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# Elastic constants identification of composite wind blade using measured strains and displacements

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## ABSTRACT

A procedure is presented to identify the elastic constants of glass fabric composite wind blades using measured blade strains and/or displacements via a numerical-experimental approach. The skins of the composite blade are fabricated using the vacuum assisted resin transfer method. The root of the composite blade is adhesively bonded to a metal connector which can be joined to a rigid frame for static load testing. A finite element model of the blade is established to predict the mechanical behavior of the blade. For elastic constants identification, the strains and displacements at some particular locations on the blade are measured during the static load testing of the blade. The measured as well as the theoretically predicted blade strains and displacements are used in an optimization method to characterize the glass-fabric/epoxy material of the blade skins. The comparison between the experimental theoretical buckling loads and mode shapes are then used to verify the accuracy of the identified elastic constants.

Keywords: Wind blade, Composite materials, material characterization, finite element analysis

## 1. INTRODUCTION

In a horizontal axis wind turbine (HAWT) system, the wind rotor blades are important elements for converting wind energy to electricity. A HAWT has to survive the attack of severe environment for at least 20 years. During the turbine's lifetime, the wind blades of the turbine have to be able to sustain the extreme wind loads that may occur. In view of these requirements, the reliability of a wind turbine blade has become an important topic of research, especially the monitoring of the material properties of the blade at different stages during its lifetime. To ensure the reliability of a wind blade, it is essential to use the correct elastic constants to predict the actual mechanical behavior of the wind blade so that any unexpected failure can be avoided. Recently, many papers have been devoted to study different aspects of wind turbine blade reliability, for instance, structural analysis and design of wind blades. All of these studies have revealed the fact that it is essential to have the knowledge of the exact values of elastic constants for performing a realistic reliability assessment of the wind blade. In particular, due to the environmental effects on material properties, the determination of the actual elastic constants becomes even more important for the wind blades of an existing wind turbine if a meaning reliability assessment of the wind turbine is desired. Regarding the elastic constants identification of composite materials/structures, many methods have been proposed to use measured vibration data, strains, or displacements for material characterization [1-5]. For instance, Chen and Kam [1] proposed a numerical-experimental method to identify four material constants of laminated composite materials using three measured strains of an angle-ply laminate.

In this paper, a method is presented to identify the elastic constants of a glass-fabric/epoxy composite wind blade using the measured strains and displacements of the blade. The identified elastic constants are then used to simulate the buckling behavior of the blade. The comparison between the theoretically predicted and experimental buckling characteristics (buckling load and mode shape) is performed to verify the accuracy of the proposed elastic constants identification method.

## 2. ELASTIC CONSTANTS IDENTIFICATION

The glass-fabric composite skin of the blade has 3 elastic constants ($E_1$, $v_{12}$, and $G_{12}$). The problem of elastic constants identification of a composite wind blade is formulated as a minimization problem. Two measured axial strains and the blade tip displacement are used to identify the three elastic constants of the constituent composite material of the blade skin in the minimization problem. In general, the minimization problem of elastic constants identification is expressed as

$$\text{Minimize } e(x_1) = \left\{ \begin{matrix} \left[\left(\varepsilon_0^* - \varepsilon_{0,1}\right)\cdot\xi\right]^2 + \left[\left(\varepsilon_{90}^* - \varepsilon_{90,1}\right)\cdot\xi\right]^2 \\ + \left[\left(d_y^* - d_{y,1}\right)\cdot\xi\right]^2 \end{matrix} \right\} \quad (1)$$

Subject to $x_{1i}^L \le x_{1i} \le x_{1i}^U$

where $e(\underline{x}_1)$ is the objective function measuring the differences between the predicted and measured strains and displacement; $\varepsilon_0^*$ and $\varepsilon_{90}^*$ are, respectively, the measured axial and lateral strains of the laminate; $d_y^*$ and $d_{y,1}$ are measured and predicted blade tip displacements,

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respectively; $\varepsilon_{0,1}$ and $\varepsilon_{90,1}$ are, respectively, the predicted axial and lateral strains of the laminate obtained in laminate strain analysis; $x_i^L$, $x_i^U$ are, respectively, the lower and upper bounds of the elastic constants $x_i$; $x_{1i} = \left[E^{(1)}, \nu^{(1)}, G^{(1)}\right]$, the elastic constants identified at the first level; $\xi$ is an amplification factor which is used to increase the sensitivity and avoid the occurrence of numerical underflow of the error function. The constraint equation can be rewritten as

$$\begin{aligned} \text{Subject to }\ & 10GPa \le E^{(1)} \le 100GPa \\ & 0.01 \le \nu^{(1)} \le 0.5 \\ & 1GPa \le G^{(1)} \le 10GPa \end{aligned} \tag{2}$$

The constrained minimization problem of Eq. (1) can be converted into an unconstrained minimization problem by creating a general augmented Lagrangian. Herein, the goal of solving the above first-level optimization problem is to attain a local minimum that is in the vicinity close to the global minimum. Therefore, in the solution process, a number of starting points are randomly generated and for each starting point, the minimization algorithm with dynamic search trajectory reported in [6] is used to search for the lowest local minimum, which is in the vicinity of the global minimum. Finally, the average values of the elastic constants determined from the several lowest local minima are treated as the best estimates of the elastic constants $x'$.

## 3. FABRICATION AND TESTING OF BLADE

The composite wind blade shown schematically in Fig. 1 has an airfoil shape of NACA4418. The blade orients in the x-direction with its root end located at x = 0. The blade consists of 3 main parts, namely, top skin, bottom skin, and longitudinal spar. The top and bottom skins are adhesively connected to the spar to form the aerodynamic profile of the blade. The spar is made of two flanges and a shear web. The shear web of the spar is a glass-fabric composite sandwich panel and the flanges of the spar are Balsa wood panels. For a 2.5m long blade, the skin lamination scheme is 6 and 3 layers in the regions [0, 800]mm and [800, 1570]mm, respectively.

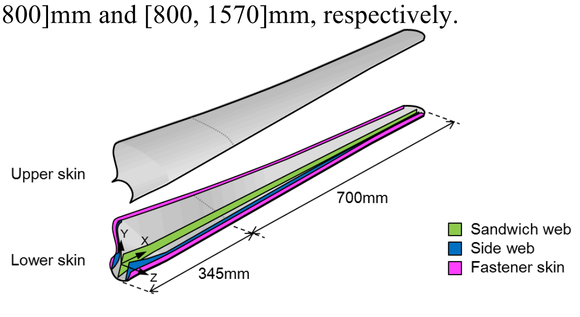

Fig. 1 Blade structure

The blade skins are fabricated using the vacuum assisted resin transfer method as shown in Fig. 2. Shown in Fig 3 is the blade finite element model and boundary conditions. The shell element of ANSYS (Shell 91) with 8 nodes is used to model the blade. The finite elements in the regions where strains are to be measured have aspect ratios close to 1.

Fig. 2 Fabrication of wind blade skin

Fig. 3 FEM model of blade

## 4. EXPERIMENTAL INVESTIGATION

In the test, the 2.5m composite blade with the bottom skin facing upward was fixed at the root end as shown in Fig. 4. Several sensors (strain and displacement gage) were mounted on the blade surfaces to measure the blade surface strains and displacement during testing. The mounting locations of the sensors on the blade are shown in Fig. 5. In this study, the static load test of a wind blade is performed via the applications of two point loads at some particular locations on the wind blade. For comparison purpose, a number of glass-fabric composite specimens were also prepared using the VRTM. The material constants of the glass-fabric composite specimen determined in accordance with the ASTM standards are E = 23GPa, $\nu_{12}$ = 0.14 and $G_{12}$ = 3.96GPa.

Fig. 4 Static load testing of blade

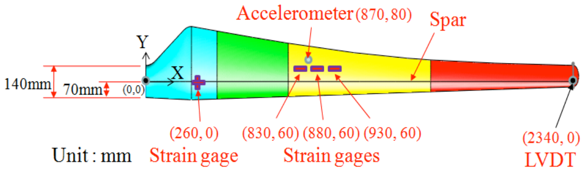

Fig. 5 Locations of sensors

## 5. RESULTS AND DISCUSSION

The strain 1, strain 2, and displacement used to identify the elastic constants are listed in Table 1. The identified elastic constants of the blade determined using the proposed method are E = 23.0 GPa (0.01%), $\nu$ = 0.14 (0.24%), and $G_{12}$ = 3.80 (-4.03%) where the values in the parentheses are percentage differences in comparing with the elastic constants obtained from the standard ASTM tests. It is noted that the largest percentage difference is equal to 4.03%.

Table 1. Measured strains and displacement

| Parameters | Skin | Location (mm) | | Measuring direction | Skin layers |
|---|---|---|---|---|---|
| | | x | y | | |
| Strain 1 | Upper skin | 650 | 40 | 90° (y-direction) | 6 |
| Strain 2 | Upper skin | 700 | 40 | 0° (x-direction) | 6 |
| Strain 3 | Upper skin | 1000 | 40 | 90° (y-direction) | 3 |
| Strain 4 | Upper skin | 1050 | 40 | 0° (x-direction) | 3 |
| Strain 5 | Upper skin | 1710 | 40 | 0° (x-direction) | 3 |
| Displacement | Lower skin | 0 | 2340 | z-direction | 3 |

Buckling is an important failure mode of thin-walled structures such as wind blades. Therefore, to verify the accuracy of the identified elastic constants, the buckling behavior of the wind blade is studied using the identified elastic constants. The geometrically nonlinear finite element module of ANSYS is used to analyze the skin buckling behavior of the blade. The theoretically predicted buckling shape of the blade is shown in Fig. 6. The theoretically predicted and experimental buckling locations and loads are listed in Table 2 for comparison. It is noted that the percentage differences between the theoretically predicted and experimental buckling locations and loads are less than 7%.

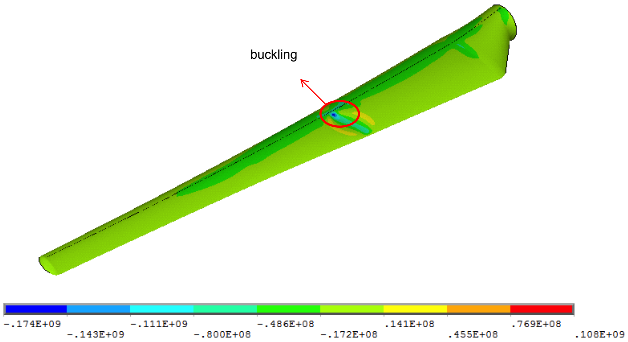

Fig. 6 Buckled shape of wind blade

Table 2 Experimental and theoretical incipient buckling loads

| Experiment | | Nonlinear-FEM | |
|---|---|---|---|
| Load (Kgf) | Location (mm) | Load (Kgf) | Location (mm) |
| 14.30 | 930 | 15.30<br>(-6.99%) | 899<br>(3.44%) |

- Percentage difference = ((Experimental - Theoretical) / Experimental) × 100%

## 4. CONCLUSION

A method has been presented to identify the elastic constants of the skin materials of composite wind blades. In the proposed method, only two strains and one displacement are required to be used in a minimization technique to identify the elastic constants of the skin material. The elastic constants determined in the standard ASTM testing have been used to verify the accuracy of those predicted by the proposed method. The experimental buckling load and location of the blade have also been used to further validate the capability of the proposed method in yielding accurate elastic constants. With some modification, the proposed method can be extended to identify the elastic constants at different locations of wind blades with different degrees of material degradation along the span of the blades.

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