Fatigue Failure Accident of wind turbine tower in Taikoyama Wind Power Plant

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1. Introduction

In 2013 the nacelle of No.3 wind turbine in Taikoyama wind power plant collapsed due to fatigue failure^[1].



(a) Collapsed nacelle (b) Fracture section

(c) Vertical cross section

Fig.1 Accident scene and schematic diagram

By observing the fracture faces of the turbine tower tube, evidence of fatigue crack propagation was found at the inner side of the tube. Furthermore, broken bolts were found during the filed investigation. By comparing the two aspects, this failure is considered to be preceded by a certain degree of fatigue damage caused by the decrease of bolts pre-tension force.

This wind turbine collapsed only 12 years after it was built, comparing to the life time of 20 years. Furthermore, the periodical inspection was carried out only three months before the accident. Additionally, there are more than 120 wind turbines in service of the same type. Therefore, it is necessary and urgent to understand the cause of this accident, so that similar failure can be prevented in the future.

2. Approach

(1) Aerodynamic model is developed to simulate the dynamic performance by GL Garrad Hassan Bladed^{[2].} The tower part references the construction drawings, the blades information is based on *Guidelines for Design of Wind Turbine Support Structures and Foundations, JSCE*^[3], and the control parameters are also based on reference [3] but modified to validate the dynamic simulation results with measured results.

The comparison of the measured results and simulation results is carried out to verify the model.

(2) Stress distribution at fracture section is calculated by aerodynamic model in order to understand the cause of the fatigue fracture;

(3) A 3 Dimensional FE model is developed to calculate the local stress at the fracture section before and after the bolts damaged;

(4) Eventually, by incorporating the time series stress distribution from aerodynamic model and the relationship between local stress and nominal stress from FE model, the fatigue life of the fracture section can be evaluated by using rain-flow counting method, Goodman formula and Miner's principle.

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3. Main body of abstract

3.1 Wind load characteristic

The tower base moment (height 12.6m) was measured by using strain gauges shown in Fig.2 to validate the aerodynamic model from Feb. 2nd 2015 to Feb. 28th 2015.

The measured results are based on the 10 minutes SCADA data during the same time.

Fig.2 shows the bin averaged turbulence intensity derives from the measured result. In dynamic simulation, measured turbulence intensity was used for wind speed lower than 15m/s. For higher wind speed the turbulence intensity is extrapolated assuming the normal turbulence intensity in IEC 61400-1 ^[4]. The red line shows the turbulence intensity used in dynamic simulation.



Fig.2 Schematic diagram of strain gauges installment

Fig.3 Turbulence intensity vs. wind speed

Fig.4 shows the comparison of bin averaged power output, rotor speed and tower base moment by measurement and dynamic simulation. The figures show good agreement with the measurement results.



Fig.4 Comparison of the measurement and simulation result

3.2 Characteristics of the tower top section

Fig. 5 (a) and Fig.5 (b) show the calculated values of axial force N and bending moment M at the fracture section of different wind speed from the dynamic simulation.





The axial force and bending moment obtained from the aerodynamic simulation are used to calculate the nominal

stress through $\sigma = \frac{N}{A} - \frac{M}{Z}$, in which A represents the sectional area and Z represents the sectional resistance moment.

The nominal stress for different wind speed is shown in Fig.5 (c). The stress range increases significantly with the increase of the wind speed. The minimum stress turns into negative value when the wind speed is higher than 11 m/s.

3.3 Investigation of the load stress considering the stress concentration

A 3 Dimensional FE model is developed to calculate the local stress at the fracture section before and after the bolts damaged. Fig.6 illustrates the difference before and after the bolts' damage.



Fig.6 Diagram of the damage area

To simulate the condition of wind speed, different thrust force at hub height is used. Fig.7 compares the local stress at the fracture section before and after the bolts are damaged in the case of wind speed is 16m/s.



Fig.7 Comparison of the local stress from FE model (wind speed is 16m/s)

Fig.7 (a) implies the cause of maximum tensile stress happens at the inner tube is because of the lever principle, which is consistent with the observation of fracture face. According to Fig.7 (b), the local stress is larger when 17 bolts are broken.

Fig.8 shows the relationship between local stress and nominal stress. The nonlinear phenomenon happens when 17 bolts are broken. The local stress with 17 bolts broken is more than three times of the local stress when bolts are normal.



Fig.8 Local stress vs. nominal stress

3.4 Fatigue life evaluation

Combined with Goodman formula, rain-flow counting method, the relationship between local stress and nominal stress shown in Fig.8 and S-N curve^[5], the cumulative fatigue damage and fatigue life in 20 years is evaluated and listed in Table 1. Frequency distribution of the wind speed is based on on Rayleigh distribution with the mean wind speed of 8.5m/s. When the bolts are in normal condition the fatigue life is 21 years, which is consistent with the design requirement. However, if 17bolts broken, the fatigue life decreases dramatically to 0.25 years, which is approximately three months.

Case	Cumulative fatigue damage in 20 years	Fatigue life (year)
All bolts are normal	0.940	21
17 bolts are broken	79.3	0.25

Table 1. Cumulative fatigue damage and fatigue life in 20 years

4. Conclusions

The cause of the collapse of the wind turbine is obtained, and the following conclusions can be drawn:

1) The power output, rotor speed and tower base bending moment are calculated from dynamic simulation which are in good agreement with measurement results;

2) With 17 bolts broken the local stress at tower top increases three times, which accelerated the fatigue initiation and propagation;

3) When the local stress increases three times, the fatigue life deceases dramatically to 1/100 of its life.

5. Learning objectives

For this Taikoyama wind turbine, the cause of the accident is not the matter of design or material, but it is because of the reduction of high tension bolts' pre-tension force;

References

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