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Effect of stress ratio on fatigue life of GFRP composites for WT blade †

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Abstract

Fatigue life of GFRP (glass-fiber reinforced plastic) composites used in wind turbine rotor blades has been evaluated considering the glass fiber orientations. Three different laminate composites with the respective laminating orientation of 0°, ±45°, and 0°±45° were prepared using vacuum infusion method. Tensile properties and S-N curves for these composites were experimentally determined at room temperature. From the tensile tests, it was found that tensile properties were greatly dependent upon the fiber orientation and the tensile strength of unidirectional composite was the largest and bidirectional (45°) composite was the weakest among three composites. The fatigue properties were determined under constant amplitude load control at different stress ratios, R, of 0.5, 0.1 and -0.2. The properties also show the dependency of stress ratios and fiber orientation. The fatigue life diagrams of these three composite were relatively well presented with the double logarithmic S-N curve. The linear slopes of the respective S-N curves for three composite were not greatly different. The fatigue limits for the composites were evaluated and predicted with linear Goodman and Gerber diagrams.

Keywords: GFRP (glass-fiber reinforced plastic) composite; Stress-strain curve; Stress ratio; S-N curve; Fatigue life

1. Introduction

As renewable energy sources have attracted worldwide attention, wind energy has been actively developed. In 2009, development of wind energy recorded an increase of 31% over the previous year [1]. Wind energy is expected to be further explosively developed along with installation of large and offshore wind turbines. Especially, for these systems, reliability must be main concern in maintaining the system.

GFRP (glass-fiber reinforced plastic) composite is a main material for wind turbine blades. The blade is subject to various random fatigue loads during in-service. So, the fatigue characteristics of the composite may be crucially important to provide reliability in design, manufacturing and operation of the wind blade. Actually, the blade is required to be designed for a lifetime of over 20 years [2]. The fatigue evaluation and prediction in GFRP composite subject to significantly variable in-service fatigue loads has been examined, including the composite strength, fatigue life evaluation methodology and failure mechanism [3-6]. These issues may be attributed from some uncertainties of the laminate composites containing fiber contents, orientation, type, and fiber-matrix adhesion, *etc.*

Therefore, in this study, fatigue characteristics of the GFRP composites were examined to provide information on reliability in design and manufacturing of the blade. Fatigue properties of three different composites considering their fiber orientations were experimentally analyzed with consideration of stress ratio's effect. Furthermore, fatigue life prediction was examined.

2. Experimental program

2.1 Materials and specimens

To characterize the strength performance of the wind turbine blade materials through tensile and fatigue tests, GFRP laminate composites were prepared considering their fiber orientations. The laminate type was E-glass/Epoxy and their fiber orientations were 0°(unidirectional glass complex, UD), ±45°(Bidiagonal glass fabric, BD), 0±45°(Triaxial glass fabric, TRI) respectively. Table 1 presents the details of the composites prepared in this study.

The laminate composites were machined to tensile and fatigue specimens according to the standard specimen dimension specified to ASTM D5083 and ISO 527-4 [7, 8]. The width and length of the specimen were 25 mm and 200 mm, respectively.

2.2 Testing method

Uniaxial hydraulic material testing system (MTS810, Max.

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Table 1. Tensile properties of GFRP composites used in the study.

Type of laminate	Tensile strength, σ_{TS} (MPa)	Yield strength σ_{YS} (MPa)	Modulus E (GPa)
UD	736.08	-	38.63
BD	119.60	58.55	14.03
Tri	651.96	-	26.43

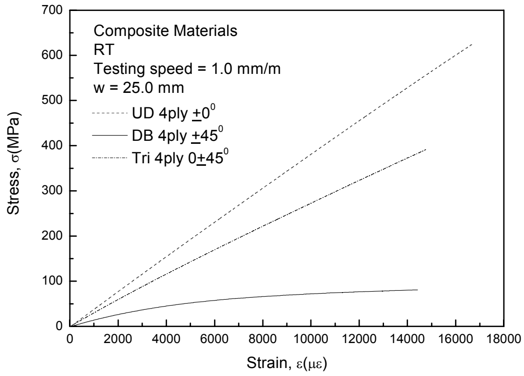


Fig. 1. Tensile stress-strain curves for three laminate composites used in this study.

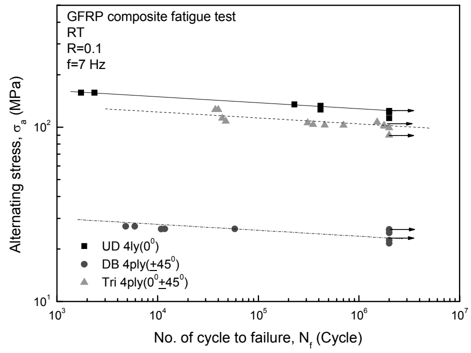
load capacity: 250 kN) was used for tensile and fatigue tests. For tensile tests, tensile stress and strain were measured, where the strain was measured from three strain gages with resistance of 120 Ω mounted on the front and back face of the specimen [7]. The strain values were acquired through DAQ system (SYSTEM 7000, Vishay) connected to the each gage, and these values were synchronized with load values from the testing machine. Tensile tests were carried out in a loading rate of 1.0 mm/min.

Fatigue tests were performed under constant amplitude stress control at room temperature with a frequency of 7 Hz at three different stress ratios of 0.1, 0.5 and -0.2.

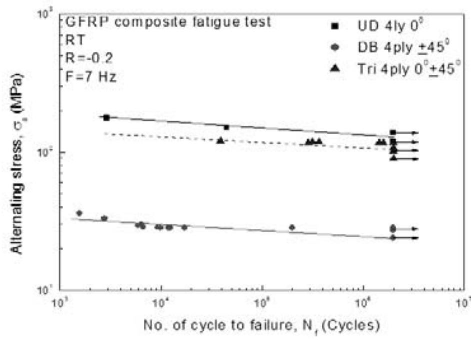
3. Results and discussion

3.1 Variation of tensile properties with the laminate type

Fig. 1 shows the typical tensile stress-strain curves for three laminate composites used in this study. The tensile tests were carried out according to standard methods, ASTM D5083 and ISO 527-4 [7, 8]. The strain values displayed in Fig. 1 represent the average strain calculated from three strain gages mounted on front and back face of the specimen at three different positions. The unidirectional laminate UD behaves mostly elastically up to failure and has the highest modulus and strength among these composites, while bidiagonal (BD) laminate shows considerable ductility and has the lowest modulus and strength among these three composites. The tensile strength of the UD laminate was measured as 736 MPa, which was the highest among these three laminates. Table 1 presents the tensile strength and elastic modulus for three laminate composites.



(a)



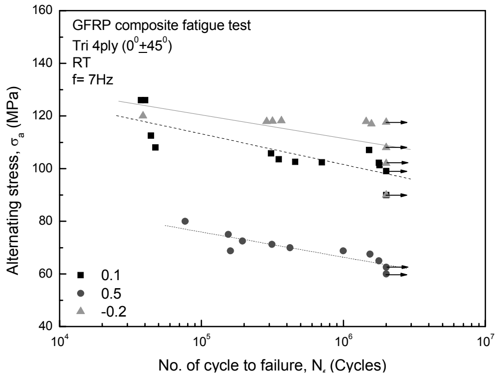
(b)

Fig. 2. S-N curves for three composites with different laminates for stress ratio of (a) 0.1 and (b) -0.2.

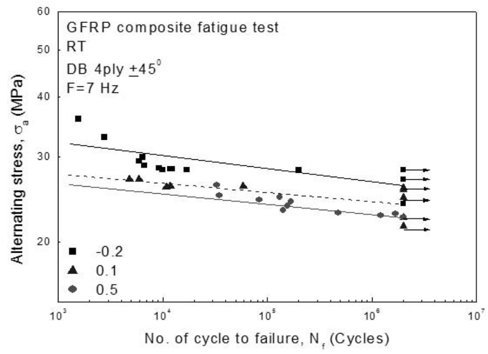
3.2 Fatigue characteristics

In general, the fatigue behavior of a composite material depends upon the response of the fiber, matrix and their interface consisting of the composite [9]. Especially, the fiber orientation of the composite has a relatively significant effect on its strength. In this study, as shown in Fig. 1, the static tensile strengths of the composites with different fiber laminates were dependent on the lay-up orientation of the fiber. It is known that the stiffness of the composite decreases with increasing the angle of fiber from 0^o to 90^o. This dependency of the fiber orientation can have an influence on the fatigue behavior of the composites. Fig. 2 shows the fatigue life curves (S-N) for three different composites used in this study. These curves were obtained at the stress ratios, R, of 0.1 and -0.2. The fatigue life, S-N diagram, of the composites is presented as a log-log formulation, as shown in Fig. 2. So, it can be found that the fatigue life data for the composites used in this study was relatively well fitted to the double logarithm presentation, $S = C(N_f)^n$.

As shown in Fig. 2(a), slopes, n, of the curves for stress ratio of 0.1 are not significantly different with change of the fiber orientations. However, the fatigue stress levels are quite different with the type of laminates. Therefore, as shown in Fig. 2, the fatigue limits, which are defined at 2 x 10^6 cycle, of the composites are remarkably dependent on the laminate orientation. The fatigue limit of UD composite, of which fiber



(a)



(b)

Fig. 3. Effect of stress ratio for (a) TRI composite; (b) BD composite.

orientation is 0°, was the largest while that of BD composite with fiber orientation of ±45° is the lowest. For the stress ratio of -0.2, the similar dependency of fiber orientation on fatigue behavior also was observed, as shown in Fig. 2(b).

3.3 Effect of stress ratio

Three composites used in this study have respective different fiber orientation and strength or stiffness as shown in Fig. 1. Those are factors contributing to the fatigue life, as shown in Fig. 2. The stress ratio or mean stress also is a crucial influencing factor on the fatigue behavior of the composite. In this study, constant amplitude loading with different three stress ratios, R, of 0.5, 0.1 and -0.2 was imposed on the respective composite specimens. Fig. 3 presents typical fatigue life curves (S-N) for BD and TRI laminates. As found from Fig. 3, the slopes of the S-N curves for the respective stress ratios are nearly identical: n = -0.014 ~ -0.045 for BD composite and n = -0.006 ~ -0.047.

However, the fatigue life becomes long as the stress ratio decreases. Moreover, the fatigue limit, which was defined at the fatigue life, 2 x 10^6 cycles, was dependent on stress ratio and fiber orientation, as shown in Fig. 4. The fatigue limits for all three composites increased linearly with increasing stress ratio. The fatigue limits for UD composite were much higher than those for BD and TRI composite. Among these three composites, BD composite had the lowest fatigue limits.

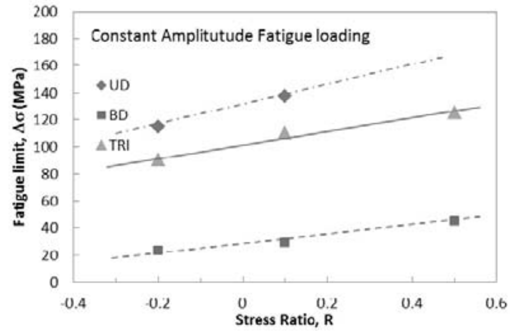


Fig. 4. Variation of fatigue limit with increasing stress ratio for GFRP composites with different fiber orientation.

3.4 Prediction of fatigue limit

Fatigue life of the wind turbine blade can be predicted from the constant life diagram like S-N curves shown in Figs. 1 and 2. In general, the fatigue life is evaluated with linear Goodman diagram. However, the recent design requirement recommended a shift Goodman diagram instead of the linear Goodman diagram [10, 11]. In this study, the linear Goodman diagram and Gerber diagram were examined to predict the fatigue life for the composites used. The linear Goodman and Gerber diagram can be formulated as the following, respectively:

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{T_s} = 1, \quad (1)$$

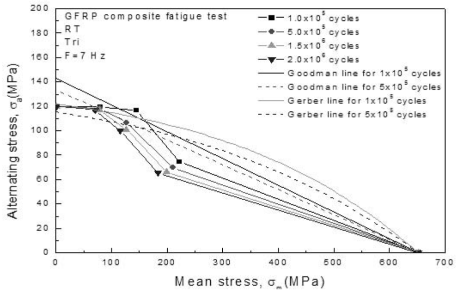
$$\frac{\sigma_a}{S_e} + \left(\frac{\sigma_m}{T_s}\right)^2 = 1. \quad (2)$$

Here, σ_a, σ_m, S_e and T_s represent stress amplitude, mean stress, fatigue limit and tensile strength, respectively.

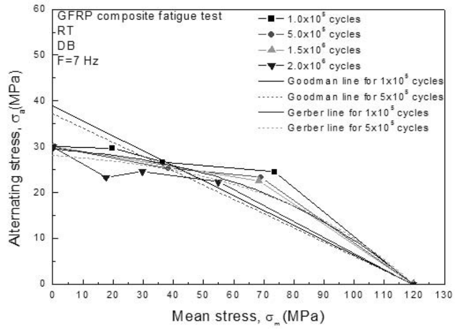
In Fig. 5, the linear Goodman and Gerber diagrams are compared with the experimental fatigue data for BD and TRI composites. As can be seen, prediction of the fatigue life according to the linear Goodman diagram seems to overestimate the life for TRI composite near the region with mean stress of zero. Comparably, for the Gerber diagram, the fatigue life was relatively well predicted. For the BD composite showing considerable ductility and relatively low modulus and strength, the prediction using both linear Goodman and Gerber diagram underestimated the fatigue life over the region with mean stress of 40 MPa and the Gerber diagram shows a relatively good prediction near the region with zero mean stress. Therefore, it can be found that the Goodman's formulation predicts the fatigue life relatively more than the Gerber's formulation.

3.5 Observation of fracture surface

Fig. 6 presents the fracture surface of the specimen failed by fatigue loading for UD, BD and TRI composites. In general, failure in GFRP composite can be explained with tensile fiber failure (operative at low angles between the interface and applied force), shear along the interface, tensile interface de-

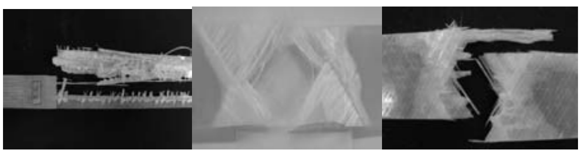


(a)



(b)

Fig. 5. Prediction of fatigue limit using Goodman diagram and Gerber diagram for (a) BD; (b) TRI composites.



(a) (b) (c)

Fig. 6. Fracture surface for (a) UD; (b) BD; (c) TRI composites.

bonding and matrix cracking [12]. For UD composite shown in Fig. 6(a), the failure happened at the fiber and the matrix surrounding to the fiber failed with loss of resistance of the fiber caused by the fibers' failure. Comparably, for BD and TRI composite, it was found from Fig. 6(b) and (c) that the failure happened with shear along the interface.

4. Summary and conclusions

Tensile and fatigue characteristics for GFRP composites used in wind turbine blade were evaluated and the effect of stress ratio on the fatigue life was examined considering the mean stress.

(1) From tensile tests, the modulus and tensile strength for UD laminate are higher than BD and TRI composites.

(2) The fatigue life (S-N) curves for the composites used in this study show linear characteristics at the respective stress ratios, and the slopes of the curves are nearly identical irrespective of material type.

(3) Prediction of fatigue life using Goodman's and Gerber's diagram was examined, and Goodman's diagram is more useful.

Acknowledgment

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References

[1] Global Wind Report 2009, GWEC.

[2] J. F. Mandell, R. M. Reed and D. D. Samborsky, *Fatigue of fiberglass wind turbine blade materials*, Sandia National Laboratory contractor report: SAND92-7005, Montana State University, August (1992).

[3] J. W. Kim, J. J. Lee and D. G. Lee, The comparison of the tensile strength of fiber-reinforced composites according to the change of fiber orientation and fiber orientation angle in one direction, *Journal of the Korean Society for Composite Materials* (2004) 284-287.

[4] R. P. L. Nijssen, *Fatigue life prediction and strength degradation of wind turbine rotor blade composites*, SAND2006-7810P,Unlimited Release, October (2007).

[5] H. Zhou, L. Mishnaevsky Jr., P. Brøndsted, J. B. Tan and L. L. Gui, *SEM in-situ laboratory investigations on damage growth in GFRP composite under three-point bending tests*, Project UpWind, Contract No.:019945 (SES6).

[6] H. Mivehchi and A. Varvani-Farahani, The effect of temperature on fatigue damage of FRP composites, *J Mater Sci* (45) (2010) 3757-3767.

[7] ISO 527-4, Plastic determination of tensile properties_part4: Test conditions for isotropic and orthotropic fiber-reinforced plastic composites.

[8] ASTM D 5083, Standard test method for tensile properties of reinforced thermosetting plastics using straight-sides specimens.

[9] A. Varvani-Farahani and A. Shirazi, A fatigue damage model for (0/90) FRP composites based on stiffness degradation of 0° and 90° composite plies, *J Reinf Plast Composite*, 26 (13) (2007) 1319-36.

[10] G. Lloyd, Rules and regulations, IV-Non-Marine Technology, Part I: Wind Energy, Hamburg, Germany (1993) 2-2.

[11] G. Lloyd, Rules and regulations, IV-Non-Marine Technology, Part I: WindEnergy, Hamburg, Germany (2003) 5-19.

[12] J. S. Stölken and A. G. Evans, A microbend test method for measuring the plasticity length scale, *Acta Materialia*, 46 (14) (1998) 5109-5115.

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