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Fatigue prediction of wind turbine high-tension bolts based on sophisticated aerodynamic and structural model

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SUMMARY:
In this study, the cause of Taikoyama wind turbine accident is investigated by conducting fatigue prediction of wind turbine high-tenson bolts. Firstly, the aeroelastic turbine model is built by identifying the structure and control parameters from the measurements and validated with tower base moment. The simulated axial force and bending moment at the tower top shows that the tensile stress occurs at the downside from the main wind direction due to the eccentricity of the rotor and nacelle gravity center. The finite element model of the full flange is built with consideration of ball bearings, yaw breaks and yaw motors. It is clarified that the tensile stress occurs inside of the tower shell due to the leverage effect. The relationship between local stress and nominal stress becomes nonlinear in the damaged bolt and the local stress is three times larger than that of normal bolt. Finally, the predicted fatigue life of high-tension bolt is three months when the existing bolt axial force is less than 30 %, which indicates that the fatigue failure of the wind turbine tower cause is induced by the failure of the tower top flange bolt.

Keywords: wind turbine, fatigue failure, high-tension bolts

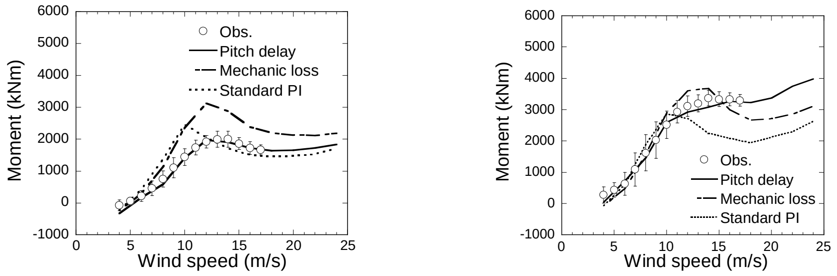
1. INTRODUCTION

In 12th March 2013, the nacelle of 750kW wind turbine at Taikoyama wind farm in Japan fell down to the ground. 16 out of 60 high-tension bolts on the tower top flange fractured and the fatigue failure occurs at the east side of the tower on the downside of the main westerly wind direction, though the downside of the turbine is generally subjected to the compressive force (Kyoto prefecture, 2013). It is necessary to clarify why the fatigue failure occurred on the downwind side and the fatigue life was about 12 years, which is shorter than the designed lifetime of 20 years. The periodic maintenance was performed only three months before the accident, which indicates that the fatigue failure life of high-tension of bolts were less than 3 months. The accident survey also found that the re-torqueing of high-tension bolts were not conducted adequately, which led the reduction of the existing bolt axial force ratio. The conventional fatigue analysis does not predict such a short fatigue life of the high-tension bolt even with the low existing bolt axial force. Firstly, the sophisticated aero-elastic wind turbine model needs to be built based on the measurement data and it needs to be clarified why the fatigue failure occurs at the downside of the turbine. Then, the relationship between the nominal stress and the axial force of high-tension bolts are unclear for the failure turbine. Bolt-fatigue life needs to be quantitively predicted with the bolt pre-tension percentage.

2. AERODYNAMIC MODEL AND WIND LOAD

2.1. Aerodynamic Model and Validation

An aero-elastic wind turbine model is built by using GH Bladed based on the design guideline (Ishihara ed., 2010). The simulated power curve, rotor speed and pitch angle with standard PI control model overestimates the measured tower base moment as Figure 1 shows. Therefore, the mechanic loss model and the pitch delay model are introduced. According to the relationship between power and wind speed, a total of 31.85 % loss is a practical assumption. 32 % reduction of lift force coefficient corresponds to approximately 5 degrees of the change of the angle of attack. The error of the first natural frequencies are less than 2 %, which validates the structure parameters. The predicted tower base moment with pitch delay control model agrees well with the measurements.

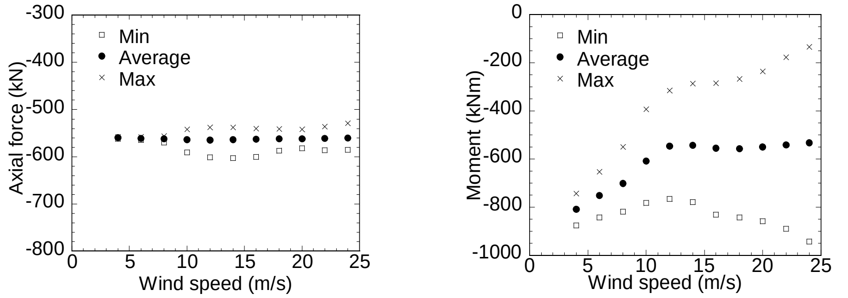


(a) Average (b) Maximum

Figure 1. Comparison between measured and predicted tower base moment.

2.2. Wind Load Analysis on Wind Turbine

The wind loading on the tower top is investigated using the measured turbulence intensity. I_v/I_u and I_w/I_u are around 1.0 and 0.7 respectively, which are higher than IEC requirement for flat terrain (IEC61400-3-1, 2019). The simulated wind loading for each wind speed are shown in Fig. 2. Here, wind direction is set as the positive in the coordination. The average of axial force and bending moment with no wind case are -533kN and -813kNm respectively, which are induced by the rotor and nacelle weight. With the increase of wind speed, the moment increases and reaches the maximum near the rated wind speed. It is found that the moment due to the rotor and nacelle weight exceeds the moment due to the wind, which induces the variable tensile force. This is the reason why the fatigue failure occurs at the downside of the tower.



(a) Axial force (b) Bending moment

Figure 2. Comparison between measured and predicted force at the fracture section

3. FATIGUE PREDICTION OF HIGH-TENSION BOLTS

3.1. Structural Model and Validation

The local stress occurring at the tower weld end is evaluated by the finite element model. The tower top model is built considering the nacelle and yaw bearing at the tower top with three channels of ball bearings, yaw breaks and yaw pinion gears as built in the previous paper (Kikuchi and Ishihara, 2020). The bolts are modelled as beam element and rigidly connected to the yaw bearing. The normal and damaged bolt cases are simulated. The bolt failure is simulated by releasing the bolt rigid connection for 17 bolts damaged in the accident. Fig. 3 represents the stress counter of the normal and damaged bolt cases. It is found that the tensile stress occurs inside of the tower shell due to the leverage effect. The larger stress occurs in the damaged bolt case at the end of weld tower. Fig.4 shows the local stress for each nominal stress. In the damaged bolt case, the relationship between the local stress and the nominal stress becomes nonlinear, while that is linear in the normal bolt case. The local stress is three times larger than that of normal bolt in tension.

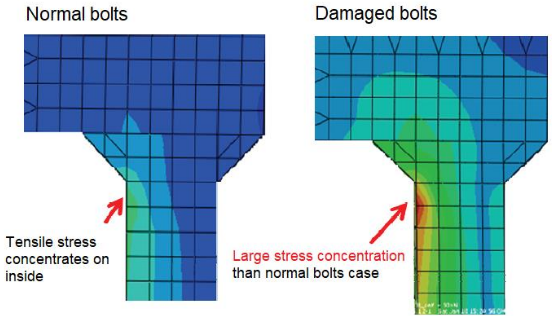


Figure 3. Stress counter on the normal and damaged bolts.

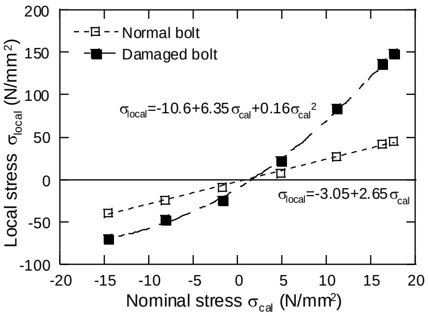
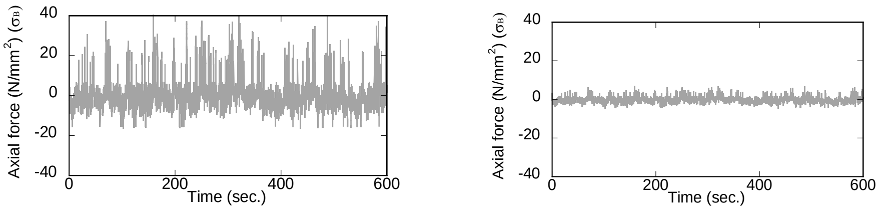


Figure 4. The local stress for each nominal stress.

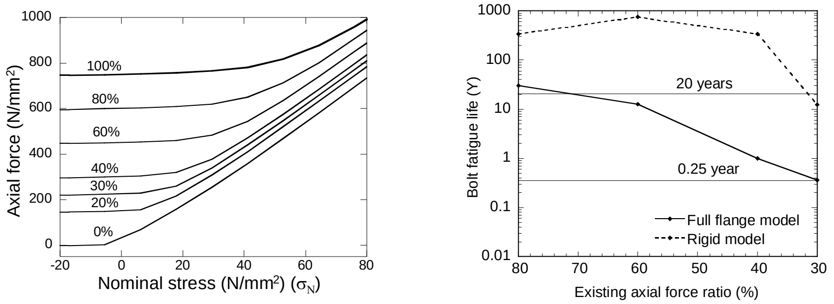
3.2. Fatigue Analysis of High-tension Bolts

The time series of axial force is calculated with 30 % and 80 % of existing bolt axial force as shown in Fig. 5. The relationship between bolt force and nominal stress for each existing bolt axial force ratio is calculated as shown in Fig.6 (a). With the nominal stress increasing, the gradient increases as pre-tension decreases, and it is much obvious in the reduced existing bolt axial force. Then, the fatigue life of the high-tension bolt is evaluated using the time series of wind loading obtained by the aero-elastic wind turbine model and the relationship between local stress and nominal stress mentioned above. By using Rain-flow counted cyclic amplitudes from the simulated time series and Goodman correction, the various stress frequency distributions are calculated. S-N curve from ENV1993-1-1 Detail Category 71 (Eurocode, 1992) is used. The calculated fatigue life becomes 21 years in normal bolt case with 80 % of the existing axial force ratio and 0.25 year in damaged bolt case with 30 % of the existing axial force ratio as shown in Fig.6 (b). The fatigue life estimated by the simple rigid tower model overestimates the actual record, indicating that the advanced tower model is critical for the accurate prediction. The actual records at the wind farm show that the bolts damages were occurred in winter within about five months, which almost matches the simulated fatigue life of 0.25 year in winter wind condition. The result indicates that the fatigue failure at Taikoyama wind farm is induced by the bolt failure at the flange of the tower. Note that re-torquing is important to prevent pre-tension reduction.



(a) 30 % of existing bolt axial force. (b) 80 % of existing bolt axial force.

Figure 5. Simulated variation of axial force.



(b) Simulated nominal stress with different bolt axial force. (b) Bolt fatigue life with bolt pre-tension percentage.

Figure 6. Bolt fatigue life with existing bolt axial force.

4. CONCLUSIONS

In this study, the fatigue life prediction of wind turbine high-tension bolts based on sophisticated aerodynamic and structural models are conducted. The conclusions were obtained as follows:

1. The aeroelastic wind turbine model is built and the wind loading on the tower is investigated for each wind speed bin. It is clarified that the tensile stress occurs at the downside from the main wind direction due to the eccentricity of the rotor and nacelle gravity center.
2. It is found that the tensile stress occurs inside of the tower shell due to the leverage effect by FEM analysis considering tower-top three dimensionality and bolt damage in the flange connection part. The relationship between local stress and nominal stress becomes nonlinear in the damaged bolt and the local stress is three times larger than that of normal bolt.
3. The calculated fatigue life becomes 21 years in normal bolt case and 0.25 year in damaged bolt case, which matches with the actual record. The fatigue failure of the wind turbine tower cause is induced by the failure of the tower top flange bolt.

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