Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

Fatigue life investigation of composite rotor blades on the wind turbine in complex terrain

Jiyune Ryu [a] , Johyug Bang [b] , Sunho Park [b] & Kyungseop Han [a]
[a] Department of Mechanical Engineering, Pohang University of Science and Technology, San 31, Hyoja-dong, Nam-gu, Pohang, Gyungbuk, 790-784, Korea
[b] Unison R&D Center, 1335, Gwanpyeong-dong, Yuseong-gu, Daejeon, 305-509, Korea
Version of record first published: 12 Nov 2012.

To cite this article: Jiyune Ryu , Johyug Bang , Sunho Park & Kyungseop Han (2012): Fatigue life investigation of composite rotor blades on the wind turbine in complex terrain, Advanced Composite Materials, 21:5-6, 433-443

To link to this article: http://dx.doi.org/10.1080/09243046.2012.743302

Advanced Composite Materials
Vol. 21, Nos. 5–6, October–December 2012, 433–443

Fatigue life investigation of composite rotor blades on the wind turbine in complex terrain

Jiyune Ryu[a], Johyug Bang[b], Sunho Park[b] and Kyungseop Han[a]*

[a]*Department of Mechanical Engineering, Pohang University of Science and Technology, San 31, Hyoja-dong, Nam-gu, Pohang, Gyungbuk 790-784, Korea;* [b]*Unison R&D Center, 1335, Gwanpyeong-dong, Yuseong-gu, Daejeon 305-509, Korea*

(*Received 18 April 2012; accepted 22 October 2012*)

In order to survey the structural characteristics of composite rotor blades on the wind turbine operated in mountainous complex terrain, on site wind data were measured and analyzed for one year. Measured gust and turbulence were compared with two existing gust models, International Electrotechnical Commission (IEC) gust model and mean gust shape model. Furthermore, mechanical load measurement and comparison were carried out corresponding to the root of rotor blades. Mainly, the fatigue safeties for the rotor blade were revaluated with the aid of finite element simulation due to highly increased gust and turbulence intensity.

Keywords: composite rotor blades; wind turbine; complex terrain; gust model; fatigue safety

1. Introduction

The total installed capacity of wind turbines in Korea exceeded 300 MW in 2010, and is being rapidly expanded to reach the goal of 7.1 GW by 2020. Almost wind turbines among them have been operated in mountainous region in Korea. In the near future, wind turbines will be still installed in such mountainous regions except offshore regions.

Till date, it was rarely investigated about real wind characteristics in complex terrain, such as gust and turbulence generated from mountainous topology in Korea as well as Japan. Also, while wind characteristics in complex terrain may have an effect on the structural characteristics of the wind turbine, it has not been evaluated in the structural safety so far.

This study analyzed on site wind data consisting of more than 4350 data-sets collected at Taebaek, severe complex terrain region in Korea. Measured data were compared with both International Electrotechnical Commission (IEC) gust model (extreme operating gust [EOG]) and mean gust shape model in order to understand wind characteristics in complex terrain.

Especially, in order to evaluate loads for the composite rotor blades operated in complex terrain, mechanical load measurement and comparison were carried out at the root of rotor blades. As well as the effects of high gust and turbulence on fatigue load, the fatigue safeties, and lifetime for the rotor blade were studied and revaluated with the aid of finite element (FE) simulation [1–5].

*Corresponding author. Email: kshan@postech.ac.kr

ISSN 0924-3046 print/ISSN 1568-5519 online

http://dx.doi.org/10.1080/09243046.2012.743302
http://www.tandfonline.com

2. Experimental

2.1. Site conditions

According to IEC standard (IEC 61400-1 Ed.3) [6] which specifies essential design requirements to ensure the engineering integrity of wind turbines, the complex terrain is defined as surrounding terrain that features significant variations in topography and terrain obstacles that may cause flow distortion. As shown in Figure 1, a site that the slope of a fitted plane (Φ) exceeds 10° is characterized as complex. This fitted plane fits the topographic variations within a specific distance from the wind turbine and passes through the wind turbine tower base. The height map in Figure 2 shows that the Taebaek site, where the 2 MW wind turbine (U88 type, see Figure 3) was installed, has the height variations more than 10° (the max. fitted plane slope is 11.3°) and definitely the complex terrain.

2.2. Measurement system

Wind characteristics and the related behaviors of rotor blades were investigated for 1 year with a met master and a real 2 MW wind turbine. The total configuration of measurement system is shown in Figure 3. For the purpose of measuring more precise wind data at the hub height of the wind turbine, excluding the effects of rotating blades, anemometers, wind vane,

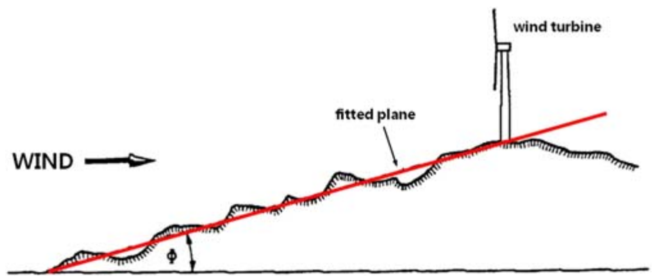


Figure 1. Terrain complexity parameters.

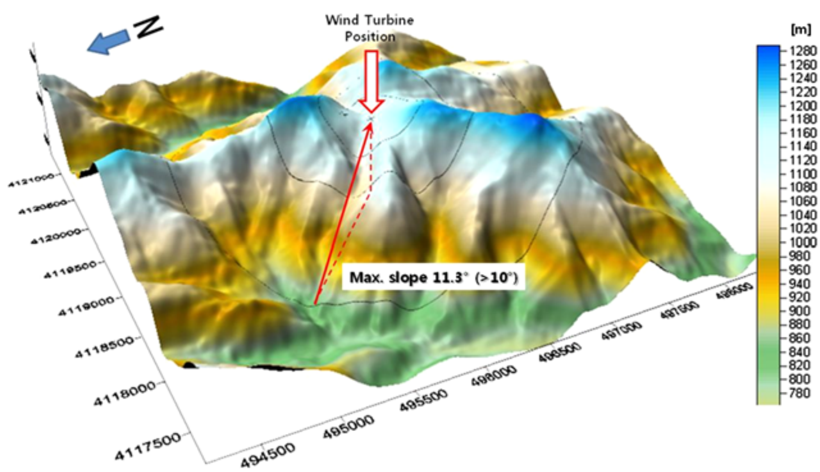


Figure 2. Height map of the Taebaek site.

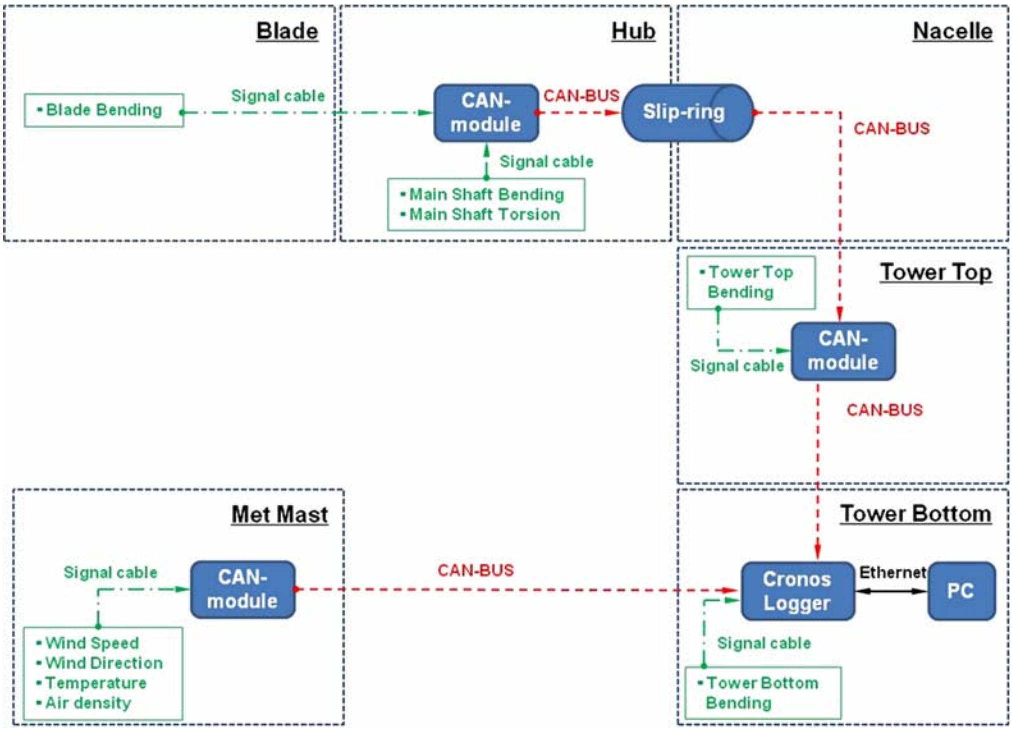


Figure 3. Total configuration of measurement system.

temperature, and atmospheric pressure, sensors were equipped on the met mast at the same height of hub. The sampling rate of wind speed is 1 Hz and others are 50 Hz. All sensor positions and technical parameters were specified in IEC 61400-12-1 [7]. Then, by calibrating wind speeds at the met mast with correction factors, the actual wind speeds at the wind turbine were obtained. Also, flapwise and edgewise bending moments at the blade root were measured using strain gauges. All data were gathered through CAN (controller area network) bus interfaces and monitored remotely.

3. Results and discussion

3.1. Measured wind characteristics

Wind characteristics are defined by two parameters, gust and turbulence intensity. The turbulence intensity (Ti) is a measure of the overall level of turbulence at hub height. It is defined as Equation (1). As the largest wind loads of the wind turbine generally occur at rated wind speed, the measured gust and turbulence intensity at rated wind speed, 12 m/s were mainly analyzed. In Figure 4, the comparison between measured gusts and calculated gust models at rated wind speed is shown. The proper gust model should be chosen to simulate the wind turbine loads and normally the IEC gust model, EOG is recommended [6]. However, the measured gusts are much larger than the IEC gust model and have differences in shape and duration, so that a new gust model, mean gust shape model suggested by W. Bierbooms [8] was adopted and modified. After several iterations by increasing amplitude, it was found that 2.52 times mean gust shape model fits the measured gusts at Taebaek more realistically. Also,

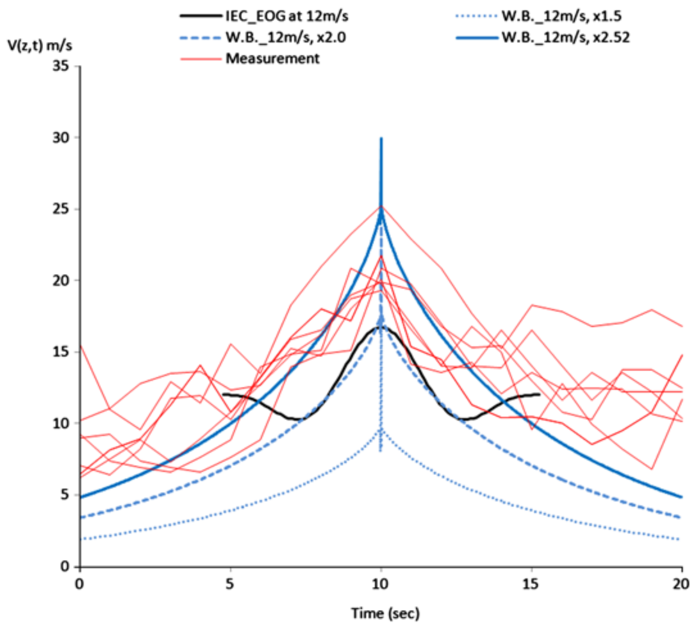


Figure 4. Comparison between measured and calculated gusts.

Figure 5 shows a large difference between measured turbulence intensity and IEC Class A turbulence intensity [6].

$$\mathrm{Ti} = \frac{\sigma}{\bar{V}} \tag{1}$$

$$\bar{V} = \frac{1}{N}\sum_{i=1}^{N} V_i \tag{2}$$

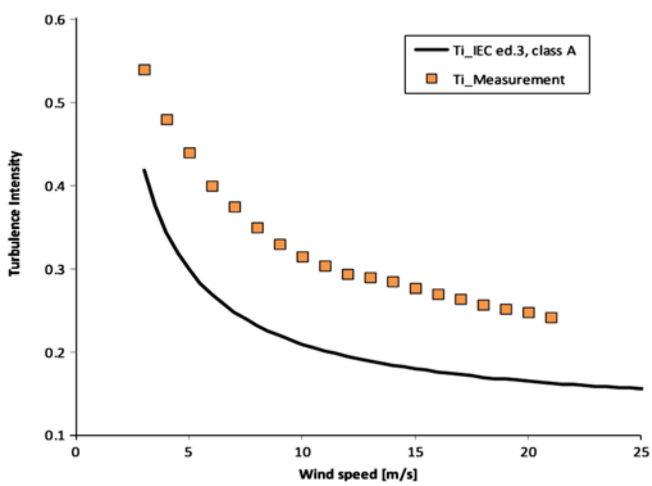


Figure 5. Comparison between measured and calculated turbulent intensity.

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_i - \bar{V})^2} \tag{3}$$

where:

Ti = turbulence intensity
$\bar{V}$ = averaged wind speed
V_i = measured wind speed
N = number of wind speed data
σ = standard deviation of measured wind speed

3.2. Extreme and fatigue loads for rotor blades

In general, higher gust and turbulence intensity cause higher extreme and fatigue loads for each wind turbine component, especially for the rotor blade. In this study, loads for the rotor

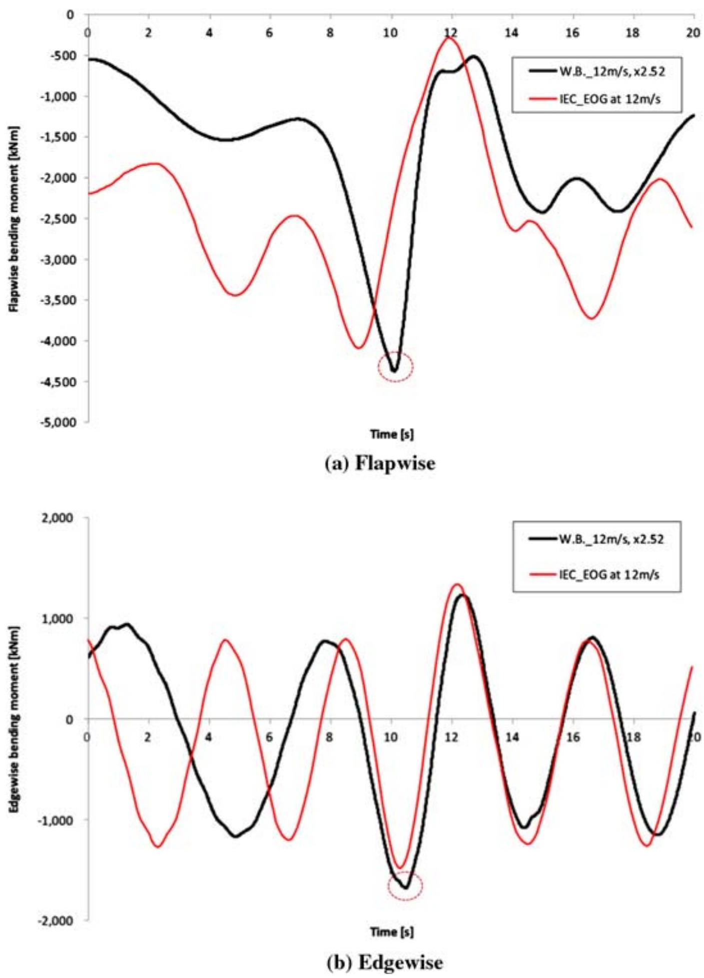


Figure 6. Root bending moments calculated with gust models.

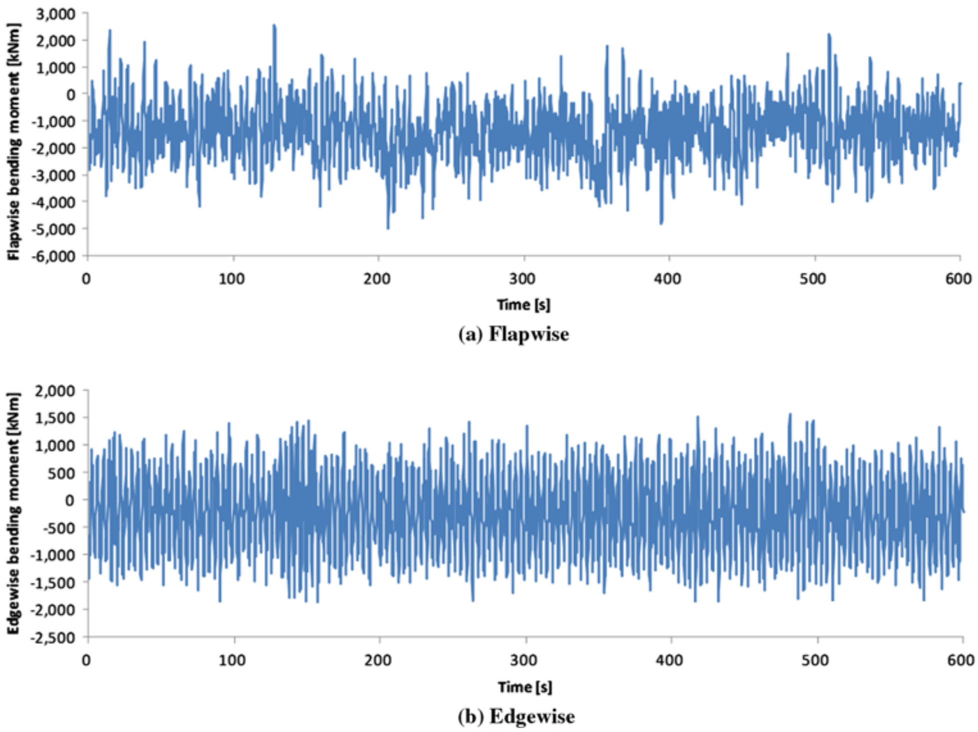


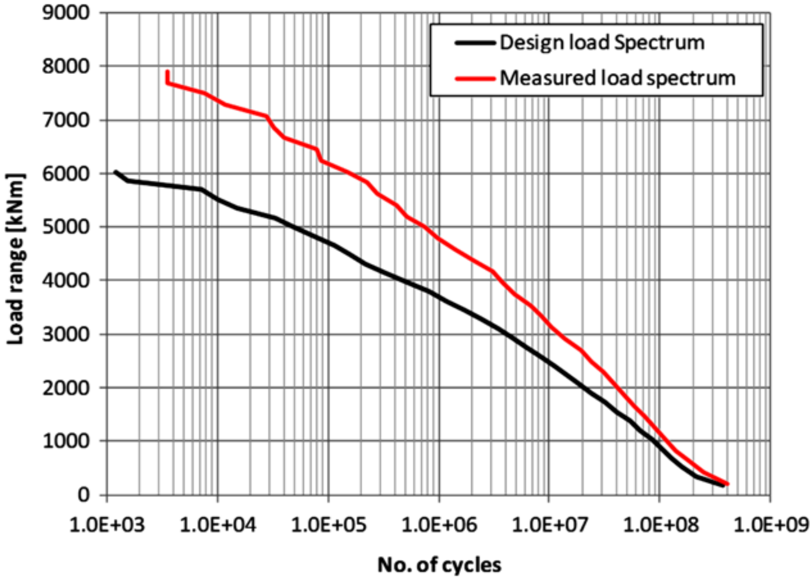
Figure 7. Time series of root bending moments (at 12 m/s).

blade were calculated using FLEX5, integrated software for wind turbine performance and loading calculation. Figure 6 illustrates the calculated flapwise and edgewise bending moments at the blade root. Root bending moments corresponding to the increased mean gust shape are around 10% larger than to the IEC EOG model.

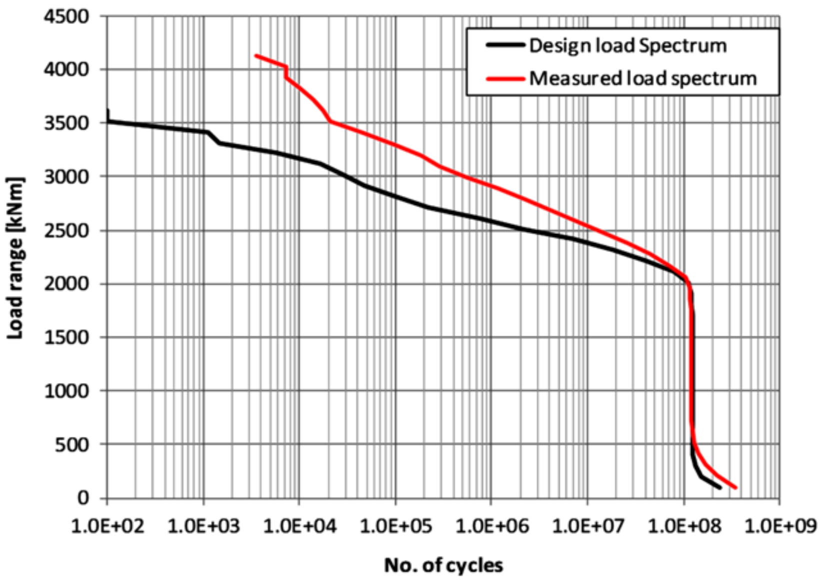
Although there are no significant differences in extreme loads represented by root bending moments, the fatigue loads for the rotor blade should be checked due to the frequent occurrence of gusts in complex terrain. Figures 7 and 8 show the 10 min time series of measured flapwise and edgewise root bending moments at rated wind speed and those fatigue load spectrum compared to design load spectrum, respectively. For more details, the damage equivalent loads are listed in Table 1. The damage equivalent loads increase by 32% for flapwise bending and by 6% for edgewise bending. This fact requires essentially the evaluation of the fatigue safety for rotor blade structures.

3.3. Fatigue analysis for the rotor blade

From the beginning stage, the composite rotor blade for 2 MW wind turbine studied here (max. chord 3.48 m, total blade length 42.5 m) was developed with higher design safety factors than those recommended by IEC standard [6] considering complex terrain. It has 20-year design lifetime and shell-spar-web structure manufactured by resin infusion method. For structural analysis, the rotor blade was simulated using commercial FEM codes, I-DEAS in modeling, and ABAQUS in analysis. Figure 9 illustrates the brief procedure of FE modeling [9,10]. The three-dimensional FE model has more than 200 shell element groups in the rotor blade direction and six element groups in the edgewise direction to apply the thickness distribution. Material properties of composite laminates used for the FE analysis are represented in Table 2.



(a) Flapwise



(b) Edgewise

Figure 8. Fatigue load spectrum.

The following Figure 10 shows the 57 element positions on a blade section. Fatigue analysis was carried out with measured 600 s load time series for the relevant blade sections, and subdivided into three steps. First, the strain time series at each element were calculated with 600 s load time series and unit strains from FE model for a blade section. As shown in Figure 11, unit strains are calculated by applying unit loads (Fx = 1 N, My = 1 Nm and Mz = 1 Nm) at a master node of FE model. Second, the rain-flow counting of the strain time

Table 1. Comparison of damage equivalent loads.

Slope of S-N curve Reference number of cycles	$m = 10$ $N_{ref} = 1.0E8$	
Load direction	Flapwise	Edgewise
Measured value	3671 kNm	2348 kNm
Design value	2770 kNm	2214 kNm
Measured/design	132.5%	106.1%

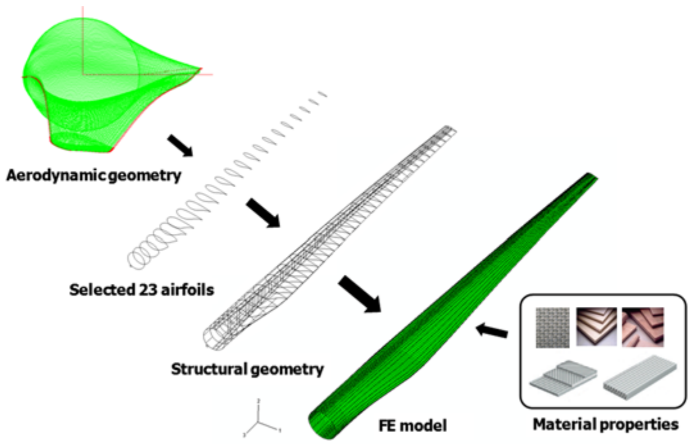


Figure 9. Blade modeling procedure.

Table 2. Minimum material properties for composite laminates.

	Unidirectional	Bi-axial	Tri-axial
Specific weight (kg/m^3)	1809	1888	1815
Layer thickness (mm)	0.97	0.61	0.92
E_1 (MPa)	32,297	11,700	29,621
E_2 (MPa)	7300	11,500	10,300
G_{12} (MPa)	3845	11,300	6856
Poisson's ratio	0.25	0.56	0.46

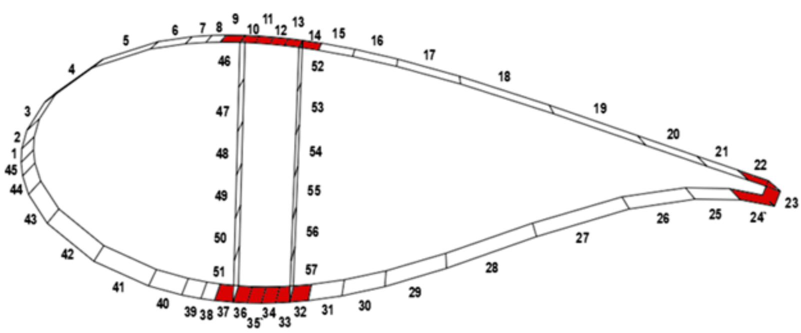


Figure 10. Element allocation.

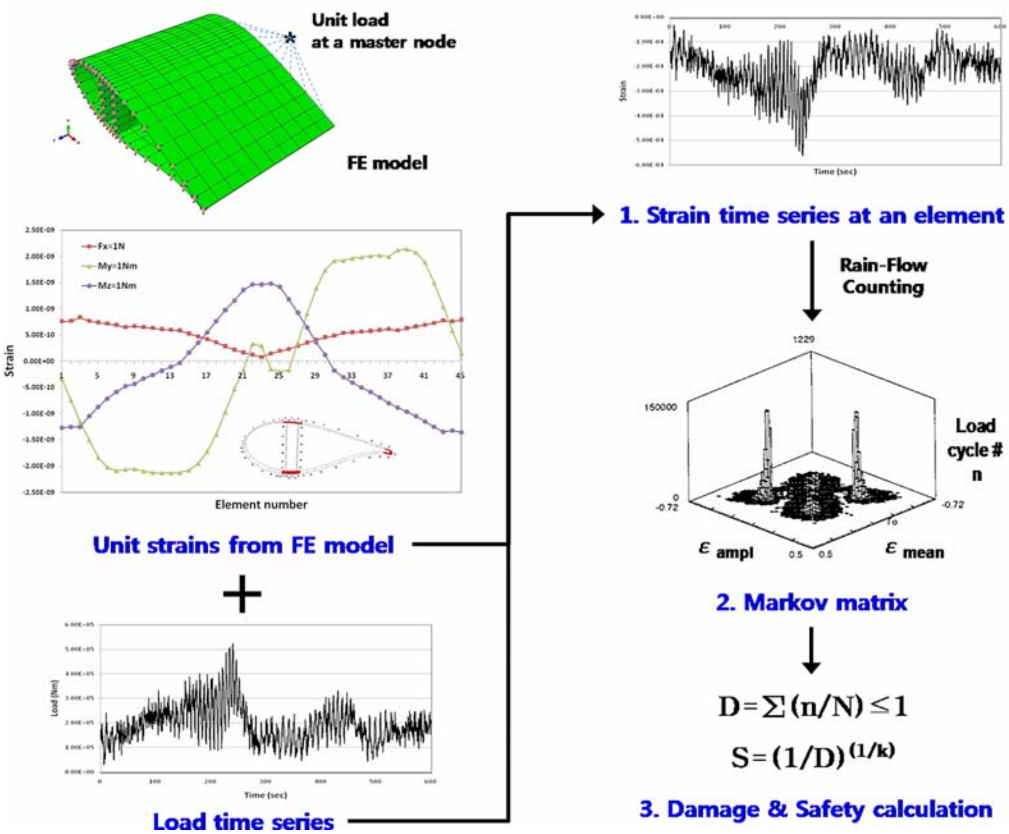


Figure 11. Fatigue analysis process.

series at each element generated the amplitude mean value matrices (Markov matrices). According to the below Equation (4) from GL guideline [11], the number of permissible load cycles (*N*) is determined based on the characteristic S/N curve established for the laminate and the Goodman diagram constructed using this curve in Figure 12. Third, fatigue damage (*D*) and safety (*S*) were calculated based on these Markov matrices. These calculation steps are performed for each node of each blade section of the structural model so that a damage value can be allocated to each element of the blade structure.

$$N = \left[\frac{R_{k,t} + |R_{k,t}| - |2 \times \gamma_{Ma} \times S_{k,M} - R_{k,t} + |R_{k,c}||}{2 \times (\gamma_{Mb}/C_{1b}) \times S_{k,A}}\right]^m \tag{4}$$

where:

$R_{k,t}$ = ultimate tensile strain
$R_{k,c}$ = ultimate compressive strain
$R_{k,A}$ = amplitude of ultimate strain for load cycle number N=1
m = slope of S/N curve, 10
$S_{k,M}$ = strain mean value
$S_{k,A}$ = strain amplitude
γ_{Ma} = static material safety factor
γ_{Mb} = fatigue material safety factor

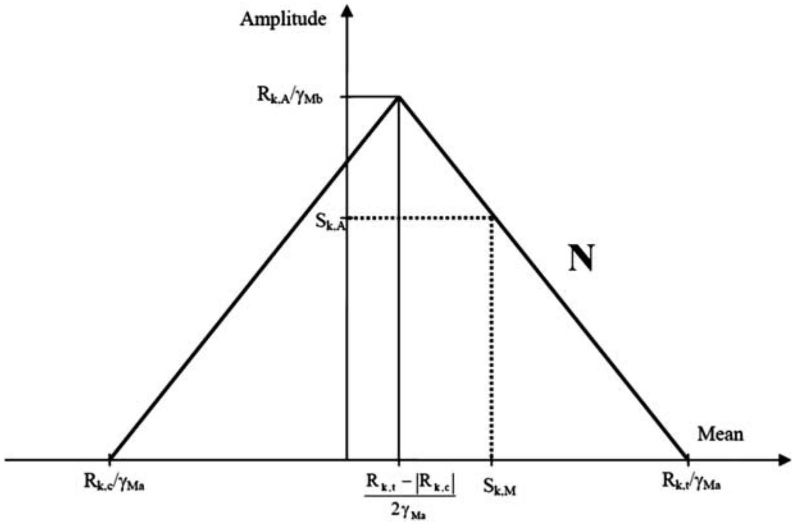


Figure 12. Goodman diagram.

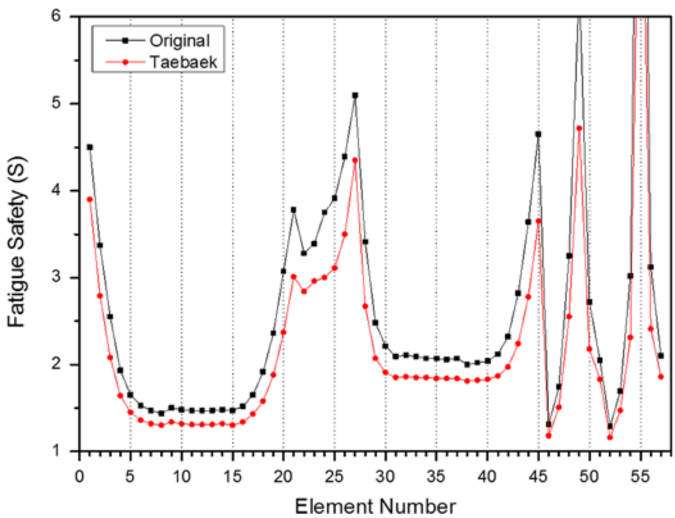


Figure 13. Fatigue safeties at blade sectional elements.

The blade section whose original design fatigue safety is minimum was investigated in this analysis. The following Figure 13 shows the fatigue safeties against real wind loads measured at Taebaek. Fatigue safeties at all blade sectional elements decreased by 10–27% compared to the original design values. The minimum fatigue safety ($S = 1.16$, #52 element, see Figure 10) ensures 20-year design lifetime for the rotor blade in complex terrain.

4. Conclusions

Wind characteristics in complex terrain were investigated and considered for the structural review of 2 MW wind turbine blades. The main findings can be summarized as follows:

- The measured gusts in complex terrain were not covered by the IEC gust model. A new gust model, mean gust shape model suggested by W. Bierbooms was modified by increasing amplitude. Mean gust shape model fits 2.52 times the measured gusts more realistically.
- The calculated root bending moments corresponding to the modified mean gust shape are around 10% larger than to the IEC EOG model. Also, the fatigue damage equivalent loads increase by around 30% for flapwise root bending moment. These facts require essentially the evaluation of the fatigue safety for rotor blade structures.
- The fatigue safeties against wind loads in complex terrain decreased by 10–27% compared to the original design values. The minimum fatigue safety more than 1.16 ensures 20-year design lifetime for the rotor blade in complex terrain. However, the normal rotor blade designed without any consideration for complex terrain would not be available for 20 years.

Acknowledgments

This research was financially supported by the Ministry of Knowledge Economy (MKE), Republic of Korea through the UNISON 2 MW wind turbine demonstration project.

References

[1] McKittric LR, Cairns DS, Mandell J, Combs DC, Rabern DA, Van Luchene D. Analysis of a composite blade design for the AOC 15/50 wind turbine using finite element model, SAND 2001-1441. Sandia National Laboratories Contractor Report; 2001.

[2] Locke J, Valencia U. Design studies for twist-coupled wind turbine blades, SAND 2004-0522. Sandia National Laboratories Contractor Report; 2004.

[3] Overgaard LCT, Lund E. Structural design sensitivity analysis and optimization of Vestas V52 wind turbine blade. 6th World Congress on, Structural and Multidisciplinary Optimization; 2005.

[4] Shokrieh MM, Rafiee R. Simulation of fatigue failure in a full composite wind turbine blade. Compos. Struct. 2006;74:332–342.

[5] Nijseen RPL. Fatigue life prediction and strength degradation of wind turbine rotor blade composite, SAND 2006-7810P. Sandia National Laboratories Contractor Report; 2007.

[6] Wind turbines – Part 1: design requirements. International Standard IEC 61400-1. 3rd ed.; 2005–08.

[7] Wind turbines – Part 12-1: power performance measurements of electricity producing wind turbines, International Standard IEC 61400-12-1. 1st ed.; 2005–12.

[8] Larsen GC, Bierbooms W, Hansen KS. Mean gust shapes. Roskilde, Denmark: Risø National Laboratory; 2003.

[9] Park SH, Han KS. Design of wind turbine blades using finite element model [PhD thesis, Korean]. POSTECH; 2010.

[10] Park SH, Park TS, Han KS. Real-time monitoring of composite wind turbine blades using fiber Bragg grating sensors. Adv. Compos. Mater. 2011;20:39–51.

[11] Guideline for the certification of wind turbines. In: Rules and guidelines, IV – industrial services. Hamburg: Germanischer Lloyd; 2003 (with Supplement 2004).