Taikoyama Wind Farm Fatigue Failure Accident Analysis
Based on Aerodynamic and FEM Modelling

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One of the wind turbine nacelles at Taikoyama wind farm collapsed due to high tension bolts fatigue failure. Turbine natural frequency and tower bending moment was measured to verify aerodynamic model. Measurement strain distribution at fracture shows differs significantly from plain section assumption. FEM model was built in order to understand accurate spatial relationship of tower wall nominal stress and high tension bolts stress. When the bolt’s pre-tension decreases, its force range increases. Hence when pre-tension is less than 80%, the bolt fatigue life decreases dramatically. Pre-tension reduction is due to miss of re-torquing.

Key Words: Fatigue failure, high tension bolt, pre-tension force, nacelle collapse.

Introduction

The Taikoyama wind farm is located at the top of Taiko Mountain, north to the Kyoto Prefecture, Japan. The wind farm location and geometric figures are shown in Fig. 1.

![Wind farm position and Topographic map](Image)

Fig. 1 Schematic diagram of Taikoyama

Taikoyama wind farm is built up with six turbines of 750kW rated power generation by Lagerwey. Rotor diameter is 50.5m and the rotor speed range is 13rpm to 33rpm. The control method of yaw control is active yaw control and power control is and pitch control respectively. The construction of Taikoyama wind farm completed in September 2001 and began to generate power at the same time. In March 2013 the nacelle of No.3 wind turbine collapsed [1]. The accident scene and schematic diagram is shown in Fig. 2. Accident investigation conclusion was drawn in reference [1], which including the following aspects:

![Collapsed nacelle and Fracture section](Image)

Fig. 2 Accident scene and schematic diagram

Fracture section investigation

By observing the fracture section, the tower wall thickness abided by the engineering drawings and the material strength of tower wall was strong enough. However, evidence of fatigue crack propagation was detected at the inner surface of the wall. Fatigue failure happened and resulted in ductile failure, which then propagated to the whole tower wall and the nacelle collapse eventually.

High-tension bolts investigation

From bolt No.13 and No.23, 17 high-tension bolts in all, were suffering from injury. Bolts No.17 to No.22 were broken or crack. Bolt strength meets the design requirement although fatigue cracks were detected as well. The fracture section is shown in detail in Fig. 3. The fracture cracks propagated 10mm below flange lower margin at this region, which is opposite to the main wind direction (W). Most of the bolts are under condition of 80% of the design pre-tension force because of construction dispersion.

![High-tension bolts arrangement and Flange connection](Image)

Fig. 3 Drawings of fracture section

Wind characteristics at site

Three-cups anemometer and ultra-sonic anemometer on MAST, that the wind characteristics satisfied the design requirement by IEC 61400-1[2] including annual wind speed, annual wind distribution, turbulence intensity and flow inclination angle. Besides the lateral and vertical turbulence intensity component are around 1.0σ1 and 0.7σ1 respectively [3], which is high according to IEC requirement [2].
Objectives

The wind turbine’s expected life time is 20 years whereas it collapsed very early within 12 years. How could the wind turbine collapse at the middle age of its life time? The bolts has injured and been replaced twice in the year of 2008 and 2012. The accident happened only one year after the replacement in 2012, and the last periodic inspection showed the bolts condition was good three months before the accident. Why the bolts broke frequently? There are more than 120 wind turbines in service of the same type across Japan. It is necessary and urgent to understand the cause of this accident, so that this kind of accident can be prevented in the future.

Field measurement

Turbine performance evaluation

No.1 wind turbine was considered as the measurement object since it is closest to the collapsed No.3 turbine and is still operating. Field measurement was conducted from Feb. 2nd 2015 to Feb. 28th 2015. The SCADA data was supplied by the wind farm operator and eventually 3010 effective data are collected.

Wind condition investigation

The occurrence frequency of predominant wind direction W, WNW and NW is 21%, 13% and 12% respectively. For turbulence intensity, bin average is considered with wind speed range of 1m/s, and the ones without a minimum of 60 min of sample data were eliminated. As shown in Fig. 4, 90% quantile measurement value is close to IEC NTM B curve.

![Fig. 4 Turbulence intensity](image)

Tower bending Moment at 12.6m height

Strain gauges with 20Hz sampling frequency were installed in eight directions at the height of 12.6m above tower base. Fig. 5 shows the strain gauges.

![Fig. 5 Strain gauges at 12.6m above tower base](image)

The nacelle was forced to rotate one circle when parked in order to estimate the strain gauges’ installment error, and the compensation value can be calculated. The average, maximum and standard deviation of bending moment are plotted in Fig. 6 in 10 minutes bin.

![Fig. 6 Scatter plot of measured moment](image)

Tower structural characteristic

From August 14th to August 16th, 2013, a field measurement was carried out to find out the tower structural characteristic. A 20Hz servo accelerator was installed at the platform. The tower vibration was excited by human beings in fore-aft direction and side-side direction. The measurement result is drawn in Table 1.

Fracture section strain distribution

In order to understand the strain distribution at fracture section, strain gauges were installed at fracture section as well. Installation layout is shown in Fig. 7. The measurement strain distribution is plotted in Fig. 12.

![Fig. 7 Strain gauges at fracture section (45.96m)](image)

Aerodynamic analysis and fatigue life investigation

Aerodynamic modelling and verification

Aerodynamic model is built by GL’s Bladed wind turbine modelling tool[4].

(1) Turbulence Intensity

Kainal model is used for turbulence spectrum, and the spectral parameters follows IEC 61400-1[1]. Because of the insufficient high wind speed measurement data, the bin average of turbulence intensity applied in aerodynamic simulation is extrapolated: measurement data for low wind speed (≤17m/s) and the extrapolated value for high wind speed (>17m/s).

(2) Structure modelling

The tower and blade geometric structures referred to engineering drawings provided by manufacturer. By referring to Wind Energy Handbook[5], we selected airfoils from NREL’s airfoil family, which are S818 for root section, S830 for primary section and S831 for tip section. The corresponding information such as thickness/chord ratio, Reynolds number, lift coefficient C_l and drag coefficient C_d were determined consequently[6]. C_l and C_d were multiplied by a correction coefficient of 1.2. Correspondingly, the natural frequency of aerodynamic model is consistent well with the measurement result.

<table>
<thead>
<tr>
<th>Tower natural frequencies</th>
<th>Measurement (Hz)</th>
<th>Simulation (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st order (fore-aft)</td>
<td>0.532</td>
<td>0.533</td>
</tr>
<tr>
<td>1st order (side-side)</td>
<td>0.542</td>
<td>0.533</td>
</tr>
<tr>
<td>2nd order (fore-aft)</td>
<td>3.838</td>
<td>3.685</td>
</tr>
<tr>
<td>2nd order (side-side)</td>
<td>3.832</td>
<td>3.578</td>
</tr>
</tbody>
</table>

(3) Wind turbine control

The manufacturer modified the maximum rotor speed and power output to control the fluctuation. Nevertheless since the detailed modification were commercial confidentiality, we adjust designed rated power output from 750kW to 630kW, as well as rated rotor speed from 33rpm to 26rpm according to the measurement data. Although the rated power output and rated rotor speed is modified close to the measurement data, while during the optimization partial load regime below rated wind speed, the modified result still does not match the measurement data for both power output, rotor speed and pitch angle as shown...
in Fig. 8.

Fig. 8 Comparison of designed and modified aerodynamic model
Consequently, we considered a 5-degree pitch angle error. It effective to reduce the difference in optimization partial load regime, pitch angle and tower bending moment as well shown in Fig. 9, which means the blades are rotating at five degrees off all the time. This method reduces both the generator torque and the aerodynamic thrust force simultaneously. Key parameters for aerodynamic modelling control are summarized in Table 2.

<table>
<thead>
<tr>
<th>Optimal mode gain $K_{opt}$</th>
<th>Demanded generator torque (Nm)</th>
<th>Rated Power generation (kW)</th>
<th>Rotor speed (rpm)</th>
<th>Error in Pitch angle (deg)</th>
<th>Torque control</th>
<th>Pitch control</th>
</tr>
</thead>
<tbody>
<tr>
<td>23340.2</td>
<td>231387</td>
<td>630</td>
<td>26rpm</td>
<td>5</td>
<td>$K_{opt}=461249$</td>
<td>$K_{opt}=0.492799$</td>
</tr>
</tbody>
</table>

Table 2 Key parameters for Bladed modelling

Characteristics of fracture section
Fig. 10 (a) and Fig. 10 (b) shows numerical axial force $N$ and bending moment $M$ at the tower fracture section (45.94m) (refer to Fig. 2(c)). The fracture sectional stress (hereafter called 'nominal stress') can be calculated from equation(1), where $A=0.062m^2$, is the sectional area and $Z=0.0309m^3$ is the sectional resistance moment.

$$\sigma = \frac{N}{A} - \frac{M}{Z}$$

(1)

Fig. 10 Aerodynamic characteristics at the fracture section (45.94m)

FEM modelling
Since the fracture section is closed to the top flange welding, the stress concentration and spatial effect may influence the stress significantly. FEM model is needed to clarify the relationship between nominal stress $\sigma_n$ and bolt pre-tension force. It is understood through in-site investigation, that nacelle and tower is connected with ball bearing, and nacelle is rotated by three yaw motors installed at nacelle platform. When wind turbine is parked (or extreme weather condition), 16 yaw breaks equally distributed around nacelle platform stop the nacelle from rotating. The FEM model is built with ABAQUS/Standard as shown in Fig. 11. Nacelle connected to tower by three main paths: 1) Ball bearing; 2) Yaw brakes and 3) Yaw motors.

Pinion gear is built up by solid element Nacelle is built up with shell element. Ball bearings are modelled by spring with small stiffness, while yaw brakes are modelled as springs too but with stronger stiffness. Beam element is considered for bolt [7]. Nacelle and rotor weight is considered as concentrated mass and it is rigidly connected to the nacelle.

Comparison of strain distribution of FEM model and
measurement is plotted in Fig. 12. The FEM model recreates the tensile increase in aft direction and compressive decrease in fore direction, which shows good agreement with measurement. As shown in Fig. 13, the nacelle-tower connection is mainly transferred by yaw motors so the elliptical yaw deformation is due to the restraint. Therefore the FEM model is necessary to evaluate the fracture section stress distribution.

Investigation of the high tension bolts fatigue life

The six broken bolts’ pre-tension force is considered in different cases which are 100%, 80%, 60%, 40%, 20% and 0% of the design pre-tension force corresponding to 850 N/mm torque. The relationship between the nominal stress and bolt pre-tension stress is given in Fig. 14. With the nominal stress increasing, the gradient increases as pre-tension decreases, and it is much more obvious when the pre-tension force decreases. The larger the gradient the larger the bolt stress range will be, and the bolt’s fatigue load as well. Since the nominal stress ranges mainly between -5 N/mm² to 25 N/mm² according to Fig. 10(c), the stress range may vary dramatically especially when the bolts pre-tension stress drops to 0% as illustrated in Fig. 14.

![Fig. 14 Nominal stress Vs. bolt stress](image1)

![Fig. 15 bolt pre-tension stress (14/m/s)](image2)

Fig. 15 shows one example of the time history of the bolt stress at the wind speed of 14 m/s. It is clear that with the pre-tension force decreasing the stress range increases significantly. Rain flow counting algorithm is used for fatigue analysis in order to reduce the spectrum of varying stress into a set of simple stress reversals. One example of the result can be seen in Fig. 16 when 6 bolts broken at the wind speed of 14 m/s as well. Goodman relation in equation (2) is used to quantify the interaction of mean and alternating stresses. σₐ is the alternating stress from rain flow counting result, σₐ₀ is the mean stress, σₖ is the fatigue limit for completely reversed loading and σₚ is the ultimate tensile strength of the material, which is 1000 Mpa for FIOTM24 bolt, and the detail category is 36 according to GL 2010[8] without considering bolt bending moment.

\[
σ_a = σ_a (1 - \frac{σ_a}{σ_p})
\]

(2)

Finally, by using Miner’s rule, the bolts fatigue life is calculated and shown in Fig. 17. When pre-tension equals 80%, the fatigue life is 28 years and it satisfies requirement even under high turbulence. However the fatigue life decreases if pre-tension is less than 80% which may result to turbine failure. Besides, when pre-tension is less than 40%, the fatigue life remains only only a few days.

![Fig. 16 Rain flow counting (14/m/s)](image3)

![Fig. 17 Bolts fatigue life vs. bolt pre-tension](image4)

Investigation of bolt pre-tension force reduction

The bolt pre-tension is applied by torqueing. Indoor experiment and field experiment at Taikoyama wind farm was conducted[9] and it concluded that if the bolt and screw are well lubricated, the bolt pre-tension can be guaranteed with 10% variability above required axial force. The relation between bolt reduction ratio (R) and bolt nut loosen circumference (L mm) is established in equation(3).

\[
R = 1 - \frac{L}{15}
\]

(3)

According to the service manual, temporary torqueing is applied first, then re-torqueing is required after 500 hours’ operation. However by checking the maintenance record, the re-torqueing was not applied. Table 3 summarized the bolts those had loosen circumference L and R after 500 hours operation.

<table>
<thead>
<tr>
<th>Bolts No.</th>
<th>L (mm)</th>
<th>R (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>3</td>
<td>80</td>
</tr>
<tr>
<td>22</td>
<td>2</td>
<td>87</td>
</tr>
<tr>
<td>23</td>
<td>3</td>
<td>80</td>
</tr>
</tbody>
</table>

80~87% pre-tension remained after 500 hours. Nevertheless the wind turbine is a rotating machine system, the contact surface and the bolt itself plasticity deforms accompany with the turbine’s operation, therefore the pre-tension reduction propagated further and resulted in fatigue failure.

Conclusions

(1) Due to high turbulence, the control of the wind turbine was adjust by manufacturer. A 5 degree of pitch error modification was applied to aerodynamic model; (2) Strain distribution at fracture section is not abiding by plain section assumption due to complex nacelle structure and yaw motors constraint. FEM model was built and shows good agreement with measurement; (3) The root cause of this accident is not considered as the matter of high turbulence or design, but due to the reduction of bolts pre-tension. When the pre-tension is less than 80% the fatigue life time may decrease drastically, and to only a few days if less than 40%; (4) Re-torqueing is important to prevent pre-tension reduction. The communication between manufacturer and operation works should be more effective.

References