Fatigue Analysis of a 500kW Wind Turbine Main Load Frame

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Abstract- **As wind industry gets larger and larger, maintenance safety and reliability of the turbine equipment become more and more important. Main load frame is one of the most critical components of the turbine, and should have an acceptable fatigue safety as the component is used for main load transmission and serve as main mount for all nacelle equipment. This work presents a fatigue life evaluation process for main load frame of a 500 kW wind turbine. While the cyclic life of the turbine is designed to be infinite, both static safety factors and weight of the main load frame are optimally balanced. In order to achieve an effective fatigue design, modified Goodman fatigue theory is used with the aid of commercial finite element codes. Dynamic strength of the materials and the safety factors of the bedplate are calculated analytically. The stress analyses are conducted using finite element methodology. The stress oscillations are determined for the both parts of the hybrid bedplate. Values of the maximum and minimum stresses are calculated with the aid of the commercial finite element solver. Through the fatigue analysis iterations reasonably high fatigue safety factors are obtained.**

Keywords: Fatigue analysis, bedplate, Goodman theory, endurance limit, proof strength.

I. INTRODUCTION

The significance of wind energy has been increasing its significance in the energy industry over the last two decades. Equipment costs, high maintenance and repair expenses are main complaints of the investors. Wind turbine nacelles generally work under dynamic loads. It is evident that fatigue life of several components are crucial for both engineers and operators in the wind industry. Specifically cast components like rotor hub and nacelle bedplate should be designed with caution ensuring infinite fatigue life approach. Three fatigue design approach are considered: Stress life, Strain life and linear elastic fracture mechanics models. Among the three models Stress-life method is used for fatigue analyses of the bedplate. Stress-cycle method is most often used for high-cycle fatigue (HCF) applications where nacelle hybrid bedplate design is evidently exposed to countless cycles over its design life.

There are three different approaches for main load frame design: fully cast, welded and hybrid structure. Most of the existing research about fatigue life of the wind turbine components are mainly focused on the cast components of the turbines. In this work, due to hybrid nacelle bedplate construction (Figure 1) both cast main load frame and welded generator support components are examined with stress-life approach.

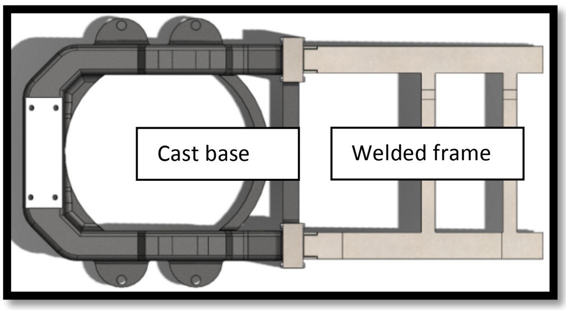

Figure 1 :Top view of hybrid bedplate design. (1)

Among the theories of the fatigue modeling, modified Goodman criterion is preferred. Throughout dynamic analysis iterations conservative material properties and endurance strength safety factors have been used.

II. FATIGUE ANALYSES AND STRESS ITERATIONS

As previously mentioned, the main reason for this fatigue analysis is to find optimum design for both engineering safety and turbine operational cost. The critical requirement during the optimization process is to achieve satisfactory margins for safety factor and stress carrying capabilities.

A. Analysis

In order to obtain reliable fatigue life for the components that are used in the hybrid bedplate design, first of all maximum and minimum stress levels should be determined. Main load frame is generally exposed to high level of wind loads and resulting forces and torques. Stress analyses are conducted with a commercial finite element software (ANSYS). It is assumed that the wind loads create zero mean cyclic stresses. Therefore, the cycle ratio will be zero to full power case (Figure 2).

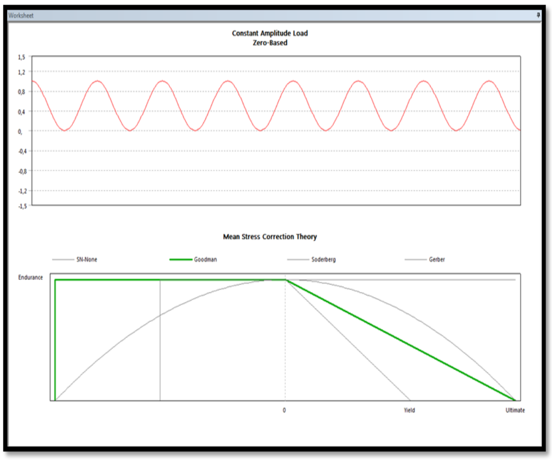

Figure 2: Zero based stress cycles. (2)

As mentioned earlier, very commonly cast parts are used for wind turbine components. Therefore, material fatigue constants are crucial for fatigue modelling of these cast parts (3).

The stress-cycle approach is most widely used among other approaches. Fatigue strength verification of a component design is a complex task. Complex geometries can be modeled by finite element models. (3)

Finite element analyses provide different required stress values for the dynamic safety factor calculations. Since main load frame includes cast and welded components, several iterations are conducted to find the stress values. Various coefficients for calculations of material endurance limits are determined in order to utilize Modified Goodman theory analytically.

B. Boundary conditions

Stress analyses are completed using Finite element method as previously mentioned. Full wind loading is applied to the system to determine the maximum stress on both components. In order to complete the analyses, load scenarios should be defined carefully, and determining boundary conditions are vital. Figure 3 and 4 illustrate the fixed support surfaces and full loading condition on the system.

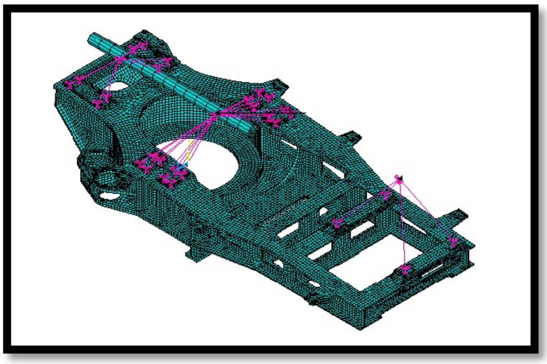

Figure 3: Meshed model of a sample bedplate. (4)

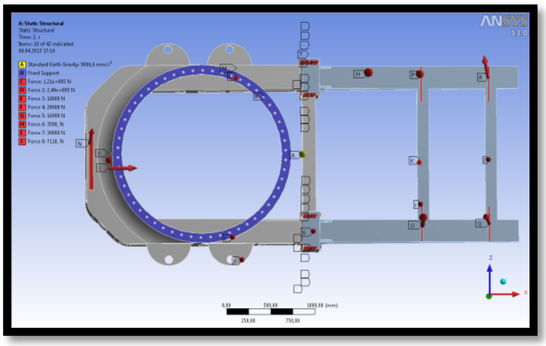

Figure 4: Fixed support for the analysis. (1)

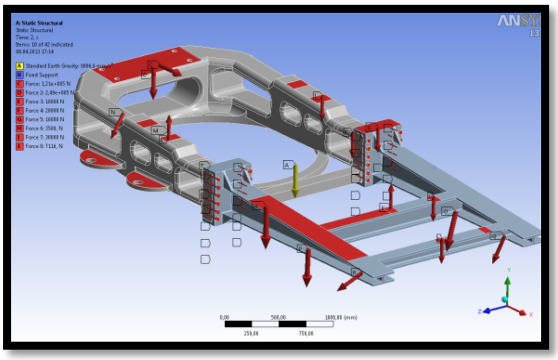

Figure 5: Full loadings on the bedplate. (1)

Full main load occurs when turbine generates full power. Wind load creates different loads on generator and gear box torques which may appear as force couples.

Table 1: Applied boundary conditions for full load. (Forces are scaled with respect to total weight of nacelle)

Reaction Force1	% 72.5
Reaction Force2	% 4.5
Wind Force	% 30
Motors weight	%7 (4 Faces)
Generator weight	%7.5
Converters weight	% 0.875
Cranes weight	% 4

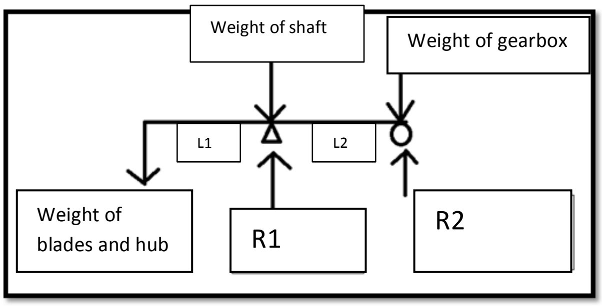

Figure 6: Reaction force calculations.

Boundary conditions given on the table are scaled with respect to total weight of the nacelle. Calculation methodology of reaction forces are illustrated in Figure 6. The maximum stresses on both parts of the bedplate are assesed. The analysis results yielded the maximum stresses (σmax).

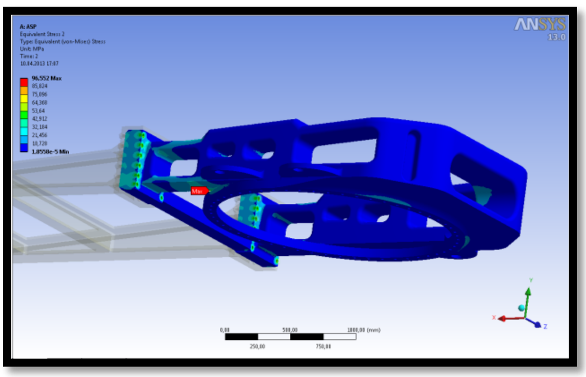

Figure 7: Maximum stress on cast nacelle part. (1)

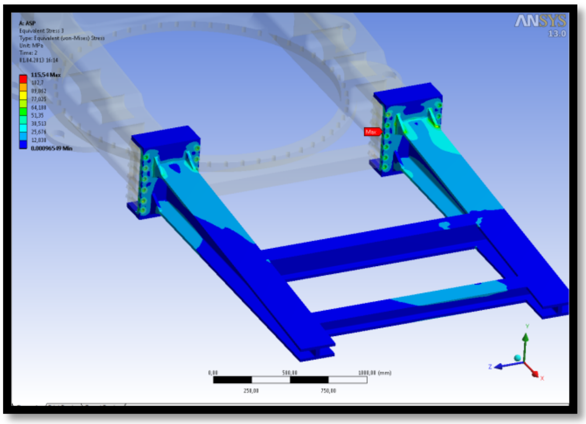

Figure 8 : Maximum stress on welded profile part.

Maximum stress values are obtained with the results shown in Figure 7 and Figure 8. Numerical calculations for minimum stresses are completed with different boundary conditions due to dynamic wind effect as well as other wind dependent loads such as generator torque and gearbox force couple. As mentioned early in this paper, the stress cycle is assumed to have zero mean value.

Table 2: Boundary conditions for minimum stress analysis. (Forces are scaled with respect to total weight of nacelle)

Reaction Force1	% 72.5
Reaction Force2	% 4.5
Motors weight	% 30
Generator weight	%7 (4 Faces)
Converters weight	%7.5
Cranes weight	% 0.875

The minimum stresse values are obtained with the simulations conducted under the boundary conditions given in Table 2. These minimum stresse values on both parts are used in the fatigue calculations.

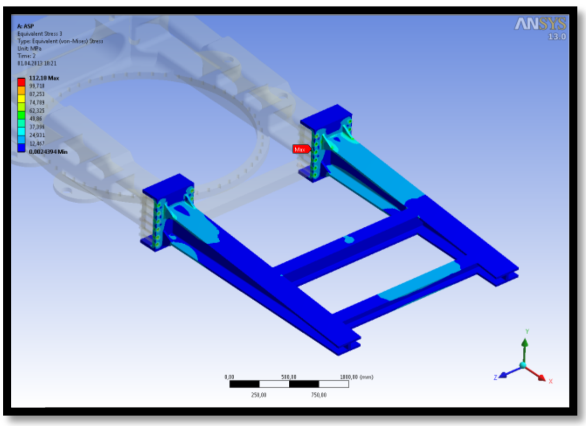

Figure 9: Minimum stress on welded frame.

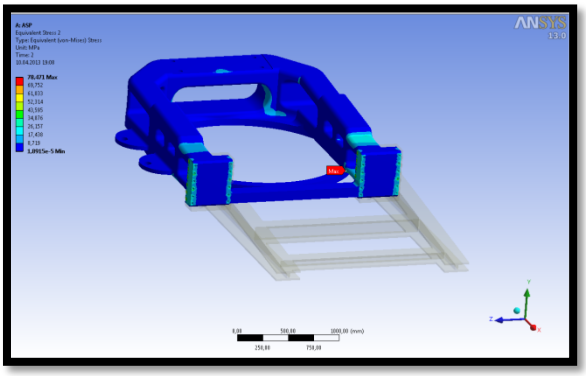

Figure 10 : Minimum stress on cast part. (1)

III. FATIGUE ANALYSIS RESULTS AND DISCUSSION

After the finite element model has been completed, minimum and maximum equivalent stress values are determined for both components of the main load frame. The bedplate is exposed to stress alterations. The minimum and maximum stress values are presented in the table given below.

Table 3 : Maximum and minimum stress values for the nacelle bedplate components. (Stress values are scaled with respect to yield points of materials.)

	Cast Part	Welded Frame
σmax	% 39	% 31.2
σmin	% 31	% 30

The stress values illustrated in the table are presented as scaled with yield point of the materials. After determining the stress values from finite element analyses, mean stress values and alternating stress levels are calculated as follows.

$$\Delta\sigma = \sigma max - \sigma min \quad (1)$$

$$\sigma m = \frac{\sigma max + \sigma min}{2} \quad \text{(Mean Stress Value) (2)}$$

$$\sigma a = \frac{\sigma max - \sigma min}{2} \quad \text{(Alternating stress) (3)}$$

Using the above formulation, alternating stress and mean stress values can be calculated for the modified Goodman criteria which leads to the dynamic safety factor.

Table 4: Mean and alternating stress values. (Stress values are scaled with respect to yield points of materials.)

	Cast Part	Welded Frame
σm	%34.95	%30
σa	%0.3	%0.04

EN_GJS_400_18_LT material is used for cast part as it is widely used in wind industry. Various correction coefficients are used for modified endurance strength calculations as shown below.

$$Se = C_{load} * C_{size} * C_{surf} * C_{temp} * C_{rel} * Se' \quad (4)\ (5)$$

There are several factors to calculate the endurance of the material. These coefficients are used to modify endurance limit.

- **Loading Effects**: The stress reduction load factor for the material was taken as $C_{load} = 0.7$ since the loading is generally axial for the analysis (6)
- **Size Effects**: "For length < 8 mm $C_{size} = 1$; For 8mm< length < 250 mm $C_{size} = 1.189 * length^{-0.097}$; For size larger than 250 mm as in this case, sizing factor is 0.6" (5)
- **Surface Effects**: Cast iron can be assigned with $C_{surf} = 1$ since their internal discontinuities dwarf the effects of a rough surface (5)
- **Temperature Effects:** $C_{temp} = 1$ for T < 450º C (5)
- **Reliability Effects**: $C_{rel} = 0.659$ for 99.999% reliability.

After determining the correction factors, the modified endurance limit can be calculated with the aid of Equation 4. Se' is given as $Se' = 0.5\, S_{ut}$ which is 200 MPA. Therefore, Se' is 55.356 MPA for the modified endurance limit of the EN-GJS-400-18.

Modified Goodman criteria can be applied after completing the calculations above. Required stress values can be applied on Equation 5 in order to find the dynamical safety factor for cast part.

$$\frac{\sigma a}{Se} + \frac{\sigma m}{Sut} = \frac{1}{n} \quad (5)$$

The modified Goodman formulation requires alternating stress, mean stress, Endurance limit of the material and Ultimate Strength of the material. By the aid of this formulation, dynamic safety factor for cast part can be calculated as shown below.

$$\frac{9.05}{55.336}+\frac{87.45}{400}=\frac{1}{n}$$

The dynamic factor of safety is calculated as 2.61, which is sufficiently safe.

Similar analysis approach is also applied on the welded profile part. Material of the welded part of the nacelle bedplate is different than the cast part. In order to apply modified Goodman criteria modified endurance limit of the materials should be calculated. Material of the welded part is DIN EN 10025-3 that is widely used in heavy industry and constructions. The load factors are considered as in cast parts factors. Therefore modified endurance limit is calculated from the Equation 4.

$$Se = C_{load} * C_{size} * C_{surf} * C_{temp} * C_{rel} * Se'$$

Se=0.7*0.6*1*1*0.659*275 = 76.1145 Mpa

Therefore, modified Goodman criterion can be applied on the welded part as shown in Equation 5. S_{ut} represents the materials ultimate strength which is 550 Mpa. Therefore $S_e^{'}$ = 0.5* S_{ut} that yields 275Mpa for the modified endurance limit calculation.

$$\frac{1.65}{76.1145}+\frac{113.86}{550}=\frac{1}{\mathrm{n}}$$

Therefore, dynamic safety factor for welded part is calculated as 4,34.

IV. CONCLUSION

Fatigue analyses of a 500 kW wind turbine nacelle bedplate have been conducted via both analytical and numerical calculations. Reasonable dynamic safety factors are determşned for both parts separately using modified Goodman fatigue formulations.

At the end of the fatigue analysis process, dynamic safety factors 2.61 and 4.34 are determined for cast and profile parts respectively. These values are sufficiently high and they show that the load frame is quite safe for fatigue.

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