TAIKOYAMA WIND FARM FATIGUE FAILURE ACCIDENT ANALYSIS BASED ON AERODYNAMIC AND FEM MODELLING

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Introduction

◆ Power output:  
6 × 750 kW = 4500 kW

◆ Location:  
Top of Taikoyama, Kyoto prefecture, Japan

◆ Terrain condition:  
Complex mountainous area

◆ History:  
Nov, 2001: Power generation began;  
Mar, 2013: Nacelle of No.3 turbine collapsed

- Complex mountainous terrain results in high turbulence intensity
- Different from the situation in Europe
Questions

1. Wind turbine design life is 20 years; However this turbine nacelle collapsed only 12 years after construction. How could it collapsed at a middle age of its life time?

2. The No.3 turbine’s high-tension bolts broke three times in 2008, 2012 and 2013. After the last bolts replacement in 2012, the nacelle collapsed within one year, although there was no damage detected according to the periodical inspection; Why the bolts broke frequently?
Flow chart

Wind condition investigation
- High turbulence;
- Ambiguous explanation is dangerous:
  1) Solving problem;
  2) Dividing responsibility.

Quantitative analysis required
- Aerodynamic modelling;
- Understanding the force;
- Fatigue life evaluation.

Fracture section investigation
- Material strength no problem;
- Fatigue cracks propagated at the tower tube inner surface.

Spatial effect & stress concentration
- Accurate FEM model;
- Clarify the relationship between nominal stress and bolt stress.
Objectives

1. Aerodynamic model is necessary in order to understand the response at the fracture section;

2. Field measurement and observation should be conducted to understand the complicated nacelle structure;

3. FEM model should be built accurately in order to recreate the complex strain distribution at fracture section, and to evaluate the fatigue life of high-tension bolt;

4. Bolts broke frequently. Root cause must be clarified.
Field measurement

◆ Moment
Ave moment, std moment and max moment

◆ Occurrence frequency
West wind predominates

◆ Turbulence intensity

\[ I_p = \frac{U_{\text{max}}}{U_{\text{mean}}} - 1, \quad P = \frac{1}{2} \ln \frac{T}{t} \]

- Extrapolated value for high wind speed (>17 m/s)
- \( I_v \approx 1.0 I_u \)
- \( I_w \approx 0.7 I_u \)
- Slope with gradient over 20 degree

High turbulence
Aerodynamic modelling & modification

- **Modelling**
  - **Tower part**
    - Engineering drawings
  - **Blade shape and aerodynamic coefficient**
    - NREL airfoil family

- **Modification of real turbine**
  - Power output: 750kW → 630kW;
  - Rotor speed: 33rpm → 26rpm;
  - Pitch angle: different

- **Modification of model**
  - No information from manufacturer
  - Pitch angle error
    - 5 degree;
    - Reduce both torque and thrust

Aerodynamic model is built based on real situation
Strain distribution at top flange joint

- Strain distribution should be understood
  - Spatial effect & stress concentration

- Strain gauges arrangement
  - Around 45.94m, CH9~CH32

- Strain distribution
  - CH19
    - Dissatisfy the plane section assumption

- Nacelle investigation
  Nacelle weight transmits in three paths
    - 3 Yaw motors
    - 16 Yaw brakes
    - 129 Ball bearings

- FEM model is necessary to recreate the strain distribution at fracture section
FEM modelling

- **FEM model**
  - Solid element
    - Ball bearing, pinion gear;
  - Shell element
    - Nacelle
  - Spring element
    - Yaw brake, ball bearing
  - Beam element
    - Bolts

- **Strain distribution**
  - Good agreement

- **Mechanism**
  - Yaw deformation is elliptical;
  - Tower strain direction aft side is large;
  - Tower strain in fore direction is small;

- FEM model shows good agreement and necessary

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Strain (με)

Tower strain distribution 45.94 m
Bolt fatigue life evaluation

- **Relationship between nominal and bolt stress**
  - Nominal stress (45.94m): $\sigma_n=N/A\cdot M/Z$
  - Nominal stress increases, gradient increases as pre-tension decreases
  - Steeper gradient when pre-tension decreases

- **Fatigue life**
  - Rainflow counting, S-N curve, miner’s rule
  - Life time drops drastically when pre-tension decreases
  - Pre-tension is 80%: fatigue life 28 years — safe
  - Pre-tension less than 80%: fatigue life < 20 years — failure
  - Pre-tension less than 40%: fatigue life only a few days

- **High turbulence is not the reason but reduction of bolts pre-tension**
Reason of bolt pre-tension reduction

- Pre-tension force is applied by torqueing
  - F10T-M24
    Torque: 850Nm → Axial force: 265kN

- Indoor experiment
  - Different wrenches and wrench
  - If well lubricated:
    Pre-tension can be guaranteed with 10% variability

- Filed experiment
  - Same with indoor

- Bolt force reduction ratio
  - $R = 1 - \frac{L}{15}$ (%)

- Re-torqueing is important

- Re-torqueing was not applied 500 hours after bolt replacement caused the reduction
Conclusions

1. Due to high turbulence, control method was adjust by manufacturer. Modification was applied to aerodynamic model;

2. The 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 accurately and shows good agreement with measurement result;

3. The root cause of this accident is not the matter of high turbulence or design, but the reduction of bolts pre-tension. When pre-tension force is less than 80% the fatigue life decreases;

4. Re-torqueing is important to prevent pre-tension reduction. Communication between manufacturer and operation workers should be more effective.
Thank you!

Acknowledgement:
This project is funded by the Kyoto Prefecture Government, New Energy and Industrial Technology Development Organization. I wish to express my deepest gratitude to the concerned parties for their assistance and contribution to this project.