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Modeling Approaches for Evaluating the Equivalent Mechanical Properties of Wind Turbine Blade Composites

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Abstract. Abstracting complex three-dimensional composite structures into one-dimensional models is an essential strategy for the efficient analysis of wind turbine blades. This work aims to evaluate the accuracy of widely used computational tools for obtaining equivalent sectional properties and to analyze their impact on the dynamic response of the structure. The methodology was divided into two stages: first, the sectional properties obtained with the PreComp, CROSTAB, VABS, and GXBeam software were compared, based on a reference study from the literature. Subsequently, a modal analysis of a 20-meter wind turbine blade was performed using the calculated properties. The results indicate that, although there is some coherence in the natural frequencies, the discrepancies increase in the higher modes and are directly related to errors in the sectional properties, especially in the coupling terms. GXBeam demonstrated good agreement with the VABS results, capturing anisotropic effects and elastic couplings with greater precision. It is concluded that, for higher-fidelity modal analyses in composite structures, the appropriate choice of sectional calculation tool is essential, with GXBeam being a robust and reliable alternative.

Keywords: Wind turbine, Composite, Beam element, Structure

1 Introduction

The ability to abstract a complex three-dimensional structure into a one-dimensional beam model is one of the most powerful tools in structural mechanics [1], enabling the optimization of simulations in engineering. The oldest and most fundamental theory, that of Euler-Bernoulli, is based on two kinematic hypotheses: (i) cross sections that are planar and normal to the beam axis before deformation remain planar and (ii) remain normal to the deformed axis. This implies that the rotation of the section is fully determined by the slope of the elastic curve, disregarding transverse shear deformation [2][3].

By neglecting shear deformation, there is a limitation on accuracy for shorter beams or for materials with low shear stiffness [4], as occurs in many composite materials. To overcome this limitation, Timoshenko[4] proposed a refined theory. Timoshenko's theory relaxes Euler-Bernoulli's second hypothesis, thus allowing the cross-section to have a rotation that is independent of the slope of the elastic curve. This leads to a system of two coupled differential equations, which are more accurate but still fundamentally linear [2][4].

Classical theories, being linear, fail to capture a range of crucial phenomena that arise in modern aircraft, where interactions between structural deformations and aerodynamic forces are strong and deflections are large [5]. Even with this intrinsic need, solving the 3D elasticity equations for an entire structure, such as a composite wing, is computationally expensive, even with supercomputers, especially in optimization contexts or aeroelastic simulations that require multiple solutions. Therefore, the modern approach is based on scale separation, made possible by the slender geometry of the structure [6].

The analysis is decomposed into two distinct but physically coupled computational steps. By analyzing through the Cross-Section Scale (two-dimensional) the focus is on local mechanical behavior. The problem is to determine the constitutive response of the cross-section, which can have a complex geometry and be made of multiple layers of anisotropic composite materials. The VABS (Variational Asymptotic Beam Sectional Analysis) is one of the methodologies developed to solve this problem [7]. In sequence, when a beam scale (one-dimensional)

is required, the structure is modeled as a line, where each point is endowed with the stiffness matrix calculated in the previous scale. The equations governing the dynamics of this line in space, under large motions, are those of GEBT (Geometrically Exact Beam Theory) [8].

This unified approach allows the analysis to retain the fidelity of 3D elasticity with a computational cost associated with a 1D problem, making high-fidelity analysis a suitable tool in engineering. To validate the utilization of common tools capable of reducing complex cross-sections into simplified beam-scale models, this work is divided into two parts. The first part aims to guarantee the reliability of the adopted software, based on the studies of Chen et al. on cross-sectional properties [9]. The second part focuses on modal analysis, verifying the results obtained by different software available in this field of study.

2 Materials and methods

Considering the objectives proposed, this work employs a structured methodology to validate the utilization of common software tools for reducing complex cross-sections into simplified beam-scale models. The foundation of this study involved a bibliographic review to consolidate the understanding of established software models. Primarily, VABS (Variational Asymptotic Beam Sectional Analysis) and BECAS (Beam Cross-Sectional Analysis) were analyzed, with the latter being essential to the GXBeam documentation. This review provided detailed insight into their operational principles and theoretical underpinnings.

According to the work by Chen et al.[9], sectional properties constitute the foundation for accurately abstracting the intricate, three-dimensional mechanical behavior of structural components, particularly those with complex or varying cross-sections like advanced composite blades, into more computationally tractable one-dimensional beam models. These properties are far more than simple geometric attributes such as the cross-sectional area or the moments of inertia; instead, they represent a comprehensive and tensorial set of stiffness and inertia characteristics that fundamentally govern precisely how a specific beam cross-section deforms and responds when subjected to a full spectrum of applied loads. This spectrum includes not only direct axial forces but also bending moments around various principal axes, transverse shear forces, and torsional moments.

Beyond these direct stiffnesses, and of paramount importance for structures fabricated from anisotropic and inhomogeneous materials, as is the case with advanced composites, the sectional properties explicitly include coupling terms. These terms represent the intricate cross-interactions where a load applied in one primary direction can induce a deformation in a seemingly orthogonal or unrelated direction. For instance, a bend-twist coupling implies that the application of a pure bending moment might simultaneously cause the beam to undergo a twisting deformation, or conversely, a pure torsional moment could inadvertently induce bending. Similarly, an extension-shear coupling would mean that an axial force applied along the beam's length could lead to transverse shear deformation. The accurate and meticulous calculation and subsequent inclusion of these coupling terms are indispensable for achieving a truly comprehensive and realistically predictive structural analysis of modern composite structures, as neglecting them would inevitably lead to significant inaccuracies in predicting the true structural response [6][9].

The overarching objective of deriving this detailed and complete set of sectional properties is to rigorously transform a complex, computationally intensive three-dimensional elasticity problem into a more manageable and highly efficient one-dimensional beam problem. This analytical simplification dramatically reduces computational cost and complexity, enabling faster and more efficient design iterations and analyses, all while rigorously maintaining a high level of accuracy for slender structural components by effectively treating the complex cross-section as a simplified beam characterized by these fundamental properties determined [8][10].

As presented by Chen et al.[9], the cross-sectional properties utilized in this work are those compatible with the Euler-Bernoulli theory. Its strain energy matrix is given by Eq. (1), where x_1 defines the beam reference line and x_2 and x_3 denote the cross-sectional plane. While this formulation suffices for most static problems, predicting the behavior of complex rotating elements, such as wind turbine blades, requires including the beam's kinetic energy, as represented by Eq. (2). A detailed explanation of the coefficients for both equations can be found in [9]. For the scope of this study, it is sufficient to acknowledge that the properties derived from the results are precisely those required for the application of Eqs. (1) and (2).

$$\mathcal{U} = \frac{1}{2} \begin{Bmatrix} \gamma_{11} \\ \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{Bmatrix}^T \begin{bmatrix} EA & S_{12} & S_{13} & S_{14} \\ S_{12} & GJ & S_{23} & S_{24} \\ S_{13} & S_{23} & EI_{22} & S_{34} \\ S_{14} & S_{24} & S_{34} & EI_{33} \end{bmatrix} \begin{Bmatrix} \gamma_{11} \\ \kappa_1 \\ \kappa_2 \\ \kappa_3 \end{Bmatrix} \tag{1}$$

$$\mathcal{K} = \frac{1}{2} \begin{Bmatrix} V_1 \\ V_2 \\ V_3 \\ \Omega_1 \\ \Omega_2 \\ \Omega_3 \end{Bmatrix}^T \begin{bmatrix} \mu & 0 & 0 & 0 & \mu x_{m3} & -\mu x_{m2} \\ 0 & \mu & 0 & -\mu x_{m3} & 0 & 0 \\ 0 & 0 & \mu & \mu x_{m2} & 0 & 0 \\ 0 & -\mu x_{m3} & \mu x_{m2} & i_{22}+i_{33} & 0 & 0 \\ \mu x_{m3} & 0 & 0 & 0 & i_{22} & -i_{23} \\ -\mu x_{m2} & 0 & 0 & 0 & -i_{23} & i_{33} \end{bmatrix} \begin{Bmatrix} V_1 \\ V_2 \\ V_3 \\ \Omega_1 \\ \Omega_2 \\ \Omega_3 \end{Bmatrix} \tag{2}$$

2.1 Common Tools for obtaining cross-sectional properties

A brief review of the software whose results were utilized in this work can be consulted in Table 1. For the core analysis in this study, the GXBeam software was utilized [11]. The primary validation in the first part of this work involved a direct comparison of the cross-sectional properties obtained from GXBeam with the results established in the studies by Chen et al.[9]. This comparative analysis was crucial to ensure the reliability and accuracy of GXBeam for the specific types of cross-sections investigated.

Table 1. Description of the software applied on the sectional properties studies

Software	Functionality	Limitations
PreComp	Computing structural properties for composite blades by integrating a modified classic laminate theory with a shear-flow approach. It is designed to be a fast pre-processor for calculating span-variant properties, inertia properties, and offsets for the shear center and tension center [12].	Primarily optimized for thin-walled, closed-section, airfoil-like geometries. Its applicability to general or solid cross-sections may be limited. It is based on a modified laminate theory, which might not accurately capture 3D stress effects. [9][12]
CROSTAB	CROSTAB models blade sections as layered shells with closed cells. It calculates complete sectional properties for the Euler–Bernoulli beam model, including coupling terms, by using the inverse of the Classical Lamination Theory membrane stiffness matrix and considering shear flow. Its advantage lies in a more rigorous treatment of composites than predecessors softwares, allowing coupling calculations. [9].	CROSTAB assumes that walls carry only in-plane loads and neglects their bending and torsional stiffness. A critical limitation is its inability to calculate the shear center, which is essential for the Euler–Bernoulli model. For thick composites, omitting wall bending/torsion stiffness can lead to additional accuracy restrictions. [9]
VABS	The VABS (Variational Asymptotic Beam Sectional Analysis) efficiently reduce a 3D slender solid with a complex, anisotropic cross-section into a model compatible with 1D engineering beam model. It computes the complete set of beam stiffness constants (tension, bending, shear, torsion) and inertia properties, originally designed to model initially curved and pre-twisted anisotropic blades. [7][9][13] .	Requires a 2D Finite Element mesh of the cross-section as input, which adds a pre-processing step. VABS provides accurate 3D fields only away from beam boundaries, concentrated loads, and sudden changes in cross-sectional geometry along the span. [9]
GXBeam	Utilize a model based in BECAS (Beam Cross section Analysis Software), a 2D FEA-based tool specifically designed to calculate the structural properties (mass and stiffness matrices) of arbitrary, inhomogeneous and anisotropic beam cross-sections. GXBeam also is a geometrically exact beam theory solver that uses the cross-sectional stiffness data to perform nonlinear analysis of flexible beam systems. [10][11][14]	As a 2D FEA tool, its accuracy is dependent on mesh density. The setup can be more involved than semi-analytical tools. The software GXBeam, by itself, is a beam solver, not a cross-section analysis tool. A significant limitation is that the current implementation does not model cross-section warping, making it unsuitable for open sections (e.g., I or C-beams) unless they are "strip-like" (width higher than height).[10][11]

Following the cross-sectional property validation, the second part of the study extended to a modal analysis. For each model, the first five mode shapes were extracted. This process involved identifying both the natural frequency and the corresponding vibration mode for each of these initial five modal responses, allowing for a comprehensive comparison of dynamic behaviors across different software and models.

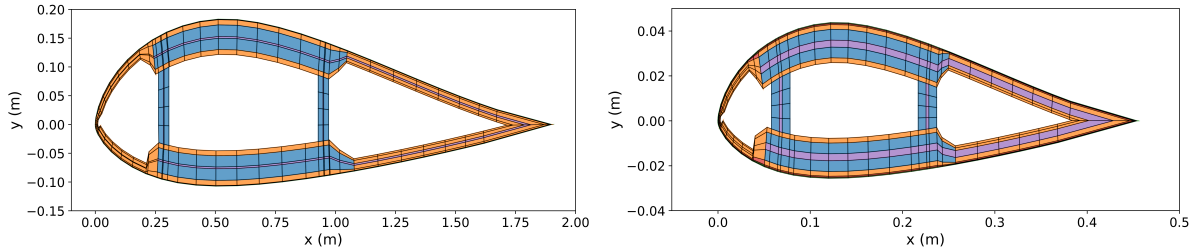
3 Results and discussions

In this work, two cross-sections of a wind turbine blade composed of five coating layers and two spars were evaluated using the GXBeam tool. The results were compared with those obtained by the PreComp, VABS, and CROSTAB software. The geometric characteristics of the section, such as chord length, twist angle, pitch axis position, and web location, as well as the results of the mentioned tools, were extracted from the work of Chen et al.[9], and are associated with the MH 104 airfoil. It should also be noted that the material properties used in the model were obtained from a realistic example of wind turbine blades, tested in the PreComp tool guide, developed by NREL [12].

Subsequently, a modal analysis was conducted for a 20-meter-long wind turbine blade, using the sectional properties associated with the first radial station. Based on the properties previously obtained through GXBeam, the stiffness and mass matrices were assembled (Eqs. (1) and (2)), enabling the formulation of the corresponding eigenvalue problem.

3.1 Sectional Properties

In most GXBeam examples, the cross-sectional stiffness and inertial properties are provided directly as input. However, in practical applications, these properties typically need to be derived from the input geometry and material definitions. This calculation is based on the two-dimensional finite element procedure described by Giavotto et al.[14] and further detailed in the BECAS user guide[10]. The stiffness matrix is computed numerically by discretizing the cross-section with two-dimensional finite elements. The code allows for the generation of nodes and mesh elements from a parameterized airfoil definition. Figures 1a and 1b illustrate the resulting mesh and the material layers that define the cross-section at the first and second radial stations, respectively.



(a) First radial station

(b) Second radial station

Figure 1. Meshes generated by GXBeam

The cross-sectional properties computed with GXBeam for both stations are listed in Table 2. The diagonal terms EA (N), GJ, EI_{22}, and EI_{33} (N·m^2) represent extensional, torsional and bending stiffness about x_2 and x_3. The sections exhibit full elastic coupling, including extension–torsion (S_{12}), extension–bending (S_{13}, S_{14}), torsion–bending (S_{23}, S_{24}), and cross-bending (S_{34}), with S_{12}, S_{13}, and S_{14} in N·m, and the others in N·m^2. These couplings define the tension center (x_{t2}, x_{t3}) and shear center (x_{s2}, x_{s3}), all in meters. The mass per unit length μ (kg/m) and the center of mass coordinates (x_{m2}, x_{m3}, in m) are also provided. Finally, i_{22} and i_{33} (kg·m) are the moments of inertia about x_2 and x_3, and i_{23} (kg·m) is the product of inertia.

Regarding Table 2, as previously noted by Chen et al.[9], tools such as PreComp and CROSTAB, which are based on simplified assumptions exhibit significant limitations in predicting coupling terms. These simplifications resulted in percentage errors exceeding $1,000\%$ for some coefficients. The authors also highlight that, despite these limitations, PreComp tends to yield better estimates for parameters such as EI_{22}, i_{22}, x_{m3}, and x_{t3}, where as CROSTAB performs more accurately in computing EA, GJ and EI_{33}.

In Table 2, among the tools evaluated, the diagonal coefficient with the best convergence to GXBeam, in the first and second radial stations, was the extensional stiffness (EA). The percentage differences recorded for each tool were 1.16% and 1.22% for VABS, 24.22% and 34.66% for PreComp, and 15.49% and 36.28% for CROSTAB. Another highlight was the torsional stiffness (GJ), in which VABS again showed the smallest deviations, with 6.33% and 4.04%, while CROSTAB resulted in 21.15% and 38.87%, and PreComp in 50.54% and 39.25%.

The coupling terms, in turn, showed more pronounced discrepancies between the evaluated tools (Table 2). For the bending-extension terms (S_{13} and S_{14}), in the first and second stations, VABS showed differences of less than 35%, while PreComp showed errors greater than 80%. CROSTAB, in turn, showed even more significant deviations, with errors greater than 100% for S_{13} and greater than $1,000\%$ for S_{14}. In the case of the extension-torsion term (S_{12}), VABS obtained values between $8 - 98\%$, while PreComp presented errors greater than 100%,

Table 2. Sectional properties of the wind turbine blade at the first and second stations

Variables	PreComp		CROSTAB		VABS		GXBeam	
	Station 1	Station 2	Station 1	Station 2	Station 1	Station 2	Station 1	Station 2
EA	3.000×10^{9}	2.090×10^{8}	2.789×10^{9}	2.115×10^{8}	2.387×10^{9}	1.533×10^{8}	2.415×10^{9}	1.552×10^{8}
GJ	1.008×10^{7}	4.103×10^{4}	2.469×10^{7}	9.379×10^{4}	2.167×10^{7}	7.027×10^{4}	2.038×10^{7}	6.754×10^{4}
EI_{22}	2.103×10^{7}	6.363×10^{4}	1.459×10^{8}	8.608×10^{5}	1.916×10^{7}	5.878×10^{4}	2.023×10^{7}	6.240×10^{4}
EI_{33}	6.309×10^{8}	2.784×10^{6}	4.878×10^{8}	2.481×10^{6}	4.398×10^{8}	1.586×10^{6}	5.571×10^{8}	2.051×10^{6}
S_{12}	7.522×10^{5}	4.719×10^{3}	-1.723×10^{9}	-3.037×10^{7}	-3.381×10^{7}	-1.314×10^{4}	-3.120×10^{7}	-4.881×10^{5}
S_{13}	-1.037×10^{6}	-1.558×10^{4}	5.216×10^{8}	1.187×10^{7}	-2.635×10^{7}	-4.297×10^{5}	-2.790×10^{7}	-4.275×10^{5}
S_{14}	-1.301×10^{8}	-7.272×10^{6}	1.685×10^{8}	1.332×10^{6}	-4.724×10^{8}	-7.224×10^{6}	-6.948×10^{8}	-1.098×10^{7}
S_{23}	-3.776×10^{5}	-9.178×10^{2}	9.002×10^{9}	1.671×10^{7}	-5.222×10^{4}	1.214×10^{2}	-1.443×10^{4}	-2.011×10^{2}
S_{24}	8.746×10^{6}	1.833×10^{4}	-1.208×10^{9}	-4.429×10^{6}	1.422×10^{6}	6.274×10^{3}	4.031×10^{6}	1.846×10^{4}
S_{34}	-8.132×10^{6}	-2.149×10^{4}	6.010×10^{7}	2.433×10^{5}	1.210×10^{7}	4.159×10^{4}	1.491×10^{7}	5.176×10^{4}
μ	2.859×10^{2}	2.005×10^{1}	2.891×10^{2}	2.207×10^{1}	2.581×10^{2}	1.676×10^{1}	2.598×10^{2}	1.692×10^{1}
i_{22}	2.211	7.229×10^{-3}	5.144	2.080×10^{-2}	2.172	7.017×10^{-3}	2.195	7.081×10^{-3}
i_{33}	6.272×10^{1}	2.644×10^{-1}	6.134×10^{1}	3.180×10^{-1}	4.642×10^{1}	1.740×10^{-1}	4.760×10^{1}	1.780×10^{-1}
x_{m2}	3.320×10^{-1}	8.900×10^{-2}	2.840×10^{-1}	8.710×10^{-2}	2.778×10^{-1}	6.190×10^{-2}	2.480×10^{-1}	1.750×10^{-1}
x_{m3}	2.700×10^{-2}	6.000×10^{-3}	-2.800×10^{-2}	-4.000×10^{-3}	2.743×10^{-2}	6.500×10^{-3}	2.700×10^{-2}	6.000×10^{-3}
x_{t2}	3.310×10^{-1}	9.200×10^{-2}	-2.900×10^{-2}	-5.100×10^{-3}	2.330×10^{-1}	4.920×10^{-2}	7.070×10^{-1}	1.630×10^{-1}
x_{t3}	2.800×10^{-2}	7.000×10^{-3}	2.273×10^{-1}	6.590×10^{-2}	2.900×10^{-2}	6.900×10^{-3}	2.900×10^{-2}	6.800×10^{-3}
x_{s2}	2.870×10^{-1}	5.800×10^{-2}	-	-	3.100×10^{-2}	1.200×10^{-3}	4.160×10^{-1}	9.200×10^{-2}
x_{s3}	2.800×10^{-2}	7.000×10^{-3}	-	-	4.000×10^{-2}	9.800×10^{-3}	4.000×10^{-2}	9.600×10^{-3}

and CROSTAB, greater than $5,000\%$. Finally, for the torsion-bending terms (S_{23} and S_{24}), all tools showed significant deviations, above 64%, with emphasis on CROSTAB, which exceeded $10,000\%$ in both cases, suggesting out-of-scale values or possible numerical instabilities in the tool.

The mass matrix coefficients should also be highlighted (Table 2). The mass per unit length (μ) obtained by VABS shows excellent agreement with GXBeam, with differences of only 0.68% and 0.93% in the first and second stations, respectively. In contrast, the other tools showed errors between $10-11\%$ in the first station and between $18-30\%$ in the second. For the shear centers (x_{s3}), VABS coincides with GXBeam in the first station and shows a deviation of only 2.08% in the second. However, for the values of x_{s2}, there are significant differences of 92.55% and 98.70%. PreComp, in turn, showed differences of less than 30% for these same terms. Finally, concerning the centers of mass and tension, both VABS and PreComp were close to the values obtained with GXBeam, while CROSTAB presented discrepancies greater than 100%.

3.2 Modal Analysis

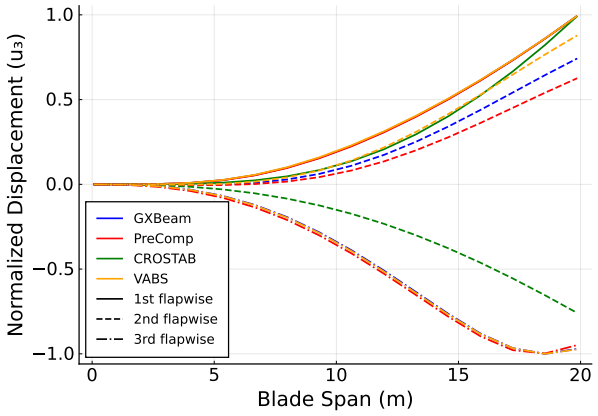
Modal analysis, as highlighted by Larsen et al.[15], is widely used in the dynamic characterization of mechanical systems because it offers illustrative and easily interpreted results, especially when combined with the visualization of mode shapes. The mechanical behavior of a vibrating structure is governed by its stiffness and mass properties, which are represented by the stiffness and mass matrices. The eigenvalue problem defines the relationship between these matrices and the natural frequencies of the system. Typically, the dynamic behavior is characterized by the first three to four bending modes and the first torsional mode. Table 3 presents the natural frequencies and their corresponding mode shapes, obtained for a 20-meter wind turbine blade using the sectional properties defined at the first radial station.

Table 3. Natural vibration frequencies (Hz)

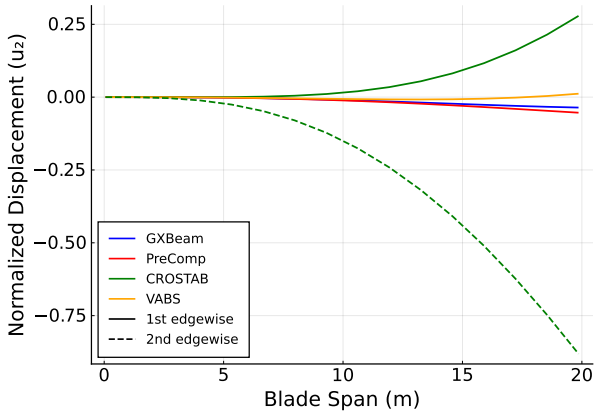
Modos	PreComp	CROSTAB	VABS	GXBeam
1st Bending x_3 (u_3)	0.379	0.991	0.381	0.390
1st Bending x_2 (u_2)	2.075	1.815	1.824	2.046
2nd Bending x_3 (u_3)	2.354	6.069	2.381	2.439
3rd Bending x_3 (u_3)	6.444	-	6.638	6.801
1st Torsion x_1 (θ_1)	6.988	9.616	10.870	9.738
2nd Bending x_2 (u_2)	-	11.293	-	-

Furthermore, the normalized modal shapes obtained by each tool are presented in Figure 2. The normalization

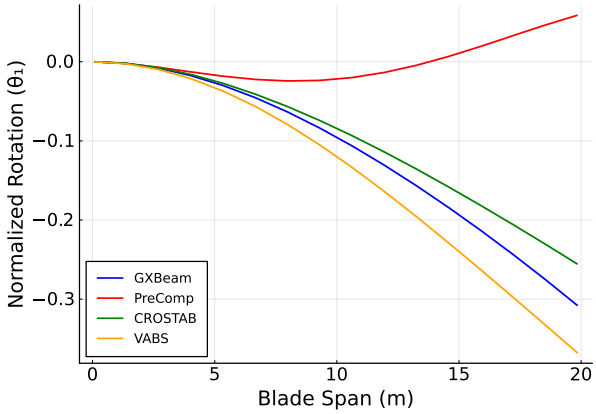
was performed by dividing the strain energy of each motion component by the total modal energy, resulting in values between 0 and 1 that represent the relative contribution of each component to the mode. For visualization, the modal displacements were additionally centered and scaled by their maximum absolute value, allowing direct shape comparison between tools.



(a) Flapwise bending modes (x_3)



(b) Edgewise bending modes (x_2)



(c) Torsional modes (x_1)

Figure 2. Modal shapes

The comparison between the estimated sectional properties and the modal results reveals a clear correlation with the natural frequencies presented in Table 3. PreComp, for example, overestimates the torsional axial stiffness (GJ) by more than 50% in relation to the value obtained by GXBeam, which leads to an underestimation of the natural torsional frequency (6.988 Hz) when compared to the CROSTAB (9.616 Hz), GXBeam (9.738 Hz) and VABS (10.870 Hz), as highlighted in the article by Chen et al.[9]. CROSTAB, despite providing a GJ value closer to GXBeam (21.15% error), shows large differences in the coupling terms, with errors exceeding $60,000,000\%$ (S_{23}), which significantly compromises the accuracy of the intermediate and higher modes. GXBeam, on the other hand, presents sectional values systematically close to those of VABS, especially the parameters (EA, GJ, μ, and i_{22}), as well as the couplings (S_{12}, S_{13}, S_{14}).

Based on Figure 2, each modal shape of the wind turbine blade is directly related to the natural frequencies presented in Table 3. The *flapwise* bending modes are presented in Figure 2a. The first mode, characterized by deflection in the plane perpendicular to the airfoil chord, exhibits the lowest frequency among those analyzed. It shows good agreement between GXBeam, PreComp, and VABS, while CROSTAB presents a significantly difference. The second and third flapwise bending modes also show compatible shapes among GXBeam, PreComp, and VABS. However, CROSTAB diverges notably, especially in the third mode, where it fails to adequately represent the stiffness distribution, leading to inconsistent curvature patterns along the blade span. The *edgewise* bending modes are shown in Figure 2b. The first edgewise mode reveals the biggest shape difference between VABS and GXBeam. CROSTAB once again stands out negatively, providing inaccurate estimates. In the higher-order edgewise mode, only CROSTAB can identify the shape, which may be attributed to its better estimation of the EI_{33} stiffness. Nonetheless, due to its overall imprecise sectional properties and coupling terms, its modal predictions remain unreliable. The *torsional* mode is presented in Figure 2c. This mode is highly sensitive to the torsional stiffness GJ and highlights the largest discrepancy between PreComp and GXBeam. The differences observed

suggest distinct interpretations of the torsional behavior and coupling among the tools.

4 Conclusions

The results demonstrate that, despite the significant differences in the sectional properties estimated by each tool, the natural frequencies exhibit an overall coherence, especially in the fundamental modes. However, as one moves towards higher modes, the discrepancies become more evident, mainly in the results obtained with CROSTAB, which shows large errors in the coupling terms, affecting the accuracy of the modal shapes and associated frequencies. The modal analysis highlighted the strong correlation between the accuracy of the sectional properties and the fidelity of the predicted dynamic response. In particular, discrepancies in parameters such as GJ, EI_{22}, EI_{33}, and especially in the coupling terms (S_{12}, S_{13}, S_{14}, S_{23}, S_{24}), had a direct influence on the predicted natural frequencies and mode shapes. PreComp and CROSTAB, due to their reliance on simplified formulations, exhibit notable limitations, most prominently in capturing elastic couplings and in locating the shear and mass centers.

GXBeam, in turn, proved to be consistent with the results obtained with VABS. The good agreement in the values of the main stiffnesses, inertias, and couplings demonstrates GXBeam's ability to capture, with greater fidelity, the anisotropic effects and complex elastic couplings characteristic of composite structures. Thus, it is concluded that GXBeam is a robust and reliable alternative for the sectional modeling of wind turbine blades, especially in contexts that demand high-fidelity dynamic analyses. The coupling terms play a significant role, since, when properly calculated, they provide an accurate prediction of the aeroelastic dynamic behavior.

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