



# Article Fatigue Analysis Design Approach, Manufacturing and Implementation of a 500 kW Wind Turbine Main Load Frame

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**Abstract:** The main load frame of a wind turbine is the primary mount for all nacelle equipment and is used as the principal load transmitter. This frame should have a reliable fatigue safety rating because it is a load-bearing component. In this work, the fatigue life design, manufacturing and implementation process for the main load frame of a 500 kW wind turbine are studied. The weight of the main load frame and static safety factors are preserved while the cyclic life of the bedplate is kept infinite. Modified Goodman theory is applied to achieve an effective fatigue design using a commercial finite element software package. Analytical calculations are carried out to obtain the safety factors of the bedplate and dynamic strength of the materials. A finite element approach is employed to perform stress analysis. Stress oscillations are established for both welded and cast parts of the hybrid bedplate, and the maximum and minimum stress values are established. Fatigue safety factors are calculated via fatigue analysis iterations. The obtained safety factors are adequate from the perspective of commonly accepted fatigue safety standards. Welding and casting techniques are applied together for manufacturing of the frame. On-site testing indicates that the wind turbine does not show any signs of fatigue. Rupture, cracks, and abrupt accelerometer reading variations are not observed.

Keywords: wind energy; wind turbine; main load frame; fatigue; Goodman; bedplate; finite element

## 1. Introduction

Energy consumption figures are rising in conjunction with the growth of the world's population and industries [1]. Concerns about energy generation and environmental pollution make clean energy sources such as wind energy attractive [2–4]. Modern wind turbines were first used in the 1980s [5,6]; although wind power has been employed for 40 years [7], its significance within the energy industry has increased over the last two decades [8]. In this field, equipment expenses such as manufacturing and repairing costs and substantial maintenance losses are main concerns of investors [9]. The components' fatigue lives are critical for both engineers and financiers in the wind industry to prevent intolerable costs [10,11]. Fatigue is an essential concept in mechanical engineering design. Research about this topic is extensive, and dates back centuries [12–24]. Since the lifetime of the turbine parts needs to be extended for as long as possible [25], parts that function under alternating impact forces and loads, such as the cast rotor hub, main shaft, and nacelles' bedplate, should be designed with the infinite fatigue life approach [26,27].

Stress-life, strain-life, and linear elastic fracture mechanics models are the most commonly employed theoretical fatigue approaches found in the literature [28,29]. In this work, the stress-life method was chosen for fatigue analysis of the bedplate. For high-cycle fatigue (HCF) applications, the stress-life method, the oldest of the three models, is generally preferred. In the wind turbine industry, it is evident that the hybrid bedplate is exposed to more than 10<sup>3</sup> stress cycles over its design life [30].

The current approaches for designing the main load frame rely on fully welded [31–34], fully cast [35–37], and hybrid structures [30]. Literature on the fatigue life of wind turbine



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**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). components indicates that the focus is on the casting parts of the turbine [38–40]. However, the fatigue life of wind turbine bedplates has not been previously examined. Since the bedplate is a main load-bearing component of a wind turbine, the fatigue life of the component must be known and requires further investigation with regard to dynamic loading safety and life expectancy. In this work, we explored the dynamic load safety for wind turbine nacelle bedplate as a novel contribution. This work is an extension of [30], where both the cast main load frame and welded generator support parts of a bedplate were examined with the stress-life approach in the hybrid bedplate construction (Figure 1). Since the modified Goodman criterion has conservative material factors and limitations on the endurance strength, it was preferred in this work over other theories of fatigue modeling for the dynamic analysis iterations of the structure [30].



Figure 1. Top view of hybrid bedplate design [30].

After the modeling and design process was completed, a hybrid bedplate was manufactured in two parts, cast and welded parts. Both parts were tested and assembled to complete bedplate manufacturing. Other components of the wind turbine were manufactured individually. The completed components were then transferred and assembled on-site. After implementation (Figure 2), the turbine was tested and connected to the electrical grid.



Figure 2. Completed implementation of the wind turbine.

The organization of the article is as follows: Section 2 presents how fatigue analysis and stress iterations were performed on the hybrid bedplate. Section 3 discusses the analysis results. Manufacturing and implementation stages of the main load frame are described in Section 4. Section 5 considers the results of manufacturing and implementation stages. Lastly, in Section 6, a discussion of conclusions is presented.

## 2. Fatigue Analysis and Stress Iterations

The design of operational expenses and the security of a turbine necessarily include fatigue analysis. During the optimization process, a fundamental requirement is to accomplish agreeable limits for the safety factor and stress-conveying abilities. The infinite life, or high dynamic safety factors, is the determining feature for turbine life and comprises critical information for the financial specialists.

### 2.1. Methodology

The maximum and minimum stress under full-wind loading conditions and zero-wind loading should be computed in order to determine the reasonable fatigue life for hybrid bedplate design components. Due to the extreme load transfer task for wind turbines, the bedplate structure is central in determining strength, stiffness, and fatigue life. A combination of wind loads and dependent forces and torques are typically applied to main load frames [41]. In order to achieve a safe and conservative fatigue approach, the maximum aerodynamic loading of the wind turbine was calculated according to IEC 61400-1 standard's extreme loading scenario. Stress analysis was performed with an ANSYS structural module of a finite element software package. The structure of the wind turbine's operating principle generates zero-based cyclic stress since it produces peaks from zero to maximum wind force. This creates couples of maximum torque and force. The cycle's ratio would therefore be zero to maximum power case (Figures 3 and 4).



Figure 3. Constant amplitude load zero-based stress cycle.



Figure 4. Mean stress correction theory.

As previously mentioned in this article, cast parts for the components of the wind turbine were typically engineered. As this work presents a cast bedplate, determination of material fatigue constants was essential for the cast sections' fatigue modeling [42].

Between the three methods, the stress-cycle method was preferred in this study. The analytical calculations require multiple stress values to obtain dynamic safety factors for the parts. Verification of the fatigue strength of the component design is a challenging task. The complex geometry of the bedplate can be modeled by finite element methods [10].

Considering the calculations of the dynamic safety factor, finite element analysis offers numerous essential stress values. Since cast and welded components were used in the main load frame, multiple iterations were performed to find the stress values. In order to calculate the modified Goodman principle analytically, multiple coefficients for computations of material endurance limits were calculated.

## 2.2. Boundary Conditions

In order to calculate the maximum stress on both parts, full-wind loadings were applied to the system. Load scenarios should be defined cautiously with respect to wind loadings to complete an analysis; therefore, defining boundary conditions is crucial. The meshed model and fixed support surface for the device are shown in Figures 5 and 6 respectively.



Figure 5. Meshed model of a sample bedplate [30].



Figure 6. Fixed support for the analysis [30].

Wind generates various loads that are distributed as force couples, such as generator and gearbox torques. As illustrated in Figure 7, the maximum static loading occurs when the turbine produces full power.



Figure 7. Full loadings on the bedplate [30].

Concerning the total weight of the nacelle, the boundary conditions provided in the Table 1 were calibrated.

**Table 1.** Applied boundary conditions for a full load [30]. (Forces were scaled as percentage of the total weight of nacelle).

Reaction Force1	72.5%
Reaction Force2	4.5%
Wind Force	30%
Weight of motors	7% (4 Faces)
Generator weight	7.5%
Weight of converters	0.875%
Crane's weight	4%
Generators Torque	3200 Nm
Gear box torque	200,536 Nm

Figure 8 demonstrates the calculation technique of reaction forces. The maximum stresses on both bedplate components were calculated, and the results of the study generated maximum stresses ( $\sigma_{max}$ ).



Figure 8. Reaction force calculations [30].



The maximum stress results are presented in Figures 9 and 10. It was observed that there was no stress concentration; therefore, no potential notch effects were expected.

Figure 9. Maximum stress on the cast part [30].



Figure 10. Maximum stress on profile part [30].

Analytical simulations for minimum stresses calculations were conducted with various boundary conditions based on dynamic wind effects and wind-based loads, including generator torque and gearbox force couple. The stress cycle was zero-based, depending on wind load flows from zero to maximum. Therefore, wind-dependent loads' dynamic effects are significant for minimum stresses, resulting in a zero-load ratio.

Along with the simulations conducted under the boundary conditions shown in Table 2, minimum stresses were determined. Considering the fatigue calculations, minimum stresses on both pieces, as shown in Figures 11 and 12, were employed.

**Table 2.** Boundary conditions of the minimum stress analysis' [30]. (Forces were measured as percentage of the overall weight of the nacelle).

Reaction Force1	72.5%
Reaction Force2	4.5%
Motors weight	30%
Generator weight	7% (4 Faces)
Converter's weight	0.875%
Crane's weight	7.5%



Figure 11. Minimum stress on the welded frame [30].



Figure 12. Minimum stress on the cast part [30].

# 3. Fatigue Analysis Results and Discussion

Minimum and maximum equivalent stress values, including both components on the main load frame, were calculated once the finite element model was finalized. Considering

the conservative fatigue method, the bedplate was subjected to stress alternation, and the load factors should have been implemented. Table 3 presents the minimum and maximum stress values, enabling the measurement of the mean stress and stress alternation.

**Table 3.** Maximum and minimum stress values on the components [30] (stress values were scaled as a percentage of yield points of materials).

	Cast Part	Welded Frame
$\sigma_{max}$	39%	31.2%
$\sigma_{min}$	31%	30%

The stress values of the bedplate components are shown as a scaled version of the yield point (Table 3). Mean stress values ( $\sigma_m$ ) and alternating stress ( $\sigma_a$ ) levels should be determined by Equations (2) and (3) after evaluating the stress values of finite element analysis.

$$\Delta \sigma = \sigma_{max} - \sigma_{min} \tag{1}$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{2}$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{3}$$

The modified Goodman criteria that contribute to the dynamic safety factor, alternating stress, and mean stress quantities can be determined using Equations (2) and (3).

Stress values were found to vary from average stress to maximum stress, as shown in Table 4. An offset value for the fluctuation of stress is the mean stress value.

**Table 4.** Mean and alternating stress values on both parts [30] (stress values were scaled as percentage of yield points of materials).

	Cast Part	Welded Frame
$\sigma_m$	34.95%	30%
$\sigma_a$	0.3%	0.04%

The material EN-GJS-400-18-LT was selected for the cast component for several properties as this material is generally used in the wind industry. This material is graphite cast iron that offers machinability and increased ductility, with the added advantage of improved, low temperature impact. For the adjusted endurance strength calculations in Equation (4), the load coefficients for the cast portion were calculated.

$$S_e = C_{load} * C_{size} * C_{surf} * C_{temp} * C_{rel} * S_{e'}$$

$$\tag{4}$$

Various factors that determine the endurance of the material are described below. Without the need for coefficients, it can be easily determined for standard Goodman criteria that 0.5  $S_{ut}$  would provide the results for steel-based materials that are not competent enough for fatigue analysis. Accordingly,  $S_e$  is endurance strength and the coefficients were calculated from the mechanical resources, and an adjusted endurance limit was identified.

- Loading Effects: As the loads are generally axial for the study, the stress reduction load factor for the material was taken as  $C_{load} = 0.7$  [29].
- Size Effects: "For length < 8 mm  $C_{size} = 1$ ; for 8 mm < length < 250 mm  $C_{size} = 1.189 * length^{-0.097}$ ; for larger sizes than 250 mm in which this case is suitable for this parameter sizing factor is 0.6" [28].
- Surface Effects: Cast iron may be assigned as  $C_{surf} = 1$  because the effects of a rough surface are dwarfed by its internal discontinuities [28].

- Temperature Effects:  $C_{temp} = 1$  for T < 450 °C [28].
- Reliability Effects:  $C_{rel} = 0.659$  for % 99.999 reliability

The adjusted endurance limit can be calculated with Equation (4) after discussing the relevant information.  $S_{e'}$  is known as 0.5  $S_{ut}$ , which is 200 MPa, from the previous information presented. Consequently, for the adjusted endurance limit of EN-GJS-400-18, the result of the given formula is 55.356 MPa.

After calculating the mandatory requirements determined above, the modified Goodman criteria can be implemented. In order to calculate the dynamic safety factor for the cast component, the necessary stress values can be added as below.

$$\frac{\sigma_{\rm a}}{S_{\rm e}} + \frac{\sigma_{\rm m}}{S_{\rm ut}} = \frac{1}{n} \tag{5}$$

The modified Goodman criteria formula is expressed using alternating stress, mean stress, material endurance maximum, and ultimate material strength. The cast component's dynamic safety factor can be determined via the formulation, represented as n in Equation (5). This equation is used as follows:

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

The calculation's dynamic safety factor is 2.61, which is reasonably safe. The welded component was also adapted to a similar design scheme. The minimum and maximum values for stresses were used for static analysis under various loadings. The composition of the profile component is different from the cast part. Therefore, the modified endurance limit of the material should be determined in order to implement the modified Goodman criteria. The material for the profile components is normalized rolled weldable fine-grained structural steel according to DIN EN 10025-3 [43], commonly used in heavy industry and construction. Since the environment and physics are the same as the cast base, the load factors can be treated as cast component factors. From Equation (4), a modified endurance limit can be determined for the profile component, as given below.

$$S_e = 0.7 \times 0.6 \times 1 \times 1 \times 0.659 \times 275 = 76.1145$$
 MPa

Consequently, in Equation (5), the modified Goodman criterion can be extended to the profile section.  $S_{ut}$  reflects the ultimate strength of the material, which is 550 MPa.  $S'_e = 0.5 * S_{ut}$  yields 275 MPa to estimate the modified endurance limit, and Equation (5) is used as shown below.

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

The dynamic safety factor for the profile component can be determined as 4.34, as shown in this formulation.

#### 4. Manufacturing and Implementation

The manufacturing phase had two stages: production of the cast part and construction of the welded frame.

The cast part of the frame was manufactured with the casting method using EN-GJS-400-18-LT cast iron, a commonly used material in the wind industry due to the elasticity, hardness, and wear resistance properties [41,44]. Since this was a research project and mass production of the frame was not accessible, a lost foam casting mold was prepared for the casting project [45] instead of a wooden mold (Figure 13). The first full-size replica of the frame was produced with CNC using lost foam casting. Then, the lost foam casting mold was buried in sand to pour in previously heated iron. The cooling-down period of the iron takes approximately one week. After cooling down, the mold was opened, and the cast part of the frame was removed. Bedplate connections, tower connections, and

gearbox connections were processed with a CNC router process to finalize the cast part of the hybrid frame. The completed cast part of the hybrid bedplate is presented in Figure 14.

Figure 13. The lost foam casting mold which was prepared for the casting project.



Figure 14. Finalized cast part of the hybrid bedplate.

Quality control of the cast part was performed with the ultrasonic examination setup shown in Figure 15. X-ray testing was applied to inspect casting gaps. This test aimed to examine cracks in the cast iron. Test results indicated there were no cracks, and the part was ready for assembly.

The welded part of the frame was manufactured with an S355J2G3 steel sheet with a thickness of 20 mm. This material is frequently used in the naval industry due to its mechanical strength and easy welding process. The material was ideal for this project for similar reasons. The frame was designed and manufactured with I-shaped profiles that had a slope of five degrees at the surface layer. Laser cutting was used to prepare parts of the steel sheet, and then pieces were connected with welding using the arc welding technique. Once the frame was formed and shaped to broad specifications (Figure 16), heat treatment was performed to remove residual stress from the welded part of the frame.



Figure 15. Quality control of the cast part.



Figure 16. Completed welded part of the hybrid bedplate.

Similar to the cast part of the frame, an ultrasonic examination was performed on the welded part. The test was operated on welded regions to find if any cracks or gaps were formed in the welding process. The tests revealed that the quality of the welded part was satisfactory according to the welding standards EN-ISO 9606-1 [46]. After the testing process was completed, both parts were bolted together to complete the hybrid bedplate manufacturing.

The first step in the implementation was the laying of the turbine foundation. After the foundation was set, the building of the tower was commenced. Tower pieces were manufactured and transported to the site in three pieces (lower, middle, and upper pieces); they were assembled on-site. Mechanical and electrical systems were constructed in the assembly area of the manufacturing facility. The completed nacelle was consequently transferred to the building site. The nacelle was elevated with a crane and attached to the top of the tower. The three blades and hub were transported to the site, assembled on the ground, then craned to the tower, and the connection between the main shaft and hub was completed. Table 5 presents the overall technical specifications of the turbine. A cross-section of the turbine is shown in Figure 17.

Туре	Horizontal Axis Wind Turbine		
Power control	Pitch control		
Electrical connection	Grid connection		
Brake system	Mechanical and dynamic speed pitch control		
Nominal power	500 kW		
Rotor diameter	45 m		
Hub diameter	2.3 m		
Hub weight	9 tons		
Tower-type	3 pieces, steel		
Hub height	55 m		
Nacelle weight	48 tons		

Table 5. Technical properties of the wind turbine.



Figure 17. Cross-section of the wind turbine.

#### 5. Implementation Results and Discussion

In this article, a bedplate fatigue design process was presented. The hybrid bedplate design was manufactured with both lost foam cast and welding structure. After the wind turbine assembly was completed on-site, ICE 61400 standardized tests were performed under various wind conditions. These tests were a zero torque test, an initial wind speed test, a nominal wind speed test, and an over speed test phase. For these tests, acceleration and displacement data were collected from the turbine via accelerometers, displacement sensors, and angle transducers.

The first test phase was the zero torque phase. In this experiment, the wind turbine was allowed to rotate freely. Initially, the wind speed should be low for this testing stage; when wind conditions were favorable, the brakes were released to allow the turbine to turn freely with wind power. In this stage, the turbine did not produce electricity and was not connected to the electrical grid. After initial results indicated the system was functioning without complications, the next testing stage began.

The second phase was the initial wind speed tests. In this stage, a reference value for active power, which was lower than the turbine's full power, was determined. For this project, the active power reference was established to be 15 kW. The reference value was provided to the system while wind speed was 4–5 m/s. A speed of 646.5 rpm was achieved

in the second phase of testing. Similarly, this stage was completed without any problems, and the next test phase was started.

The third phase was the nominal load tests. The aim was to produce full power and transfer this power to the electrical grid. At this stage, the generator had a full load capacity of 500 kW and required 850 rpm angular speed and 12 m/s wind speed to reach full power. Similar to the previous stages, the wind turbine completed the test within specifications without any problems.

Overspeed testing was performed when wind speed was higher than 12 m/s and less than 25 m/s. In this interval, the turbine tries to produce full power using a pitch system to regulate generator speed. In order to maintain angular speed, emergency breaks should not be required. The stage aimed to determine if the turbine can regularly produce 500 kW power and regulate generator speed at 850 rpm when wind speed is greater than 12 m/s. Overspeed tests, as with the previous steps, did not reveal any issues.

Lastly, emergency brakes were examined. If the pitch system does not work accurately or the wind speed is too elevated, emergency brakes are the only system to protect the wind turbine. Emergency brakes were engaged when the turbine was working at full speed. This testing produced impact forces on the turbine parts, and it fatigued the entire turbine. This experiment showed that 5 s was required from a full rotation speed of 850 rpm to entirely stopping blades. The results of these standardized tests can be seen in Table 6.

These experiments did not cause any loading effects or deformity on the bedplate. In the turbine, there is a commercial condition monitoring system that collects data continuously from all available sensors such as accelerometers, displacement sensors, angle transducers, wind speed sensors, and systems reading temperatures of the components. The wind turbine has been active since 2015, and the bedplate has experienced no sudden loading, damage, dynamic wear, or any adverse effects.

	Power Reference	Power Output	Rotation Speed (Generator)	Wind Speed
Zero torque test	0 kW	0 kW	30–60 rpm	1–2 m/s
Initial wind speed test	15 kW	15 kW	646.5 rpm	4–5 m/s
Nominal wind speed test	500 kW	500 kW	850 rpm	12 m/s
Fourth phase	500 kW	500 kW	850 rpm	15–25 m/s

Table 6. Wind turbine on-site experiment results.

# 6. Conclusions

Analytical and numerical calculations were used to optimize fatigue analysis on a 500 kW wind turbine nacelle bedplate. The guidance of modified Goodman fatigue theory was used to determine reasonable dynamic safety factors for both sections independently.

Different engineering applications require different safety factors. A common factor is 1.5 for a wide range of applications. However, different applications can demand an increase or decrease in safety factors. Projects that have pressurized fuselage or building large structures, or projects that are under dynamic loading conditions, require two as a safety factor. Dynamic safety factors are 2.61 and 4.34 for cast and profile components, respectively, and were identified at the end of the fatigue analysis procedure. These values are high enough, indicating that the load frame is safe in terms of fatigue.

The results clearly show that the guidance of the finite element solution was crucial and led to the analytical determination of dynamic safety factors.

Subsequent to manufacturing and implementation, the bedplate has not shown any fatigue signs after standardized tests, and it still has not shown any fatigue as of the time of writing this article. In addition, the overall turbine system is connected to the electrical grid and works at full capacity, producing 500 kW power for the past five years and operating

without complications. This result is a vital sign that the design and analysis process was adequate.

**Author Contributions:** A.S.P. proposed the idea of the conceptual design, conducted the simulations, and aided in manufacturing and testing of the bedplate. M.F.A. completed analytical calculations. K.E. worked on the validity and presentation of the approach. M.F.A. and K.E. acquired the funding for the research. All authors contributed to the preparation the manuscript and improved the language. All authors have read and agreed to the published version of the manuscript.

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