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Engineering and Construction Torsional Responses of Glass-Fiber/Epoxy Composite Blade Shaft for A small Wind Turbine

Yu-Chung TSENG\textsuperscript{1a} Chih-Yu KUO\textsuperscript{2b}

\textsuperscript{1,2}Department of Aviation Mechanical Engineering, China University of Science and Technology, Taiwan R.O.C

Abstract

Recently, composites made of thermosetting epoxy matrix reinforced by glass fibers have been widely used for advanced engineering and aerospace applications. This study newly proposes a developed methodology to manufacture a glass-fiber/epoxy resin composite blade of a small 1 kW wind generator system. The improved mechanical properties of the composite blade are verified in a series of systematic experiments. The study focuses on the responses of applying a torsional loading to a long straight member such as the root of the composite blade. The core aluminum shaft was wrapped in glass-fiber/epoxy to form the root of the composite blade and a composite shaft. The composite shaft is a sandwich structure combining glass-fiber/epoxy and an aluminum shaft. The composite shaft was placed in a torsional testing machine and a strain gage monitored the strain on the composite shaft. We considered the composite blade to have a circular cross section and determined both stress distribution within the member and the angle of twist. Finally, mechanical properties were obtained in torsional testing, including the relationship between applied torque and the angle of twist on the composite shaft. The torsional loading and failure locations of the blade root were measured experimentally. The experiments showed that the weakest location of the blade root is at the interface of the aluminum shaft and glass-fiber/epoxy lay-ups in the composite blade root. It is found that the quality of the aluminum shaft, the glass-fiber/epoxy layers around the shaft and the bonding at the interface between the shaft and the layers should be increased to improve the torsional strength of the composite blade. These results can provide a reference for analysts and designers of small wind turbine systems.

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Keywords: Wind-turbine, torsional test, composite shaft, angle of twist, mechanical properties

\textsuperscript{a} Corresponding author: Email: cytseng@cc.hc.cust.edu.tw

\textsuperscript{b} Presenter: Email: h0930138455@yahoo.com.tw

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1. INTRODUCTION

In this paper we investigate the effects of applying torsional loading to a composite blade root, composed of an aluminum shaft with the glass-fiber/epoxy layers, in a small wind turbine. We initially obtain mechanical properties of the various composite laminates. We then show how to measure both the stress distribution within the member and the angle of twist until failure. The composite shaft was placed in a torsional testing machine and a strain gage monitored the torsional deformation of the composite shaft during the tests. We considered the member to have a circular cross section and determined both stress distribution within the member and the angle of twist. Finally, we obtained mechanical properties of the torsional test, such as the relationship between applied torque and angle of twist in the composite shaft. The results can provide a reference for analysts and designers of small wind turbine systems.

Applications and design of wind turbine blades have previously been developed based on theories of wind energy [1-4]. In addition, IEC standard 61400 has systematically investigated design of clamping apparatuses for testing composition, manufacturing by VARTM and mechanical properties testing for glass-fiber/epoxy composite laminates, failure mode analysis for composite blade, load distribution analysis for composite blade, and free vibration analysis for composite blade [5-10]. A rheological model of an epoxy resin system has been used in processing wind turbine blades [11]. The mechanical properties of a small-scale wind-turbine composite blade have been obtained by ASTM Standard D3039-93 [12]. Predictions of deflection and first-ply failure load of thin laminated composite plates have been investigated by the finite element approach [13]. The standards for a wind energy generator are included in IEC 61400. However, none of these provide detailed study of the mechanical behavior of glass/epoxy composite wind turbine blades designed in compliance with existing standards.

2. EXPERIMENTS

One-meter wide woven glass-fiber (GF), such as TGFW-600 GF, TGFW-618P GF and TGFW-640P GF, from Lin Men Company (Taiwan) were used to make GF/ ML3564-AB epoxy-resin composite laminates for wind turbine composite blades according to the required stacking sequence [12]. This epoxy had a mix viscosity of 600-900 cps at 25°C and 200-300 cps at 40°C. A modified diaphragm curing process was applied by Lin Men co. in this work. According to ASTM D3039-93 the specimens were cut by a cutting machine with a diamond blade and water cooling. Copper sheets adhered to the specimen with resin adhesive were used as end tabs. The geometry and dimensions of a specimen are shown in Figure 1.

An MTS-810 universal material testing machine was used to conduct the tensile test at a rate of 2 mm/min as shown in Figure 2, providing the static mechanical properties of ultimate strength $\sigma_{ult}$ and longitudinal stiffness $E_{11}$. In addition, an MTS-632.26F-30 extensometer was attached to samples to continuously monitor the specimen strain during static tests.

The composite blade is a sandwich structure, where core materials include the expandable polystyrene (EPS) foam of the blade body and the aluminum shaft of the blade root, as shown in Figure 3. The core materials were wrapped with 4 GF layers and epoxy resin, and the EPS foam of core material was considered to be continuous and smooth in the composite blade body. The composite blade was manufactured by vacuum assisted resin transfer moulding (VARTM) technique in a mold, as shown in Figure 4. A VARTM technique was used to produce a composite blade these components in a vacuum, and resin was injected into the mold. The shell of the composite blade was a symmetrical fiber lay-up structure that extends along the entire airfoil section from leading edge to trailing edge [9]. A photograph of the composite blade is shown in Figure 5. The composite blade was placed in a torsional testing machine GT-7074-B as shown in Figure 6 and a strain gage KIG-5-120-C1-11 monitored the torsional
deformation of the composite blade during testing. Mechanical properties of torsional test, such as the relationship between applying torsional loading and angle of twist on the composite blade, were obtained.

3. RESULTS AND DISCUSSION

It was found that the TGFW-600 GF/Epoxy has the highest strength and stiffness, followed by TGFW-406, with TGFW-450 the lowest [12]. That indicates the TGFW-600 GF is an optimal choice and our means of the improving mechanical properties of a composite laminate are effective in these composite materials. After a series of mechanical tests, we obtained the properties listed in Table 1, including ultimate strength and longitudinal stiffness of the TGFW-600 GF/Epoxy laminates, in warp, weft, 45 degrees and angle-ply lay-ups. Thus, we adopted the TGFW-600 GF/ML3564-AB epoxy resin for the following torsional tests for a wind turbine composite blade. After the torsional tests we obtained the properties such as the maximum applied torsional loading ($T_{\text{max}}$) and the angle of twist ($\Phi$), as listed in Table 2, and the failure root of the composite shaft, as shown in Figure 7. In the torsional testing the experimental maximum loads of the composite blade root were obtained as the $T_{\text{max}}$ about 15.67 kg-m. It is noted that because the discontinuity of core material in the blade root was at the interface between the aluminum and glass/epoxy lay-ups, all the failure locations for the torsional loading occur at this interface. The progressive failure of the blade root is a nonlinear problem that needs to be treated with a nonlinear finite element technique and an appropriate material degradation method. Furthermore, if the torsional loading is to be determined experimentally, the use of acoustic emission may be an appropriate way to achieve the goal [13]. The failure load of the blade root in the torsional tests can be significantly improved if the diameter of the root or the bonding strength at the interface between the GF/epoxy layers and the aluminum shaft is increased. It is also noted that the torsional strength of the blade root with the bonding strength at the interface and the reinforced lay-ups had the most significant influence on the structure of the composite blade root. It was found that the interface between the aluminum shaft and the reinforced lay-ups in the blade root had an important effect on the applied torsional loading in the blade root of the composite structure. These results can provide a reference for analysts and designers of small-scale wind turbine systems.

4. TABLES

Table 1. Mechanical properties of the TGFW-600 GF/epoxy ML3564-AB composite laminates

| Lay-ups    | $\sigma_{ul}$ (MPa) | $E_1$ (GPa) |
|------------|---------------------|-------------|
| Warp       | 576.44 ± 41.75      | 36.06       |
| Weft       | 71.74 ± 3.80        | 5.98        |
| Angle-ply  | 61.93 ± 3.82        | 6.66        |
| 45 degree  | 30.88 ± 0.88        | 3.081       |
| Epoxy      | 27.18 ± 6.04        | 3.25        |
| Aluminum shaft | 290                | 68.9        |
| EPS foam   | 0.01831             | 0.01        |

Table 2. Maximum applying torsional loading ($T_{\text{max}}$) and the angle of twist ($\Phi$) in the root of composite blade

| Torsional loading kg-m | Angle of twist ($\Phi$) |
|------------------------|-------------------------|
| Composite blade root   | 15.67                   | 9°                     |
5. FIGURES

Figure 1: Dimensions and photograph of a specimen.

|   | 50.8 | 136.4 | 50.8 |
|---|------|-------|------|
| W | 25.4 |

End tab

Specimen

Unit: mm

Figure 2: MTS-810 servohydraulic computer-controlled universal material testing machine.
Figure 3: (a) EPS foam of the core material in the composite blade body. (b) Aluminum shaft of the core material in the composite blade root.

Figure 4: Composite blade inserted into the mold.

Figure 5: Photograph of the composite blade.
6. CONCLUSIONS

Our work can be summarized as follows. The ultimate strength and longitudinal stiffness of TGFW-600 GF and ML3564-AB epoxy-resin is an optimal choice and our means of improving mechanical properties of a composite laminate is effective for the composite materials of this study. The torsional
loading and failure locations of the blade root were measured experimentally. The experiments have shown that the weakest location of the blade root is at the interface of the aluminum shaft and the GF/epoxy lay-ups in the blade root. After the interface failure begins, the blade root fails progressively. Torsional testing obtained the maximum torsional loads of the composite blade root. A nonlinear technique together with an appropriate material degradation method should be used to analyze the progressive failure and predict the maximum torsional loading of the root. The quality of the aluminum shaft, the GF/epoxy layers around the shaft and the bonding at the interface between the shaft and the layers should be increased to improve the torsional strength of the composite blade root.

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