, S., Vinney, J., (2006), "Decoupled aerodynamic and structural design of wind turbine adaptive blades", *Renewable Energy* 32 (2007) 1753-1767, Elsevier.
- [20] Chen, H., Yu, W., Capellaro, M., (2009), "A critical assessment of computer tools for calculating composite wind turbine blade properties", *Wind Energy*, (2009), DOI: 10.1002/we.372.
- [21] Park, A. J., Jung, S. N., (2009), "General Purpose Cross-section Analysis Program for Composite Rotor Blades", *International Journal of Aeronautical & Space Sciences*, Volume 10, No:2, November 2009.
- [22] Tingrui, L. ve Yongsheng, R., (2010), "Vibration and flutter of wind turbine blade modeled as anisotropic thin-walled closed-section beam", *Mechanical & Electronical Institute, Shandong University of Since & Technology*, Qingdao, China
- [23] Jeong, M., Yoo, S., Lee, I., (2011), "Aeroelastic Analysis for Large Wind Turbine Rotor Blades", 52nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 19th, 4 - 7 April 2011, Denver, Colorado.
- [24] Lee Y., Jhan Y., Chung C., (2012), "Fluid-structure interaction of FRP wind turbine blades under aerodynamic effect", *Composites Part B: Engineering*, Volume 43, Issue 5, 2012, Pages 2180-2191.
- [25] Jeon M., Lee S. and Lee S., (2014), "Unsteady vortex lattice method coupled with a linear aeroelastic model for horizontal axis wind turbine", *J. Renewable Sustainable Energy* 6, 042006.

VITAE

Akgün Kalkan

Akgün Kalkan was born in İzmir in 1978. He graduated from Faculty of Aeronautics and Astronautics of İstanbul Technical University in 2000. He received his M.S. degree in 2002 from Faculty of Mechanical Engineering of the same university. He started his career in 2001 in Structural Design and Analysis department of Arçelik R&D Center. He mainly worked on multibody dynamics simulations and tests of reciprocating compressors and washing machines. Between 2006 and 2010 he worked in R&D company of TEMSA in engineering and project management positions. He started his own company INORES in 2010 to provide engineering solutions and services especially in wind energy sector. His ongoing Ph. D. research is on the effect of structural deformation of composite wind turbine blades on turbine performance.

Prof. Dr. Zahit Mecitoğlu

Zahit Mecitoğlu was born in Antalya in 1958. He graduated from Aeronautical Engineering Department of İstanbul Technical University in 1982. Then he received MS and PhD degrees from Aeronautical Engineering Program of İstanbul Technical University in 1984 and 1988, respectively. Dr. Mecitoğlu worked as assistant professor between 1989 and 1990 and associate professor between 1990 and 1996 in Aeronautical Engineering Department of İstanbul Technical University. He has been working as a Professor in Astronautical Engineering Department of the same university since 1996. He worked as a visiting scientist in Aerospace Department of Georgia Institute of Technology in 1991 and participated the project named “Structural Integrity of Sikorsky MH-53J Helicopters. Dr. Mecitoğlu has worked in many projects such as National Wind Turbine Prototype System Development and Production Project, Tactical UAV (Catapult / Parachute) Development Project, Aerospace Research and Application Project, Tramcar Development Design and Production Project. His research areas are dynamics of aerospace structures, structural design and testing, wind turbine design, composite structures, experimental mechanics and finite element method.