Dynamic Analysis of Floating Offshore Wind Turbines Under Extreme Operational Conditions

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DYNAMIC ANALYSIS OF FLOATING OFFSHORE WIND TURBINES UNDER EXTREME OPERATIONAL CONDITIONS

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ABSTRACT

Non-renewable energy sources such as fossil fuels have been the primary source of power generation around the world for decades. With these non-renewable energy sources rapidly depleting, the focus has switched to renewable, more environmentally friendly sources of energy, including wind energy. According to the Offshore Wind Market Report 2022, the U.S. has approximately 42 MW of offshore wind energy in operation, with 932 MW under construction and 18,581 MW in the permitting phase (Musial et al., 2022). Much of this potential comes from floating offshore wind turbines (FOWT) in waters greater than 60m of depth, where the winds are more consistent, and the turbines are larger with greater power generation potential. While researchers and industry professionals have identified the potential that FOWT can generate, past research has mainly focused on the response and optimization of the mooring lines and platforms under different loading conditions. Few studies have focused on the response of the turbine tower, specifically under extreme operating conditions. This study analyzed the behavior of a FOWT tower under extreme operating conditions. To do this, a 15 MW semi-submersible turbine was simulated at a location in the Gulf of Maine. Climate data was obtained from NOAA buoy data and extrapolated to represent conditions that the turbine would face in extreme operating conditions for a 50-year storm. These extreme conditions were used in conjunction with the aero-hydro-servo-elastic code, Horizontal Axis Wind Turbine Simulation Code 2nd Generation (HAWC2) from the Technical University of Denmark (DTU). A coupled time domain wind-wave analysis was used with a combination of different wind and wave inputs to determine how the turbine tower reacts to extreme loading. The parked condition load cases with 50-year extreme climate condition inputs were used to determine the resulting moments and stresses on the turbine tower. Results show that tower base yielding is the controlling factor in the design of a FOWT tower when compared to shear and fatigue stresses. In addition, an uncoupled time domain analysis was compared to the coupled analysis and showed that the uncoupled analysis overpredicts stresses in the tower base. While an uncoupled analysis may be suitable for preliminary design, it is important for final design to perform a coupled analysis for most accurate results. Lastly a sensitivity study was completed to analyze how the tower base reacts to changes in wind speed and wave height. It was concluded that a linear relationship between wind speed and average stress and wave height and average stress. However, changes in wind speed and wave height do not appear to have a significant effect on changes in design normal stress.
CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

1.1 Basics of FOWT

1.1.1 Definition of FOWT Components

A floating offshore wind turbine (FOWT) consists of 5 main bodies: the tower, turbine blades, the rotor-nacelle assembly system (RNA), the turbine control system, and the floating platform and mooring lines. Roga et al. (2022) describes the components of a wind turbine in Figure 1. The main structural bodies of a FOWT are the tower and blades in the RNA. The tower is typically constructed from steel, concrete or a steel lattice and works to connect the RNA to the turbine foundation (Roga et al., 2022). The blades are also constructed of a composite material and turn the wind potential energy into mechanical energy through the RNA. The RNA holds the mechanical parts of the FOWT and consists of the drivetrain, and hub (Subbulakshmi et al., 2022). This mechanism also consists of mechanical components of the turbine that make it run efficiently, including the gearbox, generator, and breaks.

![Wind Turbine Components](image)
The turbine control system is also typically housed in the RNA and helps to orientate and control the turbine to ensure maximum power is created. A wind turbine operates at a rated speed where the rated power is created. Before the wind reaches this speed, the controller is used to control the amount of torque in the rotor, for maximum power output. Once the rated speed is reached and exceeded, the controller is used to control the pitch of the turbine to maintain the rated power at a constant value (Karimirad and Moan, 2012). In the event that a storm occurs, or the wind speed exceeds the cut-out power, the turbine is shut off using mechanical breaks to prevent damage and the wind turbine goes into standstill or idling. This control system can be seen in Figure 1 which details the RNA and the control system within it. The hub links the nacelle to the turbine blades and transmits all loading that the blades generate to the RNA (Roga et al., 2022).

Also pictured in Figure 1 are mooring lines and a floating platform, specific to a FOWT. Foundations are typically comprised of floating substructures that carry dead load, wind load, upthrust, overturning, bending moments, and long-term cyclic variations (Roga et al.). These floating substructures are anchored to the seabed using mooring lines. There are 2 types of mooring lines, catenary and taut, that maintain the position of the floating platform and provide resistance against drifting and environmental loading (Bashetty and Ozcelik, 2021).

When researching and analyzing a FOWT, it is important to keep in mind the relative magnitude of the structure. For example, Jonkman et al. (2009) estimates that a single 5 MW wind turbine can power 1,250 average American homes annually. If this is scaled, the 15 MW offshore turbine used in this study can power around 5,000 average American homes annually. Figure 2 depicts the relative size of a different wind turbines in comparison to well-known structures. As seen, all wind turbines, including on shore and offshore, are larger than the Statue of Liberty while the 260-meter diameter rotor can more closely be compared to the height of the Eiffel Tower (Golston et al., 2019).
It is important to note, that Figure 2 mainly shows land-based and fixed bottom offshore wind turbines. This research revolves around FOWT, which are generally larger in power output and scale. They closely resemble the 260-meter turbine pictured in Figure 2 but are mounted on a floating platform on the water surface.

1.1.2 Floating Platforms

FOWT mainly have 4 different support structures, all adapted from offshore oil and gas rigs but modified to incorporate a wind turbine (Micallef and Rezaeiha, 2021). Figure 3 was adapted from Jahani, Langlois, and Afagh (2022) and shows all platforms that have been designed for FOWT. From left to right the substructures depicted are barge, semi-submersible, tension-leg platform (TLP), and 2 variations of a spar buoy.
The barge platform is the least used of the 4 platform types due to its cost and large wave-induced motions. The platform allows a less complex and lower cost option to other platforms; however, the disadvantages usually outweigh the cost (Bashetty and Ozcelik, 2021). A barge platform is stabilized mainly due to buoyancy considerations while some ballast stabilization is necessary (Subbulakshmi et al., 2022). For the most part, barge platforms have been abandoned as substructures for FOWT because of their large motion characteristics which do not meet the requirements of many design codes (Aubault and Roddier, 2013).

A similar and more common platform is the semi-submersible platform. Semi-submersible platforms make 79.6% of FOW projects under construction currently and the majority of FOW projects proposed in the future (Musial et al., 2022). This platform type consists of 3 or more columns located at a distance away from the turbine tower and uses buoyancy and ballast stabilization (Subbulakshmi et al., 2022). Semi-submersibles have many advantages including low construction, operation, and maintenance costs because they are able to be towed out to sea with little installation offshore. However, similar to barge type, semi-submersibles have a high sensitivity to wave motions and have large masses making them complex structures to design. In addition, they use catenary mooring lines for stabilization as opposed to
the taut mooring lines in barge and tension leg platforms (Bashetty and Ozcelik, 2021). Semi-submersible platforms are typically deployed in water depths around 50-120 meter or deeper and have a low draft requirement compared to other platforms (Jahani, Langlois, and Afagh, 2022).

The tension-leg platform (TLP) is pictured third from the right in Figure 3. This substructure uses mooring stabilization with vertically moored lines in tension. It is comprised of a substructure of buoyant pontoons and columns connected to a mooring system at the top of the column (ABS Guide for Building and Classing Floating Wind Turbines, 2020). One advantage of the TLP are that operation and maintenance are simpler. Furthermore, there is lower fatigue and wind induced motion on the turbine because of the pre-tensioned mooring lines and the small platform mass (Bashetty and Ozcelik, 2021). However, construction and installation are more difficult and the fatigue on the mooring lines tends to be greater because they are taut as opposed to catenary (Aubault and Roddier, 2013).

Lastly, the spar platform is seen as a cylindrical shape below the surface of the water that is supporting the tower and moored to the sea floor by catenary mooring lines (ABS Guide for Building and Classing Floating Wind Turbines, 2020). Two variations of the spar platform are depicted in Figure 3. This substructure uses buoyancy stabilization that comes with its deep drafts and ballast in the hull, which create a low center of gravity. This design is the second most common behind the semi-submersible because of its simplicity and inexpensive design (Roga et al., 2022). Additionally, some other advantages are the spar platform has less wave induced motion and higher stability (Bashetty and Ozcelik, 2021). Like all platforms, the spar has multiple disadvantages including the weight of the substructure, and the construction and installation. Because this platform has such a deep draft it must be used in deep waters and towed to sea horizontal before being installed. This typically requires additional equipment and in turn additional costs (Aubault and Roddier, 2013).
1.2 Current Status and Future Trends in Offshore Wind

1.2.1 Current Status of Global Offshore Wind Industry

Over the past 10 years, the push for more renewable energy sources to replace fossil fuels has led to a dramatic increase in wind energy systems around the globe. As new countries enter the offshore wind market and other countries continue to grow their capacity, the global potential has exponentially increased. According to the 2022 Offshore Wind Market Report, more than 17,000 MW of new capacity was installed around the globe in 2021, bringing the global cumulative capacity to 50,623 MW. This is distributed among 254 operating projects (Musial et al., 2022). This cumulative capacity includes both floating and fixed bottom wind, although floating wind represents a much smaller percentage currently.

![Image: Current Global Cumulative Capacity](image)

*Figure 4: Current Global Cumulative Capacity (Musial et al. 2022)*

The United Kingdom and Germany have been pioneers in the offshore wind industry for the past decade and lead the European offshore wind market which makes up about 55.1% of the total global wind energy capacity (Musial et al., 2022). Most recently, China surpassed The UK and Germany to become the largest deployer of offshore wind energy and installing 13,790 MW in 2021 alone. This is more capacity installed in one year than the entire world has installed in previous years (Musial et al., 2022).
Floating offshore wind (FOW) is a relatively new industry that has taken off in recent years and has just 10 projects in operation around the globe. These projects are located in Europe and Asia with 3 that came online within the last year adding 56.6 MW of FOW capacity. This brings the total FOW capacity to 123.4 MW (Musial et al., 2022). It is predicted that FOW will become a large industry in the next decade with at least 8,000 MW of new floating capacity already announced (Musial et al., 2022). It is important to note that FOW capacity does not include the many research and experimental projects that are in operation because they are not large enough, do not contribute to the market, or are not connected to the grid. As technology and wind energy demand continues to grow, these experimental projects will lead to more efficient and larger commercial models will be produced.

1.2.2 Current Status of U.S. Offshore Wind Industry

The United States has been slower to pick up on offshore wind energy systems than Asian and European countries. Specifically in the FOW industry, the United States has yet to construct any FOW farms, with one prediction showing Maine and California will be the only 2 states to develop floating wind technology by 2030 (Musial et al., 2022). However, the United States has multiple fixed bottom wind farms in operation and currently 42 MW of offshore wind in operation.

According to the 2022 Offshore Wind Market Report, the U.S. has a potential generation capacity of 40,000 MW, representing a 13.5% growth from projected potential in the 2021 report. This includes installed and operating projects (42 MW), projects currently under construction (932 MW), projects in the permitting phase (18,581 MW), projects in the site control phase (15,996 MW), and approved unleased areas (4,532 MW) (Musial et al., 2022). This is depicted in Figure 5 which shows each states projected capacity broken down into which phase. The majority of potential development from now until 2030 in the U.S. is shared amongst ten states, eight of which are on the east coast. Figure 5 shows that the only two states with fully operating offshore wind farms are Virginia and Rhode Island. Yet, New York and Massachusetts have the most capacity under construction as of May 2022.
In total, the U.S. has 56 sites where there is potential for offshore wind development, 31 of these sites are in the North Atlantic, 1 is in the Great Lakes, 17 are in the South Atlantic and Gulf of Mexico, and 7 are located in the Pacific. Most of these sites, specifically in the Pacific, lie in water greater than 60 meters deep where floating substructures are necessary and 8 of these sites were newly auctioned in 2022 (Musial et al., 2022).

While the United States has a large potential capacity to become a global leader in the offshore wind industry, there are also multiple challenges that the U.S faces making this potential a reality. Currently, the offshore wind market is driven by state legislation, not federal policies, leaving it up to state governments to be the drivers in pushing for renewables and offshore wind development. Furthermore, port infrastructure and the supply chain in the U.S. is not up to speed with the technology and demand of offshore wind. This makes transportation, installation, and connection of new offshore wind projects difficult to do (Musial et al., 2022). Nevertheless, with the Bipartisan Infrastructure Law that was put into law in 2021, the federal government has allocated $17 billion to modernizing port infrastructure and waterways (Musial et al., 2022). This will help to accommodate large commercial scale wind turbines now and, in the future, and help push forward offshore wind technology in the U.S.
1.2.3 Industry Projection and a Need for Floating

As new offshore wind technology develops and the need for renewables becomes more urgent, the global industry will continue to grow exponentially as it has in the last decade. According to the Offshore Wind Market Report 2022, globally, there is a projected 177,462 MW of offshore wind technology announced through 2027, 8,362 MW of this is FOW (Musial et al., 2022). China, the UK, Germany, and the United States are all predicted to be key players in the development of offshore wind technology. Projections show that the European market will continue to grow at the same rate that it is today. Asian and the United States markets are predicted to grow exponentially as they continue to become larger contributors to the industry, as seen in Figure 6 (Musial et al., 2022).

![Figure 6: Estimated Cumulative Capacity through 2027 (Musial et al. 2022)](image)

The growth of the offshore wind industry in the future can be attributed to multiple factors including the decline in costs, maturing of the supply chain, and technological innovation of larger capacity turbines and deep-water sites.

Currently, fixed bottom turbines such as the monopile, are the most common commercially operating offshore wind turbine. However, fixed bottom offshore wind is only feasible in water depths less than 60 meters. Once the water becomes deeper, a floating foundation is more economical to use. Additionally, offshore wind must coexist with shipping and other sea routes. Based on Soares-Ramos et al. (2020), this
means that only 4% of areas within 10 km from shore and 10% of areas between 30 km and 50 km to shore are available for offshore wind farms (Soares-Ramos et al., 2020). Areas further from shore become more open to wind development. In the United States, around 80% off offshore wind resources exist in areas where the water depth is greater than 60 meters and floating technology is required (Figure 7). This means that in the future, FOW will become a necessity for the wind industry to grow.

Figure 7: Potential Offshore Wind Resources in the United States (Musial, 2021)

There are many benefits to the development of FOW technology that also make it an attractive market. Further from the coast, the wind speeds become steadier with less turbulence, there is the potential for larger wind farm areas and greater capacities, and there are less visual and acoustic impacts on coastal towns (Soares-Ramos et al., 2020).

Because floating technology is such a new field, it comes with certain challenges as well. A main concern that must be addressed with FOWT, is the more severe climate conditions. Wind speeds tend to increase further from the coast and while this is beneficial for the power production of FOWT, it becomes an issue for durability. High winds coupled with wave sensitivity and mooring challenges result in a very complex structure that is subjected to more corrosion and stress conditions that typical land based and fixed bottom wind turbines (McMorland et al., 2022). The cost of floating technology tends to be greater due to the
remoteness of the size and more difficult installation and maintenance as well (Soares-Ramos et al., 2020). Nonetheless, as the market continue to grow and technology advances, FOWT are expected to be vital for the future of the wind energy market.

1.3 Literature Review and Research Gaps

In recent years, the research community has become focused on the development and optimization of offshore wind technology. While the industry is still relatively new, FOWT research has begun to divide into multiple areas of focus including hydrodynamics, aerodynamics, aeroelasticity, structures, control, materials, and manufacturing and installation (Micallef and Rezaeiha, 2021). Literature in the structural area has primarily focused on validation and comparison of reference turbine models and simulation codes. A focus on simplified methods and performance of different wind turbine models has been a large part of research in the past decade because of the time-consuming, complex simulations that need to be conducted for coupled analysis. Specifically, the fatigue performance of FOWT is of main concern to researchers because it often appears to be a controlling factor in FOWT design. On top of that, the main subject of many research studies is how the FOWT platform responds to the coupled motion of wind and wave action. The following section detail relevant studies previously done on FOWT.

1.3.1 Model and Code Comparison

OpenFAST, HAWC2, Simo-Riflex, OrcaFlex and Bladed are all common codes seen in literature across the industry. With multiple codes, each with different assumptions, the need for validation of these codes is imperative to the development of new technology and research. Multiple studies have been conducted to analyze how different software perform under a variety of loading conditions to ensure that the software presents good agreement and performance.

Al-Solihat and Nahon (2018) developed a nonlinear 3D flexible multibody dynamic model for studying the dynamics of the NREL 5 MW wind turbine with the OC3 Hywind spar FOWT. The platform, nacelle, and rotor were modeled as rigid bodies subjected to multiple loads and the tower was modeled as a 3D
flexible Euler-Bernoulli beam. The equations of motion considered hydrodynamic, hydrostatic, mooring, and aerodynamic loading and were solved symbolically for comparison with design codes. The dynamic model was found to be in excellent agreement with popular FOWT tools, HAWC2, OpenFAST, and Bladed. An important note from this paper concludes that the flexible tower model had more damping when compared to the rigid tower. This is due to the internal structural damping of the tower that is induced by flexible motion.

Karimirad (2013) uses the NREL 5 MW wind turbine with a spar-type floating platform to perform a dynamic analysis using Simo-Riflex, HAWC2, and OpenFAST. Load cases for survival and operational conditions were tested for a code-to-code comparison. The hydrodynamics were compared using wave-only cases while the aerodynamics were compared using irregular wave and steady wind. Results of the wave-only analysis showed that damping of the mooring lines does not have a significant effect on the motion response of the structure but it crucial in the mooring line tension response. The tower platform interface forces and moments and the blade root forces and moments were compared for wind-wave analysis and showed good agreement between codes, especially for the operational load cases where the sea state is moderate. However, it was observed that the differences between codes increased as the significant wave height increased. This can be attributed to the increasing nonlinearities involved as wave heights get larger.

Rinker et al. (2020) compares the response of the IEA 15 MW turbine using OpenFAST and HAWC2. Both modeling simulations are widely used but have slight differences in application of loading and structural parameters. For example, OpenFAST and HAWC2 both have different structural modeling for turbine blade structures that result in the same high fidelity. OpenFAST uses Euler-Bernoulli beam theory or geometrically exact beam theory “with Legendre spectral finite elements”. Whereas HAWC2 uses prismatic Timoshenko beam elements with the option of no torsion, torsion and bend-twist-coupled modeling. Therefore, it is essential to compare them to ensure good agreement and accurate simulations. The monopile 15 MW wind turbine was used with hydrodynamics and monopile flexibility disabled in both simulations as the focus of this research was on the aeroelastic response. Results showed good
agreement between the models with slight differences in the aerodynamic thrust for the high-fidelity structural models.

Kim et al. (2022) completed a code-to-code comparison of the IEA 15 MW wind turbine with the UMaine semi-submersible platform using three different aero-hydro-servo-elastic simulation tools, HAWC2, DIEGO, and DLW. Climate data was obtained from a site off the coast of France and multiple load cases were run. First, modal results were compared for the 3 codes and show agreement for the first model of the floating system. A wave only load case was then simulated resulting in excellent agreement for peak tower bottom bending and surge motion. This was followed by an irregular wave load simulation where all 6 degrees of freedom showed good agreement between codes with minor discrepancies in surge and pitch responses. The biggest differences appeared to be in the mooring line tension forces where there were significant differences in the standard deviation for mooring line 1 between models. Two different turbulent wind cases were also considered. The tower bottom fore-aft bending moment was observed to agree between all codes as well as the platform motion for all degrees of freedom. Lastly, the parked load case for irregular wave and turbulent wind was simulated. Forces in the tower bottom showed good agreement with small differences in mean values, but there were significant differences in platform sway, roll, and yaw dynamics that require further investigation.

Chen et al. (2017) explains different approaches for modeling FOWT and the theory behind each. They use the NREL 5 MW with the OC4 semi-submersible platform to compare single-rigid-body, corrected-single-rigid-body, multi-rigid-body, and multi-rigid-flexible-body models for accuracy and computational time. Combined wind and irregular wave simulations with a duration of 3600 seconds were conducted to evaluate the time-cost followed by a comparison of results from each model. As expected, the multi-rigid-flexible-body model was the most accurate yet most time consuming. The Multi-rigid-body and multi-rigid-flexible-body models were found to be acceptable in most cases, however, elastic effects from flexible bodies are not accounted for. Single-rigid body models are the least complex and have the smallest computational time but have limitations on the degrees of freedom, aeroelastic effects, etc.
Manolas et al. (2020) examines a fully coupled hydro-servo-aero-elastic simulation on the NREL 5 MW reference wind turbine with the OC4 phase II semi-submersible platform and the OC3 spar buoy platform. The model was verified using a comparison of the natural frequencies of the coupled FOWT in Orcaflex, HAWC2, Bladed, OpenFAST, and hGAST. Then, a time domain simulation of platform motion is performed for all codes and results show good agreement for motion in all directions. Mooring tension and axial forces are then compared and show identical mean values of tension but include a phase shift for codes that use dynamic mooring lines as opposed to quasi-static systems. While this observation does not affect the main FOWT, it is crucial to consider when designing mooring lines and foundations. The fore-aft and yawing moments in the tower base are also compared and show differences in the mean value of tower yaw moment for codes that use finite element modeling compared to modal-based codes and higher amplitude moments are found for codes using Morison’s equation.

Bachynski et al. (2014) compare results of numerical simulations from 4 floating platforms with a 5 MW turbine to determine the effect that wind-wave misalignment as on FOWT. The simulations were modeled using SIMO-Riflex-AeroDyn and the axial and shear stress were calculated using textbook equations. Using the stress time history and the rainflow counting technique, the fatigue damage was estimated for each combination of wind-wave misalignment. It was determined that there was increased platform motions with misaligned conditions, but the most severe load case was found when wind and waves were aligned. An important observation was that the maximum stress damage in the tower due to axial stresses followed the wave direction for the spar and TLP but the wind direction for the semi-submersibles.

1.3.2 Fatigue Analysis

In addition to code-to-code comparison and model comparison, fatigue analysis is at the forefront of much FOWT research. Because FOWT are subject to cyclical wind and wave loading and experience a variety of conditions, fatigue is often a controlling factor in design.

Chen and Basu (2018) researched the effects of wave-current interaction on the fatigue analysis of a spar type FOWT. A nonlinear mooring hydrodynamic model was used to consider the current effects and nonlinearity. This was coupled with a dynamic model of the NREL 5MW baseline turbine with the OC3-
Hywind spar platform. Three load cases were used in the analysis: waves with no current, wave and current without interaction, and wave and current with interaction. It was determined that the current and wave-current interaction have a significant effect on the FOWT tower and cables but an insignificant effect on the blade response. The cable tension was the most affected by the current and not including these interactions can lead to an overestimation of cable fatigue life.

Li and Zhang (2020) implement a C-vine copula model and surrogate model to reduce the computational costs of performing a long-term fatigue damage assessment on a FOWT. The NREL 5-MW reference wind turbine coupled with the OC3-Hywind spar buoy platform was simulated using OpenFAST and realistic climate conditions measured off the south coast of Alaska. The normal and shear stress time histories acting on the tower base, tower top, and mooring lines were calculated. Then an artificial neural network and Kringing model were used to predict the fatigue response for different environmental conditions. It was concluded that both models showed good accuracy in prediction of fatigue. They showed that short-term fatigue results are more sensitive to changes in wind speed and direction. At locations directly along the dominant wave direction, more fatigue damage is observed in both the tower and the mooring lines. Therefore, orientation of the turbine so that the mooring lines are not directly in line with the dominant wave direction is important. Additionally, wind loading has the greatest effect on the tower top, and it is important to strengthen areas of the tower facing both the dominant wave and wind directions.

Song et al. (2022) considered wind and wave conditions from a location in the South China Sea where typhoons are a common occurrence. They use C-vine copula method to develop a full probabilistic model of long-term environmental conditions and investigate the fatigue of FOWT. Environmental conditions were divided into summer, winter, and typhoon data. A statistical analysis was performed then applied to the NREL 5 MW reference wind turbine with the OC3-Hywind spar platform. The focus of the results was on the fatigue life of the blade and the blade root stress due to the flap-wise moment. Results showed that the number of selected load conditions used for fatigue analysis had a large effect on the damage accumulation.
Kvittem and Moan (2014) used Simo-Riflex-AeroDyn software to model the NREL 5 MW wind turbine fully coupled with a semi-submersible FOWT in the time domain. Nominal stress was analyzed for a fatigue assessment to find the simulation duration and number of random realizations to accurately capture the statistical uncertainty of joint wind-wave conditions. It was concluded that 1-hour simulations were long enough to find important fatigue results with high sensitivity. In addition, the fatigue damage in the tower was found to be unacceptable because of the resonant motion in the first bending frequency. This was caused by the blade passing frequency and the pitch motion of the platform. Another important observation was that misaligned wind and waves result in less fatigue damage than unidirectional wind-waves, however the section of the platform that receives the most fatigue damage is dependent on the directionality of the waves.

Müller and Cheng (2017) use the DTU 10 MW reference wind turbine with a semi-submersible platform to perform a fatigue analysis using realistic climate data from the Gulf of Maine. They use a Monte-Carlo based sampling approach to deal with large variations in environmental condition which results in 16,200 coupled time-domain simulations performed using OpenFAST. Results show that around 200 simulations are necessary for 10% uncertainty in lifetime fatigue damage and that underestimation of damage is more probable that over estimation when a small number of samples is used.

1.3.3 Research Gaps

As described in the sections above, many studies have been conducted in the past decade on the performance of FOWT under a variety of climate conditions. Model-to-model and code-to-code comparison are important studies to ensure progression of the research community and uniformity among results. Fatigue is also of ultimate concern when considering the performance of FOWT because of the loading experienced due to wind and waves. However, past research has mainly focused on the platform response and optimization under fatigue loading. Few studies have focused on the response of the tower, specifically for fatigue and extreme operational conditions. In addition, the most common turbine used presently in research is the NREL 5 MW turbine paired with a spar or semi-submersible tower. While this is the most common FOWT in operation today, future outlook has predicted that FOWT will grow to be
between 10 MW and 20 MW (Gaertner et al., 2020). It is important for the progression of research and the industry to focus on larger turbines in research.

1.4 Research Scope

The research presented in this paper utilizes the IEA 15 MW FOWT model with a semi-submersible platform from Allen et al. (2020) to obtain time-domain response of the turbine tower under extreme loading conditions. Estimation of extreme loads follows methods presented in Gómez et al. (2015) which uses the Weibull Distribution and Power Law Profiles to determine site specific climate characteristics based on data obtained from NOAA Buoy Station 44005 in the Gulf of Maine. Parked load cases based on IEC 61400-3 design requirements were used for analysis, specifically strength DLC 6.1. One-hundred and eight, 600 second, coupled wind-wave simulations were run using the aero-servo-hydro-elastic code HAWC2 and the time history results of the tower were obtained for analysis. An analysis of average and maximum design load case stress conditions was performed followed by a fatigue analysis. An uncoupled wind analysis and an uncoupled wave analysis were then executed to compare with coupled response and determine level of accuracy of uncoupled analyses. Lastly, a sensitivity analysis using +5%, +10%, and +15% wind speed and wave heights, was completed for the model to test the responsiveness to changes in wind and wave inputs.

1.5 Summary of Chapters

Chapter 1 provided a background on the current status of FOWT research abroad and in the United States and describes where the offshore wind industry is headed. It described research already completed and showed the significant literature gap in the study of FOWT tower under extreme and fatigue conditions as well as the need for more studies using larger capacity wind turbines. Chapter 2 aims to provide more background on how FOWT perform, loading applied to FOWT and the significance of fatigue analysis. Chapter 3 outlines the model that was chosen for this study including the turbine capacity, platform, and
the role of mooring lines in analysis. Chapter 4 describes the analysis approach taken, including a detailed description of the software used and standards for design of FOWT. Chapter 5 gives an in-depth overview of the climate conditions at the chosen site, including extreme conditions. Chapter 6 analyzes results obtained from the simulations. Chapter 7 draws conclusions from the results and provides a summary of the research done in this study. Furthermore, it gives a brief description of ideas for continuation of this research.
CHAPTER 2: FOWT DYNAMICS AND ANALYSIS

This chapter summarizes loading that a FOWT will experience in its lifetime and what assumptions and equations are used to apply this loading. It briefly discusses how these loads are modeled in programs and how to perform fatigue analysis, uncoupled, partially coupled, and fully coupled analyses.

2.1 FOWT Loading

A FOWT must be able to withstand a variety of loading throughout its lifetime. This loading can be broken into hydrostatics and hydrodynamic, aerodynamics and wind loading, structural dynamics and gravity loads, and mooring loads. Figure 8 below, adapted from Bashetty and Ozcelik (2021) and Manolas et al. (2020) provides a detailed overview of loading that a FOWT will experience during its lifetime including where it is applied.

Figure 8: FOWT Applied Loading
Together these dynamic forces create the equation of motion for the platform and wind turbine coupled system which can be given by:

\[ [M + A]\ddot{x} + [C]\dot{x} + [K]x = F_A + F_{HD} + F_B + F_M + F_w, \]  

[Eq. 1]

M is the generalized inertia matrix with mass and moment of inertia, A is the added inertia matrix, C is the damping matrix, K is the stiffness matrix, \( F_A \) is the aerodynamic force, \( F_{HD} \) is the hydrodynamic force, \( F_B \) is the hydrostatic force or buoyancy, \( F_w \) is the wind shear force and \( F_M \) is the mooring force (Bashetty and Ozcelik, 2021). In the following subsections, each external loading will be described in depth including assumptions necessary and modeling application.

### 2.1.1 Hydrodynamic and Hydrostatic Loading

A FOWT platform is subjected to hydrodynamic and hydrostatic loading from wave motion, currents, and buoyancy. Hydrodynamic forces can be modeled in multiple ways with differing complexity based on the chosen method and wave theory.

The least complex modeling method uses Morison’s equation, a semi-empirical equation, to calculate the hydrodynamic load acting on the floating platform (Subbulakshmi et al., 2020). Morison’s equation is given by:

\[ F_{HD} = \frac{\pi D^2}{4} \rho \dot{u} + \frac{\pi D^2}{4} \rho C_A(\dot{u} - \dot{v}) + \frac{1}{2} \rho C_D D(u - v) |u - v|, \]  

[Eq. 2]

\( F_{HD} \) is the total hydrodynamic force, \( C_D \) and \( C_A \) are drag and added mass coefficients, \( u \) and \( \dot{u} \) are the water particle velocity and acceleration and \( v \) and \( \dot{v} \) are the floating platform velocity and acceleration, \( D \) is the diameter of the floating platform, and \( \rho \) is the density of water. (Subbulakshmi et al., 2020).

Morison’s equations can be more simply stated as the sum of the Froude-Krylov force, the water added mass, and the drag force on the object. Froude-Krylov part of the equation accounts for the unsteady pressure field created by undisturbed waves and the water added mass term accounts for the inertia forces from moving the displaced water (DTU Wind Energy, 2018). The coefficients \( C_D \) and \( C_A \) are dependent on the surface roughness and Reynold’s Number. Morison’s equation is typically applied to slender bodies that may be flexible and accounts for wave excitation, diffraction, and hydrodynamics (Manolas et
al. 2020). However, Morison’s equation is the least complex and subject to calibration of the model, introducing a level of uncertainty. The equation further assumes that the waves are not affected by the motion of the platform and current forces are not included.

The second most common method of calculating hydrodynamic forces is using computational fluid dynamics (CFD). CFD is a more complex method that accounts for viscous, diffraction, and radiation effects using the Navier-Stokes equation. This method can “accurately capture free surface effects but takes the most computational time and effort” (Subbulakshmi et al., 2020). It is able to solve nonlinear problems associated with extreme wave events and complex flow patterns (Otter et al., 2021).

The buoyancy force is considered the hydrostatic loading ($F_B$). In the simplest form, is calculated using Archimedes’ Principle and volume of FOWT platform submerged in water. To account for the distribution of the buoyancy force over the FOWT platform, often times software codes will use the integral of external water pressure on the submerged platform (DTU Wind Energy, 2018). This is used because of the increase in static pressure with water depth. With slender members, deeper parts will experience a greater buoyancy force.

### 2.1.2 Aerodynamics and Wind Loading

Static and Dynamic Loading applied to a FOWT from wind can be created directly from the wind such as the wind shear or indirectly created by the wind such as aerodynamic loads.

Aerodynamic loading is caused by the wind spinning the turbine blades and airflow through the rotor as it moves. It is determined using the mean wind speed and turbulence, rotor rotational speed, air density, and aerodynamic shapes of the blades. Aerodynamic loads are calculated typically in two different ways with differing computational complexity.

The simplest and most used method is blade element momentum theory (BEM). BEM assumes that the blades are divided into small discrete elements that act as 2-D airfoils and do not depend on the surrounding elements. This means the aerodynamic loading of the blades is dependent on the lift and drag coefficients of the airfoil shape. Each 2-D airfoils force is calculated, and the sum of all 2-D airfoil forces
is the total force and torque on that blade (Subbulakshmi et al., 2020). The ABS Guide for Building and Classifying Floating Offshore Wind Turbines defines the rotor thrust force by:

\[ F_{\text{thrust}} = \left( \frac{\rho a}{2} \right) C_T A_{\text{thrust}} V_{\text{hub}}^2, \quad \text{[Eq. 3]} \]

where \( F_{\text{thrust}} \) is the rotor thrust load, \( \rho a \) is the mass density of air, \( C_T \) is the thrust coefficient, \( A_{\text{thrust}} \) is the swept area of the blades, and \( V_{\text{hub}} \) is the 10-minute average wind speed at the hub height. This force is generated by the wind component perpendicular to the direction of blade motion. (ABS Guide for Building and Classifying Floating Offshore Wind Turbines, 2020). Integrating \( F_{\text{thrust}} \) along the whole length of the blade will result in the total thrust on that rotor blade and adding \( F_{\text{thrust}} \) from all 3 blades results in the total aerodynamic thrust for on the turbine.

BEM is considered one of the most used methods of calculating aerodynamic loads because of its ease and good accuracy. However, because of its relative simplicity, BEM makes specific assumptions that must be considered. For example, BEM assumes uniform thrust and induction over a blade element. BEM alone cannot account for low rotational speeds and the flow separation that takes place nor can it account for 3D flow across various rotor radial elements, which can be extensive in FOWT (Micallef and Rezaeiha, 2021). Using BEM with correction models such as dynamic stall, tip loss correction, yaw correction, and wake stall correction models is a good way to substitute for the assumptions and create a more accurate model (Subbulakshmi et al., 2020).

Most complex method of calculating aerodynamic loading is computational fluid dynamics (CFD).

Similar to hydrodynamics loading, the Navier-Stokes equation is most used to evaluate the nonlinear aerodynamic problem by treating air as a fluid when CFD is chosen as the method of analysis. However, as previously stated, CFD takes a large amount of computational time and effort so often BEM is used with correction models instead.

Wind can also create direct forces on the FOWT in the form of wind shear. This is a direct force caused by the pressure that a wind speed causes normal to surfaces. It is calculated using the equation:

\[ F_w = \left( \frac{\rho a}{2} \right) C_s A_{\text{wind}} V_{\text{wind}}^2, \quad \text{[Eq. 4]} \]
where $F_w$ is the steady wind force, $\rho_a$ is the mass density of air, $C_s$ is the shape coefficient, $A_{\text{wind}}$ projected area on a plane normal to the direction of the considered force, and $V_{\text{wind}}$ is the 1-minute average wind speed at a given level above sea level (ABS Guide for Building and Classifying Floating Offshore Wind Turbines, 2020). The wind speed in this equation varies with height, creating a wind shear profile that increases exponentially as the height increases.

### 2.1.3 Mooring Line Loads

Lastly, the mooring line forces must be included in the dynamics of FOWT. Mooring line tensions create a restraining force that prevents the floating platform from drifting away due to wind, wave, and current forces. Depending on the direction and magnitude of wind and wave forces, the tension in the mooring lines will change and therefore must be included in the dynamic analysis (Bashetty and Ozcelik 2021). The most common way to include mooring line forces in a model is by creating a separate model of the mooring lines and implementing them as external applied forces and moments.

### 2.2 Structural Modeling

The most common way of modeling the complete system of a FOWT is using finite element models (FEM) that incorporate seabed interactions, elasticity, bending stiffness, torsional stiffness, and the inertia and damping forces for each component (Subbulakshmi et al. 2022). Using FEM based solvers, the full dynamic system of equations can be applied to the structure to get realistic representation. Many simulations model the blades and tower as flexible linear beam elements that deform in response to wind and wave loading. It is important to include nonlinear effects and damping of the tower and blades as well.

In contrast, the nacelle and hub/drivetrain, which includes the turbine control system, are typically shown as rigid bodies connected with flexible joints using a lumped mass model “with linear stiffness and damping connection” (Subbulakshmi et al., 2020). Similarly, the substructure, floating platform, and mooring lines can be modeled as a rigid body system with three degrees of freedom, three in rotation and
As stated above, mooring lines can be incorporated directly into the platform body or as externally applied forces. Specific modeling techniques used in the software chosen for this research are described further in Chapter 4.

2.3 Fatigue Analysis

Fatigue, in terms of structural engineering, is the application of cyclic loading on a structure that creates damage over time leading to failure. Typically, a small crack will occur, and load fluctuations will lead to crack propagation until failure occurs. Fatigue analysis is essential in offshore structures because of the repeated wave and current induced loads that occur at the base of the structure. Ma et al. (2019) also described fatigue from wave and currents to be the primary method of failure for FOWT mooring lines. Along with waves and currents, other factors that can influence the fatigue life of a FOWT include wind shear, turbulence intensity, ice and marine growth, and wind-wave misalignment (Müller and Cheng, 2018). There are 2 main methods to perform fatigue analysis, the S-N approach which predicts the cumulative fatigue damage for a stress range and number of loading cycles; and the fracture mechanics method which physically measures the crack growth over time. Fracture mechanics is a more accurate approach because it uses direct measurements, however, the initial crack size is often unknown or difficult to measure in offshore structures, so the S-N approach is more commonly used (Ma et al., 2019).

Fatigue analysis using the S-N approach is performed using a time history of stress, strain, force, acceleration, etc. (ASTM E1049-85). The widely used rainflow counting algorithm is implemented to count stress/strain cycles from the time history. Using cycle counts, the cumulative fatigue damage is calculated using Palmgren-Miner’s Rule and S-N curves (ABS Guide for Fatigue Assessment of Offshore Structures, 2020).

First, the rainflow counting algorithm, based on ASTM E1049-85, is used to summarize time histories with irregular loading and a long length by counting the cycles of various sizes that occur. The time history data then becomes a series of peaks and valley or reversals where each half cycles can be counted.
The cycle counts create an S-N curve, which defines the number of cycles, N, of stress range, S, that a material can endure until failure on a log-log scale (ABS Guide for Fatigue Assessment of Offshore Structures, 2020). Figure 9 below demonstrates a general two-segment S-N curve used for offshore structures.

Figure 9: General Two-Segment S-N Curve (ABS, 2020)

The equation used for the 2 segmented line S-N curve are:

\[
N = \begin{cases} 
    A * S^{-m} & \text{for } N < N_q \\
    C * S^{-r} & \text{for } N > N_q 
\end{cases} \quad [\text{Eq. 5}]
\]

N is the number of cycles to fatigue, S is the stress range, A and C are the fatigue strength coefficients, m and r are the fatigue strength exponents, and \( N_q \) is the cycle number where the change in slop occurs.

These coefficients are based on the desired detail class defined in ABS Guide for Fatigue Assessment of Offshore Structures (2020).

Using the desired S-N curve, the cumulative fatigue damage can be calculated from the widely accepted Palmgren-Miner Rule which assumes that each stress cycle causes an irreversible amount of damage to occur, and that damage is slowly built up until failure (Brandi and Rossetto, 1987). It assumes that the
cumulative fatigue damage is the linear sum of the individual damage from all considered stress ranges given by the equation:

\[ Damage = \sum_i \frac{n_i}{N_i}, \]  

[Eq. 6]

\( n_i \) is the number of cycles endured per year, \( N_i \) is the number of cycles to failure at a normalized tension range, \( J \) is the number of considered stress range intervals (ABS Guide for Fatigue Assessment of Offshore Structures, 2020).

### 2.4 Analysis Coupling

There are multiple ways to analyze the dynamics of a FOWT that range in complexity and computational time. The most common ways to simulate a FOWT using a code are through fully coupled, partially coupled, and uncoupled analyses. Although, the most complex and accurate analysis is done using real-time hybrid simulations.

As the name suggests, uncoupled analyses are the least complex and time consuming. With uncoupled analyses, wind and wave loading is analyzed separately and the coupling behavior between environmental conditions is neglected (Subbulakshmi et al., 2022). These simulations tend to take between 5-10 minutes in the aero-servo-hydro-elastic code, HAWC2. Uncoupled analyses are most useful when focusing on a specific behavior of the turbine such as the platform dynamics. Using an uncoupled hydrodynamic analysis, the hydrodynamics of the platform can be considered without adding the complexity of aerodynamics applied to the rotor. Likewise, wind-only simulations can predict the response of the turbine blades and rotor while neglecting the platform motion and wave effects.

Partially coupled analyses are a simplified way to considered both aerodynamics and hydrodynamics while reducing complexity and computational time. Essentially, if the focus of the study is hydrodynamics, aerodynamic forces are simplified and vice versa. In a hydrodynamic focused study, the aero-elastic and control effects are neglected, and the tower and RNA are modeled as a rigid body. Aerodynamic loads may only be wind forces applied at the tower top (ABS Guide for Building and
Classing Floating Wind Turbines, 2020). Similarly, in an aerodynamic focused study, the platform motion would be considered through external forces or forced oscillation while the aerodynamics would be modeled in full (Subbulakshmi et al., 2020).

A fully coupled simulation is considered the most complex and most time-consuming analysis but also considered the most accurate. In a coupled analysis the complete system of equations is used. This typically includes the rigid body model of the hull, elastic models of the tower and RNA, slender body models for the cables and mooring lines, as well as a control system (ABS Guide for Building and Classing Floating Wind Turbines, 2020). These complex simulations are solved using a nonlinear time domain approach to analysis using numerical simulation tools such as HAWC2, OpenFAST, Orcaflex, etc. (Subbulakshmi et al., 2020). Fully coupled analyses take much longer to run but are mainly used to study the realistic interaction between the floating platform and the wind turbine. The only model more complex than a fully coupled model is a real-time hybrid simulation in the form of a wind tunnel or wave basin.
CHAPTER 3: MECHANISTIC AND GEOMETRIC PROPERTIES OF FOWT

For the purpose of this research, the International Energy Agency (IEA) 15-Megawatt wind turbine was used in conjunction with the UMaine VolturnUS-S semi-submersible reference platform. The reference turbine is publicly available via the open-source programing platform, GitHub, and is consistently used throughout literature as a model for FOWT dynamic analysis. Having an open-source simulation model, allows for more collaboration between industry professionals and the research community and state-of-the-art technology innovations. It also allows for updates to be performed and the latest version to be available to the public quickly. Properties of the turbine, platform, and mooring lines obtained from Gaertner et al. (2020) and Allen et al. (2020) are described in the following sections.

3.1 Turbine

The wind turbine used in this study is the IEA Wind 15-Megawatt Offshore Reference Turbine. It was designed by a group of researchers of National Renewable Energy Lab (NREL), Technical University of Denmark (DTU), and the University of Maine (UMaine) in response to the current and future wind industry projections. Previously, reference turbines have ranged from 2 MW to 10 MW, however, innovation and technology has led to the need for a reference wind turbine between 10 MW and 20 MW in the future (Gaertner et al., 2020). For this reason, the IEA 15 MW Offshore Reference Wind Turbine was created.

The initial turbine design was created with a fixed monopile support structure in 20 meters of water, and blade and tower dimensions of 120m and 150m respectively. In this study, a FOWT was used with the semi-submersible platform described in the next section and is shown in Figure 10. The turbine properties, with the exception of the tower, remain the same for both the fixed bottom turbine and the FOWT. General turbine properties were obtained from Gaertner et al. (2020). Geometric properties of the turbine tower were found in the addendum report Allen et al. (2020).
In comparison with the fixed bottom monopile support structure, the properties of the FOWT tower must be much stiffer. This is due to the frequency requirements and boundary conditions associated with a floating substructure such as the semi-submersibles. A floating substructure has increased loads due to inertial forces, buoyancy, and gravity loads from the platform moving with the waves. A comparison of the fixed and floating tower properties can be seen in Table 1 where the floating tower mass is approximately 403 metric tons more than the fixed tower mass. This is due to the increased thickness of the floating tower to create a much stiffer structure. It is important to note that the diameter and flexible length of the tower remain the same for both the floating and fixed platform. Both reference turbines have a base diameter of 10 meters, equivalent to the length of a school bus or telephone pole, and a tower top outer diameter of 6.5 meters, equivalent to an adult giraffe (Cook, 2021).
Table 1: A Comparison of Geometric Tower Properties for Semi-Submersible and Fixed Turbines

<table>
<thead>
<tr>
<th></th>
<th>Floating Tower</th>
<th>Fixed Tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower Mass</td>
<td>1263</td>
<td>860</td>
</tr>
<tr>
<td>Tower Base Outer Diameter</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Tower Base Thickness</td>
<td>82.954</td>
<td>41.06</td>
</tr>
<tr>
<td>Tower Top Outer Diameter</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Tower Top Thickness</td>
<td>21.211</td>
<td>23.998</td>
</tr>
<tr>
<td>Tower Flexible Length</td>
<td>129.495</td>
<td>129.495</td>
</tr>
</tbody>
</table>

OpenFAST and the Wind-Plant Integrated System Design & Engineering Model (WISDEM) were used to design the tower properties. It was designed using isotropic steel tubes constrained by frequencies created from rotation of the rotor and platform motion. Conservative assumptions were made to design the tower’s first fore-aft and side-side natural frequency “outside modified rotation speed (1P) and blade passing (3P) ranges, taking the increased rotor speed variability into account” (Allen et al., 2020).

Cross sectional properties of the tower vary as the height increases and are calculated using the diameter and wall thickness profiles. The mass per unit length can be calculated using the equation:

\[ m = \rho \pi \left[ \left( \frac{D}{2} \right)^2 - \left( \frac{D}{2} - t \right)^2 \right], \quad [\text{Eq. 7}] \]

D is the outer diameter of the tower, t is the thickness of the tower, and \( \rho \) is the density of the material, in this case steel with a density of 7.85e3 kg/m^3 is used as seen in Table 2. Because the tower is defined as an axisymmetric circle, the center of mass in the x and y directions is defined as 0 as well as the shear and elastic center in the x and y directions. In addition, the structural pitch angle, defined as “the angle between x and the principal bending axis most parallel to x”, is also equal to zero (Allen et al., 2020).

Other properties, such as radius of gyration, moment of inertia, torsional stiffness, and cross-sectional area are calculated using textbook formulas. A complete list of tower cross sectional properties and their definitions can be found in Figure 41A and Table 37A. in Appendix A.1.

Table 2 below details the main geometric and material properties of the tower that are kept constant through its length.
Table 2: Tower Geometric and Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Modulus of Elasticity</td>
<td>200 e11 Pa</td>
</tr>
<tr>
<td>Steel Shear Modulus</td>
<td>7.93 e10 Pa</td>
</tr>
<tr>
<td>Steel Density</td>
<td>7.85 e3 kg/m³</td>
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<tr>
<td>Tower Base Outer Diameter</td>
<td>10 m</td>
</tr>
<tr>
<td>Tower Base Thickness</td>
<td>82.954 mm</td>
</tr>
<tr>
<td>Tower Top Outer Diameter</td>
<td>6.5 m</td>
</tr>
<tr>
<td>Tower Top Thickness</td>
<td>21.211 mm</td>
</tr>
<tr>
<td>Tower Flexible Length</td>
<td>129.495 m</td>
</tr>
<tr>
<td>Tower Mass</td>
<td>1263 metric tons</td>
</tr>
</tbody>
</table>

The resulting FOWT with the adjusted tower properties and semi-submersible platform can be seen in Figure 11 along with the corresponding motions with respect to the global coordinate system. As shown in Figure 11, heave sway, and surge motions relate to translational motion in the x, y, and z planes and yaw, pitch, and roll are associated with rotational motions (Micallef and Rezaeiha, 2021). Yawing is the rotation of the rotor axis about a vertical axis (torsion), while pitch and roll are rotations about the horizontal axes. Likewise, sway and surge are translations on the horizontal axes and heave is translation on the vertical axis (Micallef and Rezaeiha, 2021).

![Figure 11: Semi-Submersible FOWT with Reference Coordinate System (Allen et al. 2020)](image-url)

Figure 11: Semi-Submersible FOWT with Reference Coordinate System (Allen et al. 2020)
The structural shape of the blade consists of “two main load-carrying spars placed on a straight line connecting the root and the tip, along with reinforcement along the trailing and leading edges” (Gaertner et al., 2020). They have a total length of 117 meters which allows for around 30 meters of clearance from the mean water level (MWL) to the blade. The turbine blades weigh around 65 metric tons each and have spar caps made of carbon fiber which “provides as much stiffness with as little weight as possible” (Gaertner et al., 2020). The main constraints to the design of the blades were the tip deflection and tower clearance constraints. Specifically, the blades needed to be designed with enough prebend, 4 meters, to ensure adequate clearance from the tower. In terms of tip deflection loading, a design tip-speed ratio of 9.0 was used. This describes the wind speed applied to the turbine, compared to the wind speed of the turbine blade tips. The further away from the center hub of the turbine, the greater the wind speed and design codes allow for 9.0 time the hub velocity at the tip. Table 3 below tabulates the blade properties for the IEA 15-MW reference turbine.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blade Length</strong></td>
<td>117 m</td>
</tr>
<tr>
<td><strong>Root Diameter</strong></td>
<td>5.2 m</td>
</tr>
<tr>
<td><strong>Max Chord</strong></td>
<td>5.77 m</td>
</tr>
<tr>
<td><strong>Blade Tip Prebend</strong></td>
<td>4 m</td>
</tr>
<tr>
<td><strong>Rotor Angle Precone</strong></td>
<td>4 deg</td>
</tr>
<tr>
<td><strong>Blade Mass</strong></td>
<td>65,250 kg</td>
</tr>
<tr>
<td><strong>Blade Center of Mass</strong></td>
<td>26.8 m</td>
</tr>
<tr>
<td><strong>Design Tip-Speed Ratio</strong></td>
<td>9 --</td>
</tr>
<tr>
<td><strong>First Flapwise Natural Frequency</strong></td>
<td>0.555 Hz</td>
</tr>
<tr>
<td><strong>First Edgewise Natural Frequency</strong></td>
<td>0.642 Hz</td>
</tr>
<tr>
<td><strong>Design Cp</strong></td>
<td>0.489 --</td>
</tr>
<tr>
<td><strong>Design Ct</strong></td>
<td>0.779 --</td>
</tr>
</tbody>
</table>

Table 3: Blade Geometric and Material Properties

Wind turbines are generally classified by their wind speed (I, II, III) and turbulence parameters (A+, A, B, C). This turbine is classified as a Class IB direct-drive machine, meaning it consists of a permanent-magnet, synchronous radial flux generator and a simple nacelle layout (Gaertner et al., 2020). Class IB turbines are defined with a minimum annual average wind speed at hub height of 10 m/s and a turbulence
category for medium turbulence characteristics (ACP 61400-1-202, 2021). The site-specific turbulence and wind speed parameters for this study are described in detail in Chapter 5.

Wind turbine classes also include the cut-in, cut-out, and rated wind speeds. The cut-in wind speed is the lowest 10-minute wind speed average at hub height where the wind turbine begins producing power. Cut-out wind speed is the highest 10-minute average wind speed at hub height that the turbine is designed to produce power with steady wind and no turbulence. Rated wind speed is the minimum wind speed at hub height that the rated power, specified by the manufacturer, is achieved (ACP 61400-1-202, 2021). For the 15 MW IEA wind turbine, the cut-in, cut-out, and rated wind speeds for the turbine are defined as 3 m/s, 25 m/s, and 10.59 m/s as seen in Table 4.

<table>
<thead>
<tr>
<th>Table 4: Power Rating and Control Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Rating</td>
</tr>
<tr>
<td>Turbine Class</td>
</tr>
<tr>
<td>Specific Rating</td>
</tr>
<tr>
<td>Rotor Orientation</td>
</tr>
<tr>
<td>Number of Blades</td>
</tr>
<tr>
<td>Rotor Diameter</td>
</tr>
<tr>
<td>Control</td>
</tr>
<tr>
<td>Collective Pitch</td>
</tr>
<tr>
<td>Cut-in Wind Speed</td>
</tr>
<tr>
<td>Rated Wind Speed</td>
</tr>
<tr>
<td>Cut-out Wind Speed</td>
</tr>
<tr>
<td>1st Fore-aft Bending Mode</td>
</tr>
<tr>
<td>1st Side-side Bending Mode</td>
</tr>
</tbody>
</table>

Having a direct-drive generator, like the one used with the IEA 15 MW reference turbine, has certain advantages over geared drivetrains, which includes, less parts and complexity, higher reliability, and more flexibility in design. A precise balance of the “generator location, number of bearings, internal or external stator/rotor arrangement, rotor/stator inactive substructure geometries, ancillary component interfaces” (Gaertner et al., 2020), is necessary to avoid transportation, assembly and servicing challenges that exist for direct-drive turbines.
The blades and the turbine generator described are attached to the tower via the turbine hub and nacelle. As discussed in Chapter 1, the nacelle is where the generator and gearbox are housed, and it sits on top of the tower. Typically, other mechanical parts of the turbine are also found in the nacelle such as the controllers including the yaw and pitch systems which adjust the turbines angle according to the direction and speed of the wind (“How a Wind Turbine…”, 2022). General properties and dimensions of the nacelle and hub are described in Table 5 below.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hub Height</strong></td>
<td>150 m</td>
</tr>
<tr>
<td><strong>Hub Diameter</strong></td>
<td>7.94 m</td>
</tr>
<tr>
<td><strong>Hub Overhang</strong></td>
<td>11.35 m</td>
</tr>
<tr>
<td><strong>Rotor Nacelle Assembly Mass</strong></td>
<td>1017 metric ton</td>
</tr>
</tbody>
</table>

It is important to note that because this is a reference turbine, Gaertner et al. (2020) and Allen et al. (2020) do not specify the specific steel grade used. In general, this decision is left to industry manufacturers. Literature from Igwemezie et al. (2018), Podmore (2022), and Gilbert (2022) indicate that the yield stress of wind turbine steel ranges from 345 MPa to 355 MPa, which refers to EU S355 grade steel or equivalently US A572 grade 50 structural steel (Gilbert, 2012). For this study, structural steel with a yield strength of 355 MPa and a tensile stress range of 470 to 630 MPa is used (Igwemezie et al, 2018). This assumption was made to aid in analyzing stresses described in Chapter 6.

### 3.2 Platform

The platform used for this study is the UMaine VolturnUS Semi-Submersible Platform, designed by the University of Maine in collaboration with the U.S. Department of Energy as an addendum to the IEA 15 MW Offshore Wind Turbine report described above. As expressed in Chapter 1, the need for floating wind turbines is rapidly increasing as the U.S. is looking to invest into the offshore wind industry. About 80% of U.S. offshore wind resources are located in water deeper than 60 meters, requiring floating foundation technologies (Musial, 2021). The semi-submersible platform is one of the most used platforms.
when compared to the spar, TLP, and barge platforms and makes up around 80% of all floating projects in the pipeline (Musial, 2021).

Figure 12 below comes from the NREL technical report on the substructure design of a semi-submersible platform (Allen et al., 2020) and details dimensions of the platform in plan and elevation view. The platform consists of 4 buoyant steel columns, 3 columns equally spaced radially at 51.7 meters from the towers vertical access, and 1 column located under the tower-platform center. Each buoyant column has a diameter of 12.5 meters and is connected in the center column by a “rectangular bottom pontoon” (Allen et al., 2020) and radial struts attached to the bottom and top of the platform. The pontoons have dimensions of 12.5 meters by 7.0 meters and the radial struts have a diameter measured at 0.9 meters. The semi-submersible platform has a total mass of 17,854 metric tons, which mainly consists of the seawater ballast flooded in the 3 submerged pontoons.

Figure 12: USVolturn-S Semi-Submersible Platform Arrangement (Allen et al. 2020)
As detailed in Figure 3, the total width of the semi-submersible platform from the front elevation is 102.13 meters and from the side elevation is 90.13 meters. Comparatively, a standard soccer field has dimensions of 105 meters by 68 meters (“Field Markings & Equipment…”, 2015).

Platform mass and geometric properties are described in more detail in Table 6. These properties are directly calculated/inputted into the HAWC2 model through a DLL created for the semi-submersible platform and remain consistent throughout all simulations.

**Table 6: Properties of the UMaine Semi-submersible Platform**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Platform Mass</td>
<td>17,854 t</td>
</tr>
<tr>
<td>Hull Structural Steel Mass</td>
<td>3,914 t</td>
</tr>
<tr>
<td>Fixed iron-ore-concrete ballast Mass</td>
<td>2,540 t</td>
</tr>
<tr>
<td>Seawater Ballast in Pontoons Mass</td>
<td>11,300 t</td>
</tr>
<tr>
<td>Tower Interface Connection Mass</td>
<td>100 t</td>
</tr>
<tr>
<td>Hull Displacement</td>
<td>20,206 m³</td>
</tr>
<tr>
<td>Draft</td>
<td>20 m</td>
</tr>
<tr>
<td>Freeboard</td>
<td>15 m</td>
</tr>
<tr>
<td>Vertical Center of Gravity from SWL</td>
<td>14.94 m</td>
</tr>
<tr>
<td>Buoyancy from SWL</td>
<td>-13.63 m</td>
</tr>
</tbody>
</table>

### 3.3 Mooring Lines

The platform described above is anchored to the seabed through 3 catenary mooring lines each at 850 meters long. Catenary mooring lines refer to a mooring system where the distributed weight of the mooring lines provides the reaction and allows for some slackness in the lines (ABS Guide for Building and Classing Floating Wind Turbines, 2020). Catenary mooring lines are the most used system for mooring is waters less than 1500 meters deep (Yan, 2016). The mooring lines used in this model are comprised of a chain section and a wire rope section and spread radially and anchored at 837.5 meters from the centerline of the tower to allow for some slack in the lines. “Each line is connected at the fairlead to one of the platforms 3 outer columns at a depth of 14 meters below still water level” (Allen et al., 2020). The fairlead is considered the point of connection between the mooring lines and the platform. The water depth that was used for this model was 200 meters, which aligns closely with the water depth at the buoy station used for wind and wave data inputs described in Chapter 5 and is much shallower than
the length of the mooring lines used in the model. This allows for the mooring lines to hang underwater and lay on the seabed, so the anchors only experience horizontal forces. The mooring line system can be seen graphically in Figure 4 with associated dimensions.

*Figure 13: USVoltturn-S Semi-Submersible Platform Mooring Configuration (Allen et al. 2020)*
As seen in the figure above, the lines are also radially spaced at 120 degrees apart in the surge-sway plane (horizontal plane). Additional properties including density and stiffness of the catenary mooring system can be found in Table 7.

**Table 7: Mooring Line Properties for the UMaine Semi-Submersible Platform**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstretched Line length</td>
<td>850 m</td>
</tr>
<tr>
<td>Line Type</td>
<td>R3 Studless Mooring Chain</td>
</tr>
<tr>
<td>Line Breaking Strength</td>
<td>22,286 kN</td>
</tr>
<tr>
<td>Number of Lines</td>
<td>3</td>
</tr>
<tr>
<td>Anchor Depth</td>
<td>200 m</td>
</tr>
<tr>
<td>Fairlead Depth</td>
<td>14 m</td>
</tr>
<tr>
<td>Anchor Radial Spacing</td>
<td>837.5 m</td>
</tr>
<tr>
<td>Fairlead Radial Spacing</td>
<td>58 m</td>
</tr>
<tr>
<td>Nominal Chain Diameter</td>
<td>185 m</td>
</tr>
<tr>
<td>Dry Line Linear Density</td>
<td>685 kg/m</td>
</tr>
<tr>
<td>Extensional Stiffness</td>
<td>3270 MN</td>
</tr>
<tr>
<td>Fairlead Pretension</td>
<td>2437 kN</td>
</tr>
<tr>
<td>Fairlead Angle from SWL</td>
<td>56.4 deg</td>
</tr>
</tbody>
</table>

The chain size defined in Table 7 was used because it keeps the “system’s peak surge-sway offset under 25 meters during normal operational conditions to limit design constraints on a dynamic electrical umbilical” (Allen et al., 2020). The chain dimensions represent the largest mooring chain available at the time of the publishing of the paper. This was used for conservativism and can be modified in future models for optimization.

This model has been tested and verified and has compatibility with multiple software packages such as OpenFAST, HAWC2, and OrcaFlex.
CHAPTER 4: ANALYSIS APPROACH

For the purpose of this research, a coupled time-domain analysis was done using a well-documented aeroelastic simulation code to model the semi-submersible FOWT described in Chapter 3. In the sections below, the software and its capabilities will be described in detail followed by assumptions incorporated into the modeling process. The international and U.S. standards for offshore wind turbine design are described as well as the load case evaluated for this research.

4.1 Software Selected

The Horizontal Axis Wind Turbine Simulation Code, 2nd Generation (HAWC2) was used to simulate the turbine described in Chapter 3. HAWC2 was developed from 2003 to 2007 by the Technical University of Denmark (DTU). It is a nonlinear aero-servo-hydro-elastic code based on multibody formulation that simulates wind turbines in the time domain (DTU Wind Energy, 2018). HAWC2 is constantly under development to keep up with research and industry needs. The code has been verified with other FOWT codes such as OpenFAST and OrcaFlex and shows good agreement (Rinker et al., 2020). It can be used to simulate a variety of wind turbines, with fixed and floating substructures, subjected to wind and wave conditions.

HAWC2 uses flexible finite elements, composed of Timoshenko beam elements with 6 degrees of freedom, for structural modeling of FOWT (DTU Wind Energy, 2018). Using a general Timoshenko beam formulation allows for a variety of FOWT structures to be created and large rotations to be allowed within the structure. A Timoshenko beam is one that accounts for shear deformations and bending effect which also creates a model with high fidelity.

As described in Chapter 1, a wind turbine is made up of a tower, blades, RNA, etc. These are modeled in HAWC2 as different main bodies. These main bodies are further divided into sub-bodies and nodes, each with their own reference frame. Sub-bodies are then split into Timoshenko beam elements with 2 nodes. Each single beam element has constant structural parameters and uses both mass proportional and
stiffness proportional Rayleigh damping. HAWC2 uses beam theory and a separate input st file to describe the cross-sectional, stiffness, mass, and inertia properties at nodes along each beam element. A total of 19 different properties are defined in the st file which can be seen in Table 32A in Appendix A.1 (DTU Wind Energy, 2018). For simple/ symmetric beams such as the tower, the cross-sectional stiffness and mass properties are computed using general textbook formulas. However, elements such as blades are more complex and require additional analysis using a cross-sectional analysis software.

The main bodies are then oriented and constrained together to form a full turbine with a global coordinate system. Local coordinate systems of each body are defined using a set of Euler angles and reference bodies that relate them to the global coordinate system (DTU Wind Energy, 2018). Once the local coordinate system is oriented, it is then constrained to other elements/the ground using a variety of constraints defined by HAWC2. Main constraints utilized in this project are:

- Fix1: clamped connection
- Bearing1: frictionless bearing
- Bearing 2: bearing where a fixed angle is specified in an external DLL

The local and global coordinate systems are demonstrated in Figure 14. Both local and global coordinate systems are defined using the right-hand-rule with the z-axis indicating the length of the object and the x and y axis defining the cross section of the element.

Based on Figure 14, the x and y global directions correspond to the surge-sway coordinate plane and the heave coordinate plane corresponds to the z direction. This results in rotation about the x and y coordinate axis corresponding to the pitch and roll motions respectively, and moment about the z global coordinate axis to demonstrate the yaw moment. It should also be noted that the global z coordinate axis is pointing downward and results in the depth to the sea floor being a positive value.
In terms of applied loading on the structure, HAWC2 can account for wind, wave, structural dynamic, static, and mooring loads through various well-known theories and dynamic link libraries (DLLs). When compared to other similar software such as OpenFAST, OrcaFlex, and Bladed, HAWC2 offers high fidelity structural dynamic modeling, aerodynamic modeling, and mooring modeling. The hydrodynamic modeling in HAWC2 is the only modeling aspect that is considered low fidelity (Subbulakshmi et al. 2022).
Another important note about HAWC2 is that there is no graphic user interface (GUI) associated with the software. Additional programs are used to compliment the HAWC2 programming language and add a visual aid to the coding. The HAWC2 visualization tool and PDAP (Python Data Analysis Program), both developed by Mads M Pedersen at DTU, were used to visualize results in the time domain. In addition, MATLAB was used for post processing of data.

### 4.2 Software Specific Modeling Assumptions

Due to the nature of design and complexity of the structure, modeling assumptions must be made when simulating a FOWT. These assumptions work to simplify the model and decrease computational burden while still allowing for an accurate depiction of how FOWT behave under applied loading and environmental conditions. HAWC2 implements multiple assumptions into the programming in the structural model, wind model, aerodynamic model, and wave model. A list of the most prevalent assumptions is found below.

Structural and gravitational loads are those that consider static and dynamic gravity loads, vibrations, rotations, and seismic activity. Assumptions made for the structural model include:

- Each body is modeled as a Timoshenko beam element,
- HAWC2 assumes the node position of the blades coincides with the blade’s half chord position,
- The tower section is assumed to be symmetrical,
- Structural parameters are constant over a singular beam element and defined using a 2D cross section,
- Small deflections are assumed over a singular beam element,
- The mass center is the average location of the cross sections mass (center of gravity),
- The shear center is the point where force F is applied parallel to the plane of the cross section and produces no torsional deformation,
- The elastic center is the point where force \( F \) applied normal to cross section and will produce no bending deformation,
- Rayleigh damping is used with 6 parameters, 3 of which are mass proportional, and the other 3 which are stiffness proportional,
- Mass proportional damping is only valid when structure is fixed to the ground and is set to zero for floating structures,
- Seismic loading is neglected for this simulation.

Wind loads are those that occur from wind or gust speeds. Assumptions made for the wind input include:
- Mann turbulence model can be used, creating a spatial vector field in cartesian coordinates and the center of the turbulence box is designated at the hub height (DTU Wind Energy, 2018),
- Wind profile can be estimated using the Power Law or the Logarithmic Law depending on the user input,
- Tower shadow effect is attached to the moving tower and accounts for the variation in wind flow due to the tower,
- Neutral atmospheric conditions are assumed so wind speed profiles remain valid.

Aerodynamic loading includes loads from airflow and its interactions with the turbine structure. Assumptions made for the wind and aerodynamic loads applied to the structure include:
- Blade element momentum theory (BEM) is used for aerodynamic loads in HAWC2 to limit computational time,
- The rotor area is discretized into a nonrotating polar grid and the velocities are computed at every point on the grid,
- Blade elements are independent and do not capture the effect of variations of aerodynamic loads that one radial position has on adjacent positions based on BEM theory,
- The tip correction model is a DLL added to HAWC2 to account for the fact that a rotor with a finite number of blades has a vortex structure that is different from the ideal rotor vortex structure,
leading to different relationship between the thrust coefficient and induction factor (DTU Wind Energy, 2018),

- BEM is combined with generalized dynamic wake and dynamic stall models to create a high-fidelity software,
- The rotor aerodynamic model accounts for the variations in airflow caused by the rotor itself,
- Dynamic inflow correction model accounts for the mass of the air passing through the area of the wind turbine rotor,
- Skewed inflow correction model accounts for the induction variations from a skewed inflow.

Hydrodynamic loads come from wave heights and periods applied mainly to the base of the turbine at water level. Assumptions made include:

- Water kinematics are calculated using an external DLL called wkin.dll,
- Morison’s Equation is used for hydrodynamic load interactions which creates a low fidelity hydrodynamic model when using a semi-submersible platform,
- HAWC2 can account for regular airy, irregular airy, stream function, deterministic, and white noise wave types based on user input,
- Stream function wave input is based on the wave height, period, and current speed and adapted from a method developed by Chaplin from Southampton University (DTU Wind Energy, 2018),
- The irregular wave field is established by superposition of different sinusoidal functions,
- The buoyancy force is calculated using Archimedes principle and integrating the external water pressure on the submerged body,
- Flexibility of floating members is taken into account,
- Mooring line forces are included as external forces and moments through a DLL.
4.3 International and United States Standards

The IEC or International Electrotechnical Commission is a worldwide organization dedicated to cooperation and standardization of standards in the electrical and electronic fields. IEC 61400-1 (2005) is specifically dedicated to wind energy generation systems and IEC 61400-3 (2005) specifies offshore installations. These 2 standards are used as general guidance on design and operation for FOWT, however, they typically only provide countries a minimum design standard to follow based on global consensus.

Det Norske Veritas (DNV) is a different international organization, located in Norway, that produces recommended practices and guidelines for design and classification of FOWT. In 2014, they published Environmental Conditions and Environmental Loading (2014) which identifies how to calculate input environmental conditions and apply them to a FOWT model.

The American Bureau of Shipping (ABS) and the American Clean Power Association (ACP) are two governing bodies in the United States for the design of offshore wind structures. Both organizations have created documentation that closely follows the recommendations of the IEC 61400. The ABS published the Guide for Building and Classing Offshore Wind Installations (2020). This is a document based on existing design standards from the IEC 61400 specified for offshore wind structures in U.S. waters. The ABS guide provides means of classifying wind turbines. It also defines requirements for construction, installation, and design, including design for effects of tropical storm conditions, which is not included in IEC 61400-3. Additionally, the ABS published Guide for Fatigue Assessment of Offshore Structures (2020), as a supplement to the Guide for Building and Classing Offshore Wind Installations (2020) to specify fatigue analysis criteria not originally provided. ABS also published Global Performance Analysis for Floating Offshore Wind Turbines (2020) which specifies modeling characteristics and design load cases for FOWT (“ABS Releases Guide…”, 2020).

The ACP provides ANSI accredited standards and recommended practices that provide mandatory requirements and good practice for Wind Energy Generation Systems. These are published in ACP
61400-1-202x, Wind Energy Generation Systems-Part 1: Design Requirements. This document provides design load cases based on IEC 61400 (2005), guidance on calculating external site-specific conditions, instructions for assembly, installation and maintenance, and additional information on mechanical and control systems.

For both IEC and ABS/ACP standards, design load cases are specified to account for differing environmental and mechanical conditions that an offshore wind turbine will experience throughout its life cycle. This includes various wave and wind conditions for both normal and extreme conditions. These conditions are applied to the wind turbine for various mechanical design situation that the turbine will experience, such as power production, start-up, normal shutdown, emergency stop, and parked conditions.

Table 8, below, comes from ACP 61400-1-202 (2021) which details all design load cases and their various conditions. These load cases are the same as those specified in the IEC 61400 (2005) guidance.

<table>
<thead>
<tr>
<th>Design Situations</th>
<th>DLC</th>
<th>Wind Condition</th>
<th>Other Condition</th>
<th>Type of Analysis</th>
<th>Partial Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Power Production</td>
<td>1.1</td>
<td>NTM ( V_{in} &lt; V_{hub} &lt; V_{out} )</td>
<td>For extrapolation of extreme events</td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>NTM ( V_{in} &lt; V_{hub} &lt; V_{out} )</td>
<td></td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>ETM ( V_{in} &lt; V_{hub} &lt; V_{out} )</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>ECD ( V_{hub} = V_{t} - 2\text{m/s}, V_{t}, V_{t}+2 \text{m/s} )</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>EWS ( V_{in} &lt; V_{hub} &lt; V_{out} )</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td>(2) Power Production plus Occurrence of Fault</td>
<td>2.1</td>
<td>NTM ( V_{in} &lt; V_{hub} &lt; V_{out} )</td>
<td>Normal Control system fault or loss of electrical network or primary layer control function fault</td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>NTM ( V_{in} &lt; V_{hub} &lt; V_{out} )</td>
<td>Abnormal control system fault or secondary layer protection function related fault</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>EOG ( V_{hub} = V_{t} +/- 2\text{m/s and } V_{out} )</td>
<td>External or internal electrical fault including loss of electrical network</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>2.4</td>
<td>NTM ( V_{in} &lt; V_{hub} &lt; V_{out} )</td>
<td>Control system fault, electrical fault, or loss of electrical network</td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td>(3) Start-Up</td>
<td>3.1</td>
<td>NWP ( V_{in} &lt; V_{hub} &lt; V_{out} )</td>
<td>Low voltage ride through</td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>EOG ( V_{hub} = V_{t} +/- 2\text{m/s and } V_{out} )</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td>(4) Normal Shutdown</td>
<td>4.1</td>
<td>NWP ( V_{in} &lt; V_{hub} &lt; V_{out} )</td>
<td></td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>EOG ( V_{hub} = V_{t} +/- 2\text{m/s, } V_{out} )</td>
<td></td>
<td>U</td>
<td>N</td>
</tr>
</tbody>
</table>
### 4.4 Load Case Evaluated

For this study, the parked condition load case, DLC 6.1, was evaluated. Design load conditions for this load case were found in IEC 61400-3 (2005), ACP- 61400-1-202 (2021), and “Design Load Basis for Offshore Wind Turbines” by DTU (Natarajan et al., 2016). This load case defines the wind turbine with the rotor in either standstill or idling conditions and subject to extreme wind speeds (EWM). The parked condition refers to a survival situation where the applied wind speed is greater than the cut-out wind speed defined by the turbine manufacturer. The turbine has stopped producing power and is idling to withstand the extreme wind speed. This load case is considered a strength or ultimate/extreme case as opposed to fatigue because extreme 50-year storm values are used in analysis. Strength load cases test the effects of environmental loads combined with permanent and variable loads to produce the combination with the most severe effect (ABS Guide for Building and Classing Floating Offshore wind turbines, 2020).

Design load case 6.1 combines the EWM with extreme sea state conditions (ESS) which includes extreme water level, wave height and current conditions. The conditions necessary for DLC 6.1 are defined in Table 9.

<table>
<thead>
<tr>
<th>(5) Emergency Stop</th>
<th>5.1</th>
<th>NTM $V_{hub} = V_r +/- 2\text{m/s}$ and $V_{out}$</th>
<th>U</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>(6) Parked (standing still or idling)</td>
<td>6.1</td>
<td>EWM 50-year return period</td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>6.2</td>
<td>EWM 50-year return period</td>
<td>Loss of electrical network connection</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>EWM 1-year return period</td>
<td>Extreme yaw misalignment</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>6.4</td>
<td>NTM $V_{hub} &lt; 0.7 V_{out}$</td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td>(7) Parked and Fault Conditions</td>
<td>7.1</td>
<td>EWM 1-year return period</td>
<td>U</td>
<td>A</td>
</tr>
<tr>
<td>(8) Transport, Assembly, Maintenance, and Repair</td>
<td>8.1</td>
<td>NTM $V_{mean}$ to be stated by the manufacturer</td>
<td>U</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>8.2</td>
<td>EWM 1-year return period</td>
<td>U</td>
<td>A</td>
</tr>
</tbody>
</table>
The EWM is described by the 50-year wind speed using either a steady extreme wind model (EWM) or a turbulent extreme wind model (ETM). Based on ACP 61400-1-202 (2021), when the ETM is used, the response is estimated using a full dynamic simulation or a quasi-steady analysis that applies appropriate corrections for gusts and dynamic response. If the NTM is used the effect of resonant response is estimated from the quasi-steady analysis (ACP 61400-1-202, 2021). Should the ETM be used, a turbulence intensity of 11% is specified by DLC 6.1. For this parked load case, wind shear is estimated by the vertical power law with a power law exponent of 0.11 and wind gust characteristics are not specified. For a wind turbine with an active yaw system, such as the IEA 15 MW reference turbine, a yaw misalignment of ± 8° is used along with the ETM, given that restraint against yaw slippage can be accounted for (ACP 61400-1-202, 2021).

The ESS refers to the 50-year nonlinear wave height combined with the 50-year current conditions, and the extreme water level using the highest observed water level and lowest observed water level depending on which is more extreme. Wave directions are defined as misaligned from wind direction and multi-directional with ± 30°.

For DLC 6.1, the IEC specifies that the simulation length must be at least 600 seconds (10 minutes). However, a 10-minute simulation is rarely long enough to cover all “the phase differences between 10
minutes of wind time series and 10 minutes of wave time series” (Natarajan et al., 2016). For this reason, 6 turbulence seeds are included for each load case, to create a total 1-hour simulation length. This is repeated for 3 water depth that account for differing water depths as well as 2 wave directions. This creates a total of 108 individual simulations, including 18 combinations of wind, wave, and water depth, each with 6 random turbulence seeds.

A partial safety factor is also included to account for uncertainties and variability in loads and resistances. For DLC 6.1, the safety factor is “derived assuming that the coefficient of variation of the annual maximum wind speed is smaller than 15%” (ACP 61400-1-202, 2021). The partial safety factor is included in the design by using the equation:

\[ F_d = \gamma \times F_k, \]  

[Eq. 8]

where \( F_d \) is the design value of the applicable load, \( \gamma \) is the partial safety factor, and \( F_k \) is the characteristic or worst-case computed value for the load (ACP 61400-1-202, 2021). In the case of DLC 6.1, the partial safety factor, \( \gamma \), is specified as 1.35. This is applied after the simulations are completed to the time history of forces and moments to create design loads.
CHAPTER 5: SITE AND CLIMATE CONDITIONS

5.1 Chosen Site

Climate data use in this study was determined from an analysis of wind and wave conditions in the Gulf of Maine. This site was chosen due to its localness and potential wind energy capacity. In addition, the water depth at the buoy location aligned closely with the mooring line depth of the model platform described in Chapter 3.

According to the United States Department of Energy (Musial et al., 2022), the Gulf of Maine has been identified as a potential leasing site for floating offshore wind farms in the next decade. Climate data was obtained from NOAA Buoy Station 44005, located 78 nautical miles off the coast of Portsmouth, NH in 176.8 meters of water (“Station 44005…” 2022). The location of this site is denoted by the red X in Figure 15.

![Figure 15: NOAA Buoy Station 44005 Location ("Station 44005..." 2022)](image)

This station is managed by National Data Buoy Center and consists of a 3-meter-tall discus buoy with an anemometer height of 4.9 meters above sea level.
Data obtained from this buoy includes 37 years of continuous wind, wave, and temperature data. Specific standard meteorological data and their respective definitions include (“Measurement Descriptions and Units”, 2022):

- Wind Direction (°): in degrees clockwise from true North,
- Wind Speed (m/s): average 8-minute wind speed reported hourly,
- Gust Speed (m/s): averaged 5 or 8 second wind gust speed measured during an 8-minute period,
- Wave Height (m): significant wave height, the highest 1/3 of all wave heights from a 20-minute sampling period,
- Dominant Wave Period (seconds): wave period where maximum wave energy is obtained,
- Mean Wave Direction (°): direction clockwise from true North that the dominant wave periods are coming from,

Table 10 shows each of the standard climate characteristics yearly and overall averages. This data and specific wind and wave climate data is further described in the following sections, including how extreme conditions were estimated for the hub height of the wind turbine model.
5.2 Wind Climate

“The IEC 61400-1 defines the annual average wind speed as the mean value of a set of measured data of sufficient size and duration to be considered as a representative set of a certain site under study” (Gómez et al., 2015). Data from 1982 to 2021 provided a sufficient size and duration of data and a full analysis of all the data available would provide the most accurate results. Previous studies including Dagher et al. (2017), Gómez et al (2015), and Viselli et al. (2012) provided references for performing a full climate analysis but used smaller subsets of the data or did not include data from most recent years. For this reason, it was decided to complete a separate climate analysis for this study.
Average wind speed can be taken over multiple sampling periods including 10-minute, 1-hour, and 1-minute. For this location, the only available data included an 8-minute average wind speed.

Recommended Practice and literature suggest that the 8-minute average wind speed must be converted into a 10-minute averaging period for most accurate results. To do this, a gust factor was used. From DNV-RP-C205 (2014), the conversion equation for different averaging periods is defined as:

\[ U(t,z) = U_{10} \times \left[ 1 + 0.137 \times \ln \frac{z}{H} - 0.047 \times \ln \frac{T}{T_{10}} \right] \]  \hspace{1cm} [Eq. 9]

\( U(t,z) \) is the average wind speed for the needed averaging period, \( t \), at height above the ground, \( z \). For this calculation, \( z \) is equal to 4.9 meters above sea level, the height of the anemometer where the wind speed was measured, and \( t \) is the 8-minute average period given. \( H \) is defined as the wind reference height (4.9 meters), \( T_{10} \) is 10 minutes, \( T \) is the averaging period of 8-minutes, and \( U_{10} \) is the 10-minute mean wind speed. The gust factor was calculated to be 1.0105 and the resulting equation for the 10-minute average wind speed becomes:

\[ U_{10,4.9} = \frac{U_{(8.4.9)}}{1.0105} \]  \hspace{1cm} [Eq. 10]

This equation was used for converting all wind speeds and the 10-minute average wind speed is used moving forward for all calculations and results. Yearly and overall averages can be found in Table 10 which compares the 8-minute averages with the 10-minute averages.

Depicted in Figure 16 is the yearly average 10-minute wind speed and maximum average 10-minute wind speed over time. The yearly average wind speed remains relatively consistent over 37 years and ranges from 5 to 10 m/s with an overall average of 6.54 m/s. The maximum wind appears to vary much more than the average wind speed, ranging from 16 m/s to over 25 m/s. This is expected as the average is representative of all wind speeds, while the maximums represent an extreme condition or storms experienced each year.
5.2.1 Wind Shear Profile using Power Law Profile

All original data measured from the buoy was obtained at the sensor height of 4.9 meters above sea level. Based on the model described in Chapter 3, the hub height of the wind turbine is 150 meters above sea level and the wind speed must be estimated at the hub height to ensure an accurate wind shear profile. A review of literature found the recommended practice for estimating wind speeds at different heights was using the Power Law Profile or the Logarithmic Profile. The power law is defined as:

\[ V(z) = V_{hub} \times \left( \frac{z}{z_{hub}} \right)^\alpha, \]  

[Eq. 11]

\( V(z) \) is the wind speed in m/s at the desired height, \( z \) is the desired height in meters, \( z_{hub} \) is the height of the original measurement taken, 4.9 meters for this data set, and \( \alpha \) is the power law exponent. Gómez et al. (2015) and Viselli et al. (2012) recommend using 0.14 as \( \alpha \) based on the IEC 61400-3 design code recommendations.

The logarithmic profile is defined as:

\[ V(z) = V_{hub} \frac{\ln \left( \frac{z}{z_{hub}} \right)}{\ln \left( \frac{z}{z_0} \right)}, \]  

[Eq. 12]
V(z), and \(z_{\text{hub}}\) are defined as the same as in the power law, \(H\) is defined as the desired height in meters and \(z_0\) is defined as the surface roughness coefficient where Viselli et al. (2012) recommends using 0.0002. This represents a conservative estimate of the terrain roughness in open seas with waves. A full table of surface roughness and power law coefficients can be found in Table 35A in Appendix A.1 for reference.

Both methods are presented in Figure 17 and Table 11, where the wind speed is extrapolated from the station height to the hub height with intermediate heights for reference. Both profiles were compared with NOAA data and reference papers and presented agreement with both. Based on recommendations from DNV-RP-C205 (2014) and Viselli et al. (2012), the more conservative estimation using the Power Law Profile was chosen moving forward for analyzing data.

Table 11: A Comparison of Logarithmic and Power Profiles for Wind Speed at Different Heights

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Logarithmic Profile</th>
<th>Power Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.9</td>
<td>6.55</td>
<td>6.55</td>
</tr>
<tr>
<td>5</td>
<td>6.57</td>
<td>6.57</td>
</tr>
<tr>
<td>10</td>
<td>7.02</td>
<td>7.24</td>
</tr>
<tr>
<td>20</td>
<td>7.47</td>
<td>7.98</td>
</tr>
<tr>
<td>30</td>
<td>7.73</td>
<td>8.45</td>
</tr>
<tr>
<td>40</td>
<td>7.92</td>
<td>8.79</td>
</tr>
<tr>
<td>50</td>
<td>8.06</td>
<td>9.07</td>
</tr>
<tr>
<td>60</td>
<td>8.18</td>
<td>9.31</td>
</tr>
<tr>
<td>65</td>
<td>8.23</td>
<td>9.41</td>
</tr>
<tr>
<td>70</td>
<td>8.28</td>
<td>9.51</td>
</tr>
<tr>
<td>80</td>
<td>8.36</td>
<td>9.69</td>
</tr>
<tr>
<td>90</td>
<td>8.44</td>
<td>9.85</td>
</tr>
<tr>
<td>100</td>
<td>8.51</td>
<td>10.00</td>
</tr>
<tr>
<td>110</td>
<td>8.57</td>
<td>10.13</td>
</tr>
<tr>
<td>120</td>
<td>8.63</td>
<td>10.26</td>
</tr>
<tr>
<td>130</td>
<td>8.68</td>
<td>10.37</td>
</tr>
<tr>
<td>140</td>
<td>8.73</td>
<td>10.48</td>
</tr>
<tr>
<td>150</td>
<td>8.77</td>
<td>10.58</td>
</tr>
<tr>
<td>200</td>
<td>8.96</td>
<td>11.02</td>
</tr>
</tbody>
</table>

From this, it was extrapolated that the average normal wind speed at the hub height of 150 meters above sea level is estimated at 10.58 m/s.
5.2.2 Weibull Distribution for Wind Speed Extreme Conditions

ABS Guide for Building and Classing Floating Offshore Wind Turbines (2020), IEC 61400-3 (2005), and ACP 61400-1 (2021) define the extreme sea state as a 50-year storm. This defines the annual probability of exceedance as \( \frac{1}{50 \, \text{years}} = 0.02 \) each year. To do this, recommended practice is using a Weibull Probability Distribution to fit the data to find the probability density function and cumulative density function.

The Weibull distribution at any height above the ground can be described by (DNV-RP-C205, 2014):

\[
P(u) = 1 - \exp \left( -\frac{u}{A} \right)^k \quad [\text{Eq. 13}]
\]

\( P(u) \) is the probability distribution, \( u \) is the mean wind speed, \( A \) is the scale coefficient, and \( k \) is the shape coefficient. The 10-minute average wind speed data was first fit to the distribution to ensure that it was a good fit for estimation. As seen in Figure 18 on the left, the histogram and the overlapping Weibull
probability distribution function show good agreement. The Weibull Distribution describes the variation in wind speed for this site using a probability distribution. The total area under the curve is equal to 1 and is fitted to the histogram of the data using the shape and scale coefficients (“Describing Wind Variation”, 2003).

![Figure 18: Weibull Distribution Fit for All Wind Data and Yearly Maximum Data](image)

In order to get most extreme conditions that accurately represent a 50-year storm, the yearly maximum data was also fit to a Weibull Distribution. The right side of Figure 18 shows the yearly maximum data fit to a Weibull Distribution with relatively good agreement.

**Table 12: Weibull Distribution Parameters for Wind Speed**

<table>
<thead>
<tr>
<th>Weibull Distribution Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale Coefficient (A)</td>
<td>21.099</td>
</tr>
<tr>
<td>Shape Coefficient (k)</td>
<td>10.098</td>
</tr>
</tbody>
</table>

Table 12 describes the Weibull Distribution parameters using the yearly maximum data seen in Figure 18 on the right side. These distribution parameters are used to create the cumulative distribution function seen in Figure 19 which depicts the yearly maximum probability distribution to estimate extreme loading. Using the scale and shape parameters presented in Table 12 and the cumulative distribution function shown in Figure 19, the extreme storm conditions were found for return periods of 10, 50, and 100 years.
These extreme wind speeds were found to be 22.92 m/s, 24.15 m/s, and 24.54 m/s for storm return periods of 10, 50, and 100 years respectively and can be seen in Table 13. Based on ACP 61400 (2021), these extreme wind speeds represent the wind shear events, peak wind speeds from storms, or rapid changes in wind speed (ACP 61400, 2021). These extreme wind speeds were also compared to results found in Viselli et al. (2012) for verification.

The Power Law Profile was then used to extrapolate the extreme conditions to the hub height of 150 meters. Recommendations from Gómez et al. (2015), ABS (2020) and DNV-RP-C25 (2014), indicate using the 0.11 Potential Profile is most accurate. This results in using 0.11 as the power law exponent, \( \alpha \), instead of 0.14 that was used for normal conditions. Table 13 shows the wind speeds for the different return periods at the hub height. These extreme wind speeds were compared with Viselli et al. (2012) and Gómez et al. (2015) and showed agreement with both.
<table>
<thead>
<tr>
<th>Storm Return Period (yrs)</th>
<th>Extreme Wind Speed at 4.9m (m/s)</th>
<th>Extreme Wind Speed at 150m (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-year</td>
<td>22.92</td>
<td>33.39</td>
</tr>
<tr>
<td>50-year</td>
<td>24.15</td>
<td>35.19</td>
</tr>
<tr>
<td>100-year</td>
<td>24.54</td>
<td>35.76</td>
</tr>
</tbody>
</table>

Based on recommendations from DNV-RP-C205 (2014) and IEC 61400-1 (2005), the 50-year storm return period is used for design loads case extreme conditions, resulting in an average 10-minute wind speed of 35.19 m/s at 150 meters hub height.

### 5.2.3 Wind Direction and Wind Rose

To describe the wind direction, a wind rose was created based on data obtained from NOAA buoy 44005 over 37 years. The wind direction, as defined earlier, is measured in degrees clockwise from true North. Table 10 shows that the yearly average wind direction to range from around 193° clockwise from true North to around 221° clockwise from true North, or wind generally comes from the southwest.

A wind rose has been provided that represents how the wind speed and directionality correlate in a circular graphical format. The length of each of the “spokes” around the circle indicate the frequency that the wind blows in that direction. The colors on each of the “spokes” represent different ranges of wind speed (“Wind Roses - Charts and Tabular Data”, 2022).

Using the wind speed and direction data from NOAA and the MATLAB wind rose file exchange function from Al Mac (2022), Figure 20 was created. Wind speed in the Gulf of Maine appears to be extremely variable as seen in Figure 20, where spokes appear for all directions. This could indicate that the site location may not be idea for a wind turbine, as typically one would prefer a site where wind comes consistently from one direction. Having variable wind makes it more difficult to orient the wind turbine correctly to ensure maximum power output and minimum structural stress. However, Figure 20 does show that the majority of the wind comes from the southwest direction for normal wind speeds. Yet, it is observed that more extreme wind speeds ranging from 12-30 m/s occur more frequently coming from the west or northwest. Using this observation in conjunction with the overall average wind direction obtained
from Table 10, wind in the Gulf of Maine location general directionality comes from the southwest for most cases but extreme winds are generated from the northwest. For the purpose of this research, a wind directionality of 300° cw from true North was used for average wind direction for more extreme wind conditions.

![Wind Rose](image)

*Figure 20: Wind Rose (Al Mac, 2012)*

It should also be observed that this directionality is measured from the anemometer height of 4.9 meters above sea level. For simplification, the assumption was made that the wind directionality does not change as observation height increases, thus the wind directionality at the anemometer height also represents the directionality at the hub height of the turbine.

### 5.2.4 Wind Gusts Profile and Extreme Conditions

Wind gusts are defined as a “sudden brief increase in wind speed” (DNV-RP-C205, 2014), typically having a duration less than 20 seconds and followed by a slowing of wind speed. A wind gust considered a natural fluctuation during a 10-minute wind speed sampling period. Data in this study, uses a 5-8 second gust speed measured at a height of 4.9 meters above sea level. The wind gusts were analyzed in a similar
way to average wind speed data. Figure 21 shows the average and maximum yearly wind gust speed over time.

As seen in the figure, the wind gust speed stays relatively consistent over 37 years, as does the maximum gust speed, with the exception of 1988, where the maximum wind gust exceeds 40 m/s. Excluding the outlier from 1988, the maximum wind gust ranges from 25 m/s to 35 m/s and the average wind gust speed hovers between 7 and 10 m/s with an overall average seen in Table 10 of 8.24 m/s.

The Power Rule Potential Profile was again used to extrapolate the wind gust speed from the sensor height of 4.9 meters to the hub height of 150 meters. At 150 meters, the average gust speed was found to be 13.30 m/s.

The Weibull distribution was then used to determine extreme conditions using the maximum wind gusts at the sensor height and then extrapolated to hub height as seen in Table 14.
Table 14: Extreme Wind Gust Speeds for Different Storm Return Periods

<table>
<thead>
<tr>
<th>Storm Return Period (yrs)</th>
<th>Extreme Wind Gust at 4.9m (m/s)</th>
<th>Extreme Wind Gust at 150m (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 year</td>
<td>33.22</td>
<td>48.40</td>
</tr>
<tr>
<td>50 year</td>
<td>36.52</td>
<td>53.21</td>
</tr>
<tr>
<td>100 year</td>
<td>37.60</td>
<td>54.78</td>
</tr>
</tbody>
</table>

This data was compared with Gómez et al (2015), who used similar analysis techniques for buoy E01, also located in the Gulf of Maine to find agreement between estimations. For the purpose of this analysis, the 50-year storm wind gust speed at 150 meters above sea level is measured to be 53.21 m/s.

5.2.5 Turbulence Intensity

Turbulence intensity is another descriptive parameter of wind speed needed to ensure accurate modeling. It is defined as “the ratio between the standard deviation of the wind speed and the 10-minute averaged wind speed” or the variability of the wind speed about the mean (DNV-RP-C205, 2014). Data obtained from Buoy 44005 did not include information regarding the standard deviation of the wind speed, nor did other buoys positioned in the Gulf of Maine. When this is the case, IEC 61400-1(2005) and DNV-RP C205 (2014) recommend using the wind turbine class to obtained parameters for turbulence intensity. The table below was taken from DNV-RP C205 (2014) and used for turbulence intensity parameters based on the wind turbine class and the reference wind speeds.
Defined in Chapter 3, the IEA 15MW Reference Wind Turbine is classified as a 1B turbine. From Figure 22, above, this classifies the turbine as having medium turbulence characteristics and a reference wind speed averaged over 10 minutes of 50 m/s. The reference turbulence intensity, $I_{\text{ref}}$, can be seen to be 0.14. This value is not site specific but is made to represent many different sites with similar conditions. Using these parameters for the turbine class, it can be guaranteed that the turbulence will generally be less severe or equal to the measured site conditions.

### 5.3 Wave Climate

Wave data was obtained from NOAA buoy 44005 for the significant wave height, dominant wave period, and average wave direction that the dominant wave period is coming from. The significant wave height and dominant wave period were analyzed using all 37 years of data provided by NOAA. The wave
directional data for buoy 44005 was not collected until 2016, as a result data was averaged from 2016 to 2021 to the wave direction.

The significant wave height is defined as the average wave height of the highest third of waves measured during the specified period (“Measurement Description and Units”, 2022). Figure 23 depicts the yearly average and yearly maximum significant wave height over time. Similar to the wind data, the average significant wave height remains relatively constant over the past 37 years, indicating that the average will be a valid estimate to use and represent the significant wave height. The average significant wave height depicted in Figure 23 and shown in Table 10 was found to be 1.52 meters above sea level.

The maximum significant wave height varies greatly over time ranging from around 5 meters above sea level to 12 meters above sea level as seen in Figure 23.

![Yearly Average Wave Height over Time](image)

**Figure 23: Yearly Average Wave Height Over Time**

### 5.3.1 Wave Height Profile and Extreme Conditions

The extreme conditions significant wave height was determined using the same method used to the extreme wind conditions, with the exception of using the Power Law for conditions at the hub height. The
Weibull Distribution is again used for estimating extreme significant wave height as described in Mackay and Johanning (2018). The histogram and Weibull Distribution of the significant wave height are shown in Figure 24 and show good agreement.

![Figure 24: Weibull Probability Distribution for All Wave Data (left) and Yearly Maximum Data (right)](image)

The Weibull distribution was then fit to the yearly maximum data, as it was for the wind speed, which yielded Weibull shape and scale coefficients of 5.446 and 7.927 respectively.

**Table 15: Weibull Distribution Parameters for Wave Height**

<table>
<thead>
<tr>
<th>Weibull Distribution Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale Coefficient (A)</td>
<td>7.927</td>
</tr>
<tr>
<td>Shape Coefficient (B)</td>
<td>5.446</td>
</tr>
</tbody>
</table>

These coefficients were used to determine the 10-year, 50-year, and 100-year significant wave heights shown in Table 16. These results were verified with Gómez et al. (2015) and Viselli et al. (2012) and showed agreement with both.

**Table 16: Extreme Wave Height for Different Storm Return Periods**

<table>
<thead>
<tr>
<th>Storm Return Period (yrs)</th>
<th>Extreme Significant Wave Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-year</td>
<td>9.24</td>
</tr>
<tr>
<td>50-year</td>
<td>10.18</td>
</tr>
<tr>
<td>100-year</td>
<td>10.49</td>
</tr>
</tbody>
</table>
Defined in IEC 61400-1 (2005) and DNV-RP C205 (2014), the wave height used for this simulation is the 50-year storm period with a significant wave height of 10.18 meters above mean sea level.

### 5.3.2 Wave Direction and Wave Rose

A wave rose was developed to depict wave direction in relation to wave height. The same MATLAB function from Al Mac (2022) was used for visualizing the wave direction, shown in Figure 25. Again, the directionality is measured in degrees clockwise from True North and wave direction appears to be very scatter similar to the wind rose, waves come from all directions. The majority of the waves come from the southeast direction, specifically between 120° and 180° clockwise from True North.

Unlike the wind directionality, there does not appear to be a significant difference in the wave height with directionality. From Figure 25, it is hard to distinguish if larger wave heights are coming from a specific direction. For this reason, the average wave direction was used for this study and determined to be 163.9 degrees clockwise from True North.

![Wave Rose](image)

*Figure 25: Wave Rose (Al Mac, 2012)*
5.3.3 Dominant Wave Period Characteristics

Waves can also be defined by their dominant wave period, the period that corresponds to the peak frequency and highest energy waves (“Measurement Descriptions and Units”, 2022). The averaged dominant wave period and maximum over time can be seen in Figure 26, where it ranges from 6.2 seconds to 8 seconds with an average of 7.38 seconds. For this simulation, the average value of 7.38 seconds was used.

![Dominant Wave Period over Time](image)

*Figure 26: Yearly Dominant Wave Period Over Time*

5.4 Sea Current and Other Climate Conditions

5.4.1 Sea Current

Ocean currents are an important part of analysis of a FOWT because they add additional fatigue stresses to the turbine over time. Furthermore, currents contribute to drag and lift forces on the floating platform and can interact with waves leading to variable wave heights and periods. Currents are induced by wind, tidal, circulation, and longshore currents and are typically measured in as a speed in m/s (DNV-RP-C205, 2014). Each type of current is caused by a different environmental factor and can be added together to
find the total current velocity at a chosen site. The different types of currents and their definitions are listed below:

- Wind generated currents: “caused by wind stress and atmospheric pressure gradient through a storm” (DNV-RP-C205, 2014),
- Tidal currents: regular currents based on the harmonic motions of the planet corresponding to high and low tide. Typically, they are weaker in deeper water and continue to strengthen closer to the shoreline,
- Turbidity currents: sometimes called circulational currents, are caused by the circulation of the ocean. They can also be caused by earthquakes,
- Longshore currents: typically found in coastal regions, are a result of the waves breaking on the shore.

Current velocity varies with water depth and time and is the sum of each of the current components defined above.

\[ V_c = V_{c,\text{wind}} + V_{c,\text{tide}} + V_{\text{circ}} + V_{\text{longshore}}, \quad \text{[Eq. 14]} \]

This equation determines the total current at a given time and location and is used in recommended practice for determining the current velocity.

Current speeds can also be calculated at different depths below the water level using prediction profiles. Tidal currents use the power law profile to determine velocities, whereas wind generated currents use a linear profile until a depth of \( \frac{1}{2} \) the total water depth is reached. At this point, the wind generated current will dissipate and current will mainly be caused by tides (DNV-RP-C205, 2014).

NOAA buoy 44005 does not include any current data. For this study, current data was taken from buoy E01 also located in the Gulf of Maine and values from Gómez et al. (2015) were used for implementation of current data into the model. These values are seen in Table 1 which shows the total current speed and wind and tidal induced current speeds at the mean water level for multiple storm return periods. For this research, the 50-year storm current speed of 1.13 m/s is used during the simulation.
Table 17: Current Data from NOAA Buoy E01 (Gómez et al., 2015)

<table>
<thead>
<tr>
<th>Return Period</th>
<th>Current Speed (m/s)</th>
<th>Wind Induced Current</th>
<th>Tides Induced Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>0.17</td>
<td>0.15</td>
<td>0.02</td>
</tr>
<tr>
<td>50-year Extreme</td>
<td>1.13</td>
<td>0.70</td>
<td>0.43</td>
</tr>
<tr>
<td>10-year Extreme</td>
<td>1.00</td>
<td>0.66</td>
<td>0.34</td>
</tr>
<tr>
<td>1-year Extreme</td>
<td>0.82</td>
<td>0.59</td>
<td>0.23</td>
</tr>
</tbody>
</table>

It should be noted that because the model that is considered for this simulation is a FOWT with a semi-submersible platform. Because the semi-submersible platform is relatively shallow, the current speed profile is neglected and the current is assumed to be acting at the mean sea level depth, or the surface of the water.

5.4.2 Mean Water Level

Mean sea level or mean water level is the “average level of the sea over a period long enough to remove variations due to waves, tides, and storm surges” (ABS Guide for Building and Classing Floating Offshore Wind Turbines, 2020). A similar procedure was followed for the sea level conditions. Data from buoy 44005 did not contain information relating to the sea level and tides. Instead, tidal data is taken from Gómez et al. (2015) which uses onshore Rockland station (8415490). The water level range can be described by the highest astronomical tide (HAT), lowest astronomical tide (LAT), highest observed water level, and lowest observed water level as seen in Table 18. The HAT and LAT are the highest and lowest water levels that are “expected to occur under average meteorological conditions and under any combination of astronomical conditions” (DNV-RP C205, 2014). They are determined over the span of many years.

Table 18: High and Low Extreme Wave Levels (Gómez et al., 2015)

<table>
<thead>
<tr>
<th>Extreme Water Levels</th>
<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest Observed Water Level</td>
<td>4.319</td>
</tr>
<tr>
<td>Highest Astronomical Tide (HAT)</td>
<td>3.22</td>
</tr>
<tr>
<td>Lowest Observed Water Level</td>
<td>-0.795</td>
</tr>
<tr>
<td>Lowest Astronomical Tide (LAT)</td>
<td>0</td>
</tr>
</tbody>
</table>
The highest and lowest observed water levels are relative to the still water level and defined as the “highest astronomical tide including storm surge” and the “lowest astronomical tide including negative storm surge” (DNV-RP C205, 2014). Typically, the highest and lowest observed water levels have a larger range than the HAT and LAT as seen with the values obtained from Gómez et al. (2015) in Table 18.

For this study, the highest observed water level and lowest observed water level are both used in the simulation to ensure that the most extreme conditions can be achieved and include storm surges.

### 5.4.3 Temperature and Density

Other climate conditions important to this study are the temperature and density of the water and the air. For design purposes, it was assumed that these values would be kept constant and are defined using recommendations from IEC 61400-1 (2005) and DNV-RP C205 (2014). The wind and water density are defined as 1.225 kg/m$^3$ and 1025 kg/m$^3$ respectively.

While a temperature range is not specified in the model, it should be noted that the normal temperature shall range from $-10^\circ$C to $40^\circ$C while the extreme temperature ranges from $-20^\circ$C to $50^\circ$C (ACP 61400-1-202, 2021).

### 5.5 Implementation of Climate Conditions into HAWC2 Model

The climate conditions defined in the previous sections were implemented into the HAWC2 code in different combinations to determine the most extreme wind-wave combination. Table 19 details each of the climate inputs in HAWC2 and where they were determined. Certain characteristics such as the wind density and the water density are defined in DNV-RP C205 (2014) as constant throughout all simulations. Other constant parameters such as the wind speed at hub height, the current speed, and the significant wave height, were defined by the 50-year extreme storm conditions through analyzation of site-specific data previously discussed. Average wind direction found in Chapter 5.2.3 with $\pm 8^\circ$ was used resulting in wind directions of $292^\circ$ and $308^\circ$ clockwise from true north chosen for analysis. Similarly, 3 mean water
levels were analyzed as the mean water level, 0 meters, the highest observed sea level, 4.319 meters, and the lowest observed sea level, -0.795 meters. The wave direction also had 3 inputs. The original direction of 0° was used as a baseline. Then the ±30° from the average direction of 163.9° were used resulting in wave directions of 133.9° and 193.9°. Table 19 shows input characteristics for the simulations.

<table>
<thead>
<tr>
<th>Climate Input</th>
<th>Value</th>
<th>Units</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Density</td>
<td>1.225</td>
<td>kg/m^3</td>
<td>Defined in Recommended Practice</td>
</tr>
<tr>
<td>Extreme Wind Speed at Hub Height</td>
<td>35.19</td>
<td>m/s</td>
<td>50-year storm</td>
</tr>
<tr>
<td>Water Density</td>
<td>1025</td>
<td>kg/m^3</td>
<td>Defined in Recommended Practice</td>
</tr>
<tr>
<td>Water Depth</td>
<td>200</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Significant Wave Height</td>
<td>10.18</td>
<td>m</td>
<td>50-year storm</td>
</tr>
<tr>
<td>Dominant Wave Period</td>
<td>7.383</td>
<td>sec</td>
<td></td>
</tr>
<tr>
<td>Wave Direction</td>
<td>0</td>
<td>deg</td>
<td>Origin Direction</td>
</tr>
<tr>
<td>Extreme Wind Gust Speed at Hub Height</td>
<td>53.21</td>
<td>m/s</td>
<td>50-year storm</td>
</tr>
<tr>
<td>Turbulence Intensity Ratio</td>
<td>0.11</td>
<td>-</td>
<td>Defined by Load Case DLC6.1</td>
</tr>
<tr>
<td>Turbulence Intensity Ratio</td>
<td>0.11</td>
<td>-</td>
<td>Defined by Load Case DLC6.1</td>
</tr>
<tr>
<td>Wind Shear Exponent (Power Profile)</td>
<td>0.11</td>
<td>-</td>
<td>Defined by Load Case DLC6.1</td>
</tr>
<tr>
<td>Water Shear Exponent (Power Profile)</td>
<td>0.11</td>
<td>-</td>
<td>Defined by Load Case DLC6.1</td>
</tr>
<tr>
<td>Extreme Current Speed</td>
<td>1.13</td>
<td>m/s</td>
<td>50-year storm</td>
</tr>
<tr>
<td>Mean Water Level</td>
<td>0</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Depth of Water</td>
<td>200</td>
<td>m</td>
<td>Depth to seabed</td>
</tr>
<tr>
<td>Highest Observed Sea Level</td>
<td>4.319</td>
<td>m</td>
<td>Above mwl</td>
</tr>
<tr>
<td>Lowest Observed Sea Level</td>
<td>-0.795</td>
<td>m</td>
<td>Below mwl</td>
</tr>
</tbody>
</table>

5.6 Further Investigation of Load Case and Revised Input Conditions

Upon further investigation of the DLC 6.1, it was determined that certain characteristics from Table 19 were implemented incorrectly into the simulations. As a result, a second set of input conditions and simulations were run with the new conditions.

First, Table 19 uses the average dominant wave period of 7.383 seconds. It was determined that this wave period does not align with the 50-year significant wave height of 10.18 meters. As a results, the 50-year extreme dominant wave period characteristics were evaluated using the Weibull Distribution. Results can
be seen in Table 20, which details the 10-year, 50-year, and 100-year dominant wave periods. These values fall within the range of 9-16 seconds found in Gómez et al. (2015) and is closely aligned with results from Viselli et al. (2015).

*Table 20: Dominant Wave Period Extreme Conditions*

<table>
<thead>
<tr>
<th>Storm Return Period (yrs)</th>
<th>Extreme Dominant Wave Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-year</td>
<td>10.73</td>
</tr>
<tr>
<td>50-year</td>
<td>12.64</td>
</tr>
<tr>
<td>100-year</td>
<td>13.29</td>
</tr>
</tbody>
</table>

In addition, the 50-year dominant wave period was verified in Figure 27 which plots the wave height vs. the dominant wave period. The black line identifies the 50-year extreme wave height of 10.18 meters and matches it to the dominant wave period of 12.64 seconds from Table 17 to confirm that this wave height and period combination is accurate. The red line represents the average dominant wave period used in the first set of models and it can be observed that this does not match with the 50-year dominant wave height. As a result, the 50-year extreme dominant wave period replaced the average wave period in the second set of simulations.

*Figure 27: Wave Height vs. Dominant Wave Period*
In addition, DLC 6.1 characterizes the yaw direction as ±8°, not the wind directionality changing ±8°. For the second set of simulations the average wind direction of 300° was used with yaw angle directions of 0°, +8°, -8° were used. For simulation purposes, it was assumed that the turbine is orientated in the extreme wind direction. Wind direction was also considered using only the average wave direction of 163.89° clockwise from true north was used along with a 0° direction as a baseline. This results in Table 21 which details the second set of simulation input characteristics in full.

Table 21: HAWC2 Simulation 2 Input Characteristics

<table>
<thead>
<tr>
<th>Climate Input</th>
<th>Value</th>
<th>Units</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Density</td>
<td>1.225</td>
<td>kg/m³</td>
<td>Defined in Recommended Practice</td>
</tr>
<tr>
<td>Extreme Wind Speed at Hub Height</td>
<td>35.19</td>
<td>m/s</td>
<td>50-year storm</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>300.00</td>
<td>deg</td>
<td>Clockwise from true North</td>
</tr>
<tr>
<td>Yaw Direction</td>
<td>±8°</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td>Extreme Wind Gust Speed at Hub Height</td>
<td>53.21</td>
<td>m/s</td>
<td>50-year storm</td>
</tr>
<tr>
<td>Turbulence Intensity Ratio</td>
<td>0.11</td>
<td>-</td>
<td>Defined by Load Case DL6.1</td>
</tr>
<tr>
<td>Wind Shear Exponent (Power Profile)</td>
<td>0.11</td>
<td>-</td>
<td>Defined By Load Case DL6.1</td>
</tr>
<tr>
<td>Water Density</td>
<td>1025</td>
<td>kg/m³</td>
<td>Defined in Recommended Practice</td>
</tr>
<tr>
<td>Water Depth</td>
<td>200</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Significant Wave Height</td>
<td>10.18</td>
<td>m</td>
<td>50-year storm</td>
</tr>
<tr>
<td>Dominant Wave Period</td>
<td>12.637</td>
<td>sec</td>
<td></td>
</tr>
<tr>
<td>Wave Direction</td>
<td>163.89</td>
<td>deg</td>
<td>Clockwise from true North</td>
</tr>
<tr>
<td>Extreme Current Speed</td>
<td>1.13</td>
<td>m/s</td>
<td>50-year storm</td>
</tr>
<tr>
<td>Mean Water Level</td>
<td>0</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Depth of Water</td>
<td>200</td>
<td>m</td>
<td>Depth to seabed</td>
</tr>
<tr>
<td>Highest Observed Sea Level</td>
<td>4.319</td>
<td>m</td>
<td>Above mwl</td>
</tr>
<tr>
<td>Lowest Observed Sea Level</td>
<td>-0.795</td>
<td>m</td>
<td>Below mwl</td>
</tr>
</tbody>
</table>
CHAPTER 6: RESULTS

Results analyzed in this report focus on the stress in the tower under different loading conditions. First, the original 18 different combinations of wind and wave input conditions were analyzed in for maximum, average, and fatigue stresses. The coupled analysis of one load case was then compared to the uncoupled analysis with the same input conditions. Lastly, a sensitivity analysis was completed to determine how changes in input conditions affect the output stresses. Below is the naming convention that was used to describe wind-wave input conditions that were used for the original set of simulations. In the following sections, this naming convention will be used when discussing load cases.

Table 22: Original Load Case Nomenclature

<table>
<thead>
<tr>
<th>Wind Direction (deg)</th>
<th>Mean Water Level (m)</th>
<th>Wave Direction (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wdir292_mwl0795_wvdir0</td>
<td>292</td>
<td>-0.795</td>
</tr>
<tr>
<td>wdir292_mwl0795_wvdir133</td>
<td>292</td>
<td>-0.795</td>
</tr>
<tr>
<td>wdir292_mwl0795_wvdir193</td>
<td>292</td>
<td>-0.795</td>
</tr>
<tr>
<td>wdir292_mwl0_wvdir0</td>
<td>292</td>
<td>0</td>
</tr>
<tr>
<td>wdir292_mwl0_wvdir133</td>
<td>292</td>
<td>0</td>
</tr>
<tr>
<td>wdir292_mwl0_wvdir193</td>
<td>292</td>
<td>0</td>
</tr>
<tr>
<td>wdir292_mwl432_wvdir0</td>
<td>292</td>
<td>4.32</td>
</tr>
<tr>
<td>wdir292_mwl432_wvdir133</td>
<td>292</td>
<td>4.32</td>
</tr>
<tr>
<td>wdir292_mwl432_wvdir193</td>
<td>292</td>
<td>4.32</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir0</td>
<td>308</td>
<td>-0.795</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir133</td>
<td>308</td>
<td>-0.795</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir193</td>
<td>308</td>
<td>-0.795</td>
</tr>
<tr>
<td>wdir308_mwl0_wvdir0</td>
<td>308</td>
<td>0</td>
</tr>
<tr>
<td>wdir308_mwl0_wvdir133</td>
<td>308</td>
<td>0</td>
</tr>
<tr>
<td>wdir308_mwl0_wvdir193</td>
<td>308</td>
<td>0</td>
</tr>
<tr>
<td>wdir308_mwl432_wvdir0</td>
<td>308</td>
<td>4.32</td>
</tr>
<tr>
<td>wdir308_mwl432_wvdir133</td>
<td>308</td>
<td>4.32</td>
</tr>
<tr>
<td>wdir308_mwl432_wvdir193</td>
<td>308</td>
<td>4.32</td>
</tr>
</tbody>
</table>

Figure 28 further, details the assumptions made about the wind and wave directionality in the original load cases. As seen, it was originally assumed that the wind turbine was not rotated in the direction of the maximum wind speed and instead was oriented towards the wind rose origin. In the following section the results for this orientation will be described.
6.1 Coupled Wind-Wave Analysis

First, 18 wind-wave combinations were evaluated based on DLC 6.1 described in Chapter 4. These load combinations were simulated using 600 second HAWC2 simulations with 50-year storm inputs analyzed in Chapter 5. Each combination used a total of 6 turbulence seeds to accommodate for the recommended 1-hour simulation time for complete design results. Maximum and average results were multiplied by DLC 6.1 partial safety factor of 1.35 and evaluated against the approximate yield strength of $3.55 \times 10^5$ kPa.

6.1.1 Average Results

The simulations provided forces and moments at the tower top and base and conventional textbook equations were used with the tower cross-sectional properties to calculate the normal and shear stresses in the tower over time. The combined stresses were then multiplied by the partial safety factor for DLC 6.1. Averages of combined shear and normal stresses were then calculated from the time series data. Figure 28
depicts the average normal stress at the tower base for each load case for comparison. As shown, the tower base stress is greatest for load combination wdir292_mwl432_wvdir193 which has an average combined stress of 107,153 kPa. However, the average base stresses appear relatively constant between all load cases. It ranges from 100,151 kPa to 107,153 kPa. This is expected as the input conditions do not change drastically between load cases.

![Tower Base Average Normal Stress](image)

**Figure 29: Tower Base Average Design Stress for All Load Combinations**

The base stresses were then normalized to the approximated yield stress of 3.55*10^5 kPa (Igwemezie et al, 2018). This is shown in Table 23 which present the average design normal stresses and the average design shear stresses for all load cases for comparison divided by the approximate yield stress. An interesting observation of note is that load cases where the wind direction is 308º clockwise from true North produce average results that are slightly lower than load cases where the wind direction is 292º clockwise from true North. This could be because of the wind-wave misalignment is greater when wind directionality is 308º causing lower stresses. In addition, when the water level is at the HAWT of 4.32 meters above sea level, average normal stresses appear the greatest.
Table 23: Average Combined Design Stress Normalized to Yield Stress

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$</th>
<th>$\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>wdir292_mwl0795_wvdir0</td>
<td>0.2983</td>
<td>0.01738</td>
</tr>
<tr>
<td>wdir292_mwl0795_wvdir133</td>
<td>0.2938</td>
<td>0.01764</td>
</tr>
<tr>
<td>wdir292_mwl0795_wvdir193</td>
<td>0.2964</td>
<td>0.01769</td>
</tr>
<tr>
<td>wdir292_mwl0_wvdir0</td>
<td>0.2965</td>
<td>0.01731</td>
</tr>
<tr>
<td>wdir292_mwl0_wvdir133</td>
<td>0.2913</td>
<td>0.01717</td>
</tr>
<tr>
<td>wdir292_mwl0_wvdir193</td>
<td>0.2918</td>
<td>0.01729</td>
</tr>
<tr>
<td>wdir292_mwl432_wvdir0</td>
<td>0.3013</td>
<td>0.01766</td>
</tr>
<tr>
<td>wdir292_mwl432_wvdir133</td>
<td>0.3005</td>
<td>0.01766</td>
</tr>
<tr>
<td>wdir292_mwl432_wvdir193</td>
<td>0.3018</td>
<td>0.01807</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir0</td>
<td>0.2854</td>
<td>0.01642</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir133</td>
<td>0.2821</td>
<td>0.01671</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir193</td>
<td>0.2842</td>
<td>0.01682</td>
</tr>
<tr>
<td>wdir308_mwl0_wvdir0</td>
<td>0.2880</td>
<td>0.01644</td>
</tr>
<tr>
<td>wdir308_mwl0_wvdir133</td>
<td>0.2887</td>
<td>0.01684</td>
</tr>
<tr>
<td>wdir308_mwl0_wvdir193</td>
<td>0.2858</td>
<td>0.01694</td>
</tr>
<tr>
<td>wdir308_mwl432_wvdir0</td>
<td>0.2915</td>
<td>0.01653</td>
</tr>
<tr>
<td>wdir308_mwl432_wvdir133</td>
<td>0.2836</td>
<td>0.01646</td>
</tr>
<tr>
<td>wdir308_mwl432_wvdir193</td>
<td>0.2876</td>
<td>0.01683</td>
</tr>
</tbody>
</table>

The shear stresses calculated at the tower base appear to be much smaller than the normal stresses. This can be seen visually in Figure 30 which breaks down each of the stresses for wdir292_mwl432_wvdir193 to determine which one dominates the design. The moments about the x axis create the largest stresses experienced at the tower bottom followed by moment about the y axis and axial forces. This is due to the input direction of the wind and wave conditions. The wind speed coming from the northwest and the waves coming from southwest create a large back and forth movement and force on the turbine tower which causes a large fore aft moment and stress to occur. However, because the wind and wave conditions are not implemented exactly along the axis, a secondary side-to-side moment is also created which causes the stress in the y direction. Much of the weight of the turbine (blades and RNA) is concentrated at the top of the tower, creating a large axial stress as well.
In addition, the shear stresses appear to be significantly smaller than the normal stresses as designated in Figure 30. The lowest stress appears to be torsion with a magnitude of only 1,316 kPa which is significantly less than the stress caused by the fore aft moment of 61,703 kPa. This is because of the stiffness of the tower specified in the model. With the tower being designed as a steel tube with a high stiffness, it ensures that twisting will be minimal. Because shear stresses have a minimal effect on the overall stress in the tower, they will be neglected in results going forward.

In addition to checking stresses at the base of the tower, it is important to consider stresses occurring at the tower top as well. This can be seen in Figure 31, which shows the combined normal and combined shear stresses at the tower top and tower base for comparison. As seen, the stresses at the base of the tower far exceed the stresses at the top of the tower. This is because of the application of the loading applied to the turbine. The turbine tower act similarly to a cantilever beam with a distributed wind load applied along its length and concentrated point loads at the end or tower top. This creates the maximum
moment and shear at the tower base compared to the tower top. This also describes why the tower cross sectional properties decrease with height of the tower.

A second observation is that the shear at the tower top is greater than the normal stress at the tower top. This is also due to the application of the loading on the tower. While the normal stress at the tower top will be smaller, there is a greater magnitude of wind shear force applied to the top of the tower. In addition, the top of the tower is allowed more torsion than the base because it is not a fixed constraint.

![Average Stress Tower Top vs Tower Bottom for wdir292_mwl432_wvdir193](image)

Figure 31: Average Stress in Tower Top vs. Tower Base for wdir292_mwl432_wvdir193

6.1.2 Maximum Results

Similar to averages, the maximum stress was calculated using conventional textbook equations. Figure 32 shows the results of the maximum tower base design stress for all combinations of wind and wave input conditions.

As shown in Figure 31, the ultimate load case with the worst conditions is the wdir292_mwl432_wvdir193, which produces a maximum stress magnitude at the tower base of 380,431
kPa. This is the same load case that provided the worst-case stress magnitude for average results, however, using maximum stresses the differences can be observed more clearly.

![Figure 32: Tower Base Maximum Design Normal Stress for All Load Cases](image)

An interesting trend to note that is clearly seen in the maximum data is that wind coming from 292° from true north produces larger maximum tower base stresses in general than wind coming from 308° from true north. This can be seen in Table 2 which depicts the design stress normalized to the approximated yield stress of \(3.55 \times 10^5\) kPa (Igwemezie et al., 2018). As discussed with average results, this could be because of the wind-wave misalignment is greater when wind directionality is 308°.

A second observation of note is that multiple input conditions produce stress that exceed the approximated allowable yield stress of the tower. Load case `wdir292_mwl0795_wvdir193` and `wdir292_mwl432_wvdir193` both produce maximum tower base stresses above the yield stress. Other load cases produce stresses that come close to yielding as well. While not a part of the scope of this research, a more in-depth study of the construction materials should be considered to increase the strength and durability of the tower to resist ultimate loads. In addition, Subbulakshmi et al. has references that
materials such as concrete and steel that are currently used in FOWT construction will soon be replaced with composite materials that will consider this durability to environmental loading (Subbulakshmi et al., 2022).

Table 24: Maximum Combined Design Stresses Normalized to Yield Stress

<table>
<thead>
<tr>
<th></th>
<th>( \sigma )</th>
<th>( \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>wdir292_mwl0795_wvdir0</td>
<td>0.99</td>
<td>0.061</td>
</tr>
<tr>
<td>wdir292_mwl0795_wvdir133</td>
<td>0.97</td>
<td><strong>0.067</strong></td>
</tr>
<tr>
<td>wdir292_mwl0795_wvdir193</td>
<td><strong>1.05</strong></td>
<td>0.060</td>
</tr>
<tr>
<td>wdir292_mwl10_wvdir0</td>
<td>0.88</td>
<td>0.056</td>
</tr>
<tr>
<td>wdir292_mwl10_wvdir133</td>
<td>0.85</td>
<td>0.051</td>
</tr>
<tr>
<td>wdir292_mwl10_wvdir193</td>
<td>0.80</td>
<td>0.053</td>
</tr>
<tr>
<td>wdir292_mwl432_wvdir0</td>
<td>0.92</td>
<td>0.058</td>
</tr>
<tr>
<td>wdir292_mwl432_wvdir133</td>
<td>0.89</td>
<td>0.055</td>
</tr>
<tr>
<td>wdir292_mwl432_wvdir193</td>
<td><strong>1.07</strong></td>
<td>0.062</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir0</td>
<td>0.78</td>
<td>0.048</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir133</td>
<td>0.79</td>
<td>0.047</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir193</td>
<td>0.89</td>
<td>0.049</td>
</tr>
<tr>
<td>wdir308_mwl10_wvdir0</td>
<td>0.80</td>
<td>0.051</td>
</tr>
<tr>
<td>wdir308_mwl10_wvdir133</td>
<td>0.86</td>
<td>0.053</td>
</tr>
<tr>
<td>wdir308_mwl10_wvdir193</td>
<td>0.78</td>
<td>0.045</td>
</tr>
<tr>
<td>wdir308_mwl432_wvdir0</td>
<td>0.74</td>
<td>0.045</td>
</tr>
<tr>
<td>wdir308_mwl432_wvdir133</td>
<td>0.69</td>
<td>0.044</td>
</tr>
<tr>
<td>wdir308_mwl432_wvdir193</td>
<td>0.76</td>
<td>0.052</td>
</tr>
</tbody>
</table>

Table 24 also shows the design shear stress normalized to the same yield stress. The maximum shear stress comes from wdir292_mwl0795_wvdir133, however, shear stress appears to have a minuscule effect on the overall stress in the tower and is therefore neglected in the rest of this study.

6.1.3 Fatigue Results

The tower base stress was then evaluated from a fatigue perspective to determine the worst-case scenario. A MATLAB function created by Carlos Souto (2022), was used to evaluate the cumulative fatigue damage from a stress time history using the Palmgren-Miner rule, Eurocode 3 EN 1993-1-9 and ASTM E1049-85. The fatigue damage accumulation function used provides the evaluated time history (A), a plot of local extrema (B), the rainflow histogram for cycle counting of stress ranges (C), the S-N fatigue
strength curve (D), and the cumulative fatigue damage based on the Palmgren-Miner Rule (E). A cumulative damage of greater than 1 indicates fatigue failure of the structure, while damage less than 1 is indicated in Figure 33 by a green bar.

The tower base stress time history was used in this analysis because it was determined that the tower base would experience the most significant stress magnitudes in comparison with the tower top. Stress time history used accounts for the bending stress (roll and pitch) and the axial (heave) stress in the vertical direction. Shear stresses (yaw, sway, and surge) were not included in fatigue analysis because of their insignificant effects on the tower base described in the previous section.

Table 25, below, shows the total damage accumulation from all 18 load combinations. Fatigue damage for all load cases was found to be less than 1 with an average of $4.45 \times 10^{-5}$ and a maximum of $5.50 \times 10^{-5}$ indicating that no load case failed under fatigue damage conditions. This can be explained by the misalignment of the wind and waves. Previous studies indicate that misaligned wind and waves produce lower fatigue values and worse fatigue cases occur when wind and wave directionality is aligned (Bachynski et al., 2014). Similar to results found in maximum and average stress results, when waves are more closely aligned, it produces a higher total cumulative fatigue damage as seen in Table 25.

The worst-case load scenario for fatigue was found to be a wind direction 308° clockwise from true north, a mean water level of -0.795 meters below mean sea level (lowest astronomical tide level), and a wave direction of 0° clockwise from true north. Figure 32 shows the fatigue damage accumulation function outputs graphs for this worst-case scenario.
Table 25: Fatigue Damage Accumulation for All Load Cases

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Total Damage Accumulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>wdir292_mwl0795_wvdir0</td>
<td>4.02E-05</td>
</tr>
<tr>
<td>wdir292_mwl0795_wvdir133</td>
<td>4.56E-05</td>
</tr>
<tr>
<td>wdir292_mwl0795_wvdir193</td>
<td>4.82E-05</td>
</tr>
<tr>
<td>wdir292_mwl0_wvdir0</td>
<td>3.82E-05</td>
</tr>
<tr>
<td>wdir292_mwl0_wvdir133</td>
<td>3.52E-05</td>
</tr>
<tr>
<td>wdir292_mwl0_wvdir193</td>
<td>3.60E-05</td>
</tr>
<tr>
<td>wdir292_mwl1432_wvdir0</td>
<td>3.84E-05</td>
</tr>
<tr>
<td>wdir292_mwl1432_wvdir133</td>
<td>3.79E-05</td>
</tr>
<tr>
<td>wdir292_mwl1432_wvdir193</td>
<td>5.13E-05</td>
</tr>
<tr>
<td><strong>wdir308_mwl0795_wvdir0</strong></td>
<td><strong>5.50E-05</strong></td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir133</td>
<td>4.34E-05</td>
</tr>
<tr>
<td>wdir308_mwl0795_wvdir193</td>
<td>5.15E-05</td>
</tr>
<tr>
<td>wdir308_mwl0_wvdir0</td>
<td>5.30E-05</td>
</tr>
<tr>
<td>wdir308_mwl0_wvdir133</td>
<td>4.81E-05</td>
</tr>
<tr>
<td>wdir308_mwl0_wvdir193</td>
<td>5.31E-05</td>
</tr>
<tr>
<td>wdir308_mwl1432_wvdir0</td>
<td>4.57E-05</td>
</tr>
<tr>
<td>wdir308_mwl1432_wvdir133</td>
<td>3.43E-05</td>
</tr>
<tr>
<td>wdir308_mwl1432_wvdir193</td>
<td>4.65E-05</td>
</tr>
</tbody>
</table>

The S-N curve created in Figure 33 used default conditions of slope one equal to 3 and slope two equal to 5 which describes curve classes D through G for non-tubular details in air and seawater and the tubular detail curve class, T, as defined in ABS Guide for Fatigue Assessment of Offshore Structures (ABS. Guide for Fatigue Assessment of Offshore Structures, 2020). It does not focus on a specific design detail, rather uses the overall stress at the bottom of the tower. This was done in order to get a general idea of how the tower performs under fatigue loading. In addition, the detail category that was used was 160, which is defined in the Eurocode 3 EN 1993-1-9 as the highest detail level (Eurocode 3 EN 1993-1-9, 2005). During final design and construction, it is important to consider all curve classes based on which details are present as well as consider possible stress concentrations. However, as seen in Table 25, the total damage accumulation for all load cases appears to be small and the yielding described in previous sections is likely the controlling factor in design of the turbine tower.
6.2 Coupled vs. Uncoupled Analysis

Using the worst-case fatigue loading scenario (wdir308_mwl0795_wvdir0), an uncoupled analysis was performed to determine the effects of coupling on the simulation. This analysis helps to determine if complex, time consuming coupled analysis of FOWT is necessary or if uncoupled analysis could be suitable for preliminary design.

To perform the uncoupled analysis, wind and wave conditions were inputted separately into the simulation, then results were added together. For wind only simulations, the water kinematics DLL was removed from the simulations, taking out the dynamic wave and current loading applied to the structure. For wave only simulations, the wind speed was set to 0 m/s and the wind shear, turbulence, and tower shadow effect were removed from the simulation. Once the individual simulations were completed, the
tower bottom stress was calculated at each time step and the wind and wave simulations were added together to create the uncoupled wind-wave model. This can be seen in Figure 34 which depicts the wind and wave stress time history individually as well as the wind-wave time history added together.

![Uncoupled Stress](image)

**Figure 34: Wind and Wave Uncoupled Stress Time History**

Figure 34 not only shows how the wind and wave analyses were added together, but also helps to identify which loading contributes the most to tower base stress. As shown, wind loading conditions appear to have a much more significant effect on the tower than wave loading does. This is expected as the wind loading is applied to the top of the tower and creates a much larger moment at the base than hydrodynamic loading that is applied at the base.

The uncoupled wind and wave analysis was then compared to the coupled analysis in the time stress time history plot shown in Figure 35. It shows that the uncoupled analysis almost always over predicts the stress compared to the coupled analysis. This shows that coupling the wind and wave analysis together produces a damping effect and indicates that an uncoupled analysis is acceptable for preliminary design of FOWTs, but a coupled analysis is needed for final design to ensure accurate results.
Figure 35: Coupled vs. Uncoupled Stress Time History

Figure 35 also zooms in on a section of stress from 500 to 550 seconds to better show how the coupled and uncoupled analysis compare. As seen, the coupled analysis appears to have smaller stress values with more variation than the uncoupled analysis does. The peak stresses appear at the same time step but the variation between peak stresses is not found in an uncoupled analysis. This can be attributed to the nonlinear nature of the analysis. Adding separate wind and wave analyses together does not account for the nonlinear behavior that occurs when a FOWT experiences wind and wave loads together.

A comparison of uncoupled and coupled results can also be seen in Table 26 which shows maximum and average results for all axial and bending stresses. As expected, the uncoupled analysis showed that the x and y stress were the most significant followed by axial. Axial and x stresses for the uncoupled analysis
tended to be 2x larger than the coupled analysis. While y stresses were larger for the coupled analysis. Overall, the uncoupled analysis was found to have 1.5 to 1.7 times larger stress results than the coupled analysis. This again reinforces the idea that an uncoupled analysis is adequate for preliminary design, however, a coupled analysis is necessary for final design to prevent over designing.

Table 26: Coupled vs. Uncoupled Stress Results

<table>
<thead>
<tr>
<th></th>
<th>Coupled Analysis</th>
<th>Uncoupled Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average Values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\sigma_x) (kPa)</td>
<td>4.24E+04</td>
<td>8.95E+04</td>
</tr>
<tr>
<td>(\sigma_y) (kPa)</td>
<td>2.42E+04</td>
<td>1.91E+04</td>
</tr>
<tr>
<td>(\sigma_{axial}) (kPa)</td>
<td>8.45E+03</td>
<td>1.69E+04</td>
</tr>
<tr>
<td>(\sigma_{combined}) (kPa)</td>
<td>7.50E+04</td>
<td>1.25E+05</td>
</tr>
<tr>
<td><strong>Maximum Values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\sigma_x) (kPa)</td>
<td>1.67E+05</td>
<td>2.53E+05</td>
</tr>
<tr>
<td>(\sigma_y) (kPa)</td>
<td>6.12E+04</td>
<td>8.49E+04</td>
</tr>
<tr>
<td>(\sigma_{axial}) (kPa)</td>
<td>9.86E+03</td>
<td>1.79E+04</td>
</tr>
<tr>
<td>(\sigma_{combined}) (kPa)</td>
<td>2.06E+05</td>
<td>3.04E+05</td>
</tr>
</tbody>
</table>

The uncoupled and coupled analysis were also compared for fatigue and result in a total fatigue damage accumulation shown in Table 27. As expected, the uncoupled analysis produces more fatigue damage than the coupled analysis and results in a total damage accumulation 2x larger than the coupled analysis.

Table 27: Coupled vs. Uncoupled Fatigue Damage Results

<table>
<thead>
<tr>
<th>Total Damage Accumulation</th>
<th>Coupled Analysis</th>
<th>Uncoupled Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.50E-05</td>
<td>1.11E-04</td>
<td></td>
</tr>
</tbody>
</table>

6.3 Sensitivity Study

Lastly, a sensitivity analysis was completed to determine how the model simulation responses to changes in wind speed and wave height. The wind speed and wave height were increased by 5%, 10%, and 15%, adding an additional 15 model simulations. The additional wind and wave conditions created can be seen in Table 28.
Table 28: Sensitivity Analysis Input Conditions

<table>
<thead>
<tr>
<th>Wave Height (m)</th>
<th>0%</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wind speed=</td>
<td>wind speed=</td>
<td>wind speed=</td>
<td>wind speed=</td>
</tr>
<tr>
<td></td>
<td>35.19</td>
<td>36.95</td>
<td>38.71</td>
<td>40.47</td>
</tr>
<tr>
<td></td>
<td>wave height=</td>
<td>wave height=</td>
<td>wave height=</td>
<td>wave height=</td>
</tr>
<tr>
<td></td>
<td>10.18</td>
<td>10.18</td>
<td>10.18</td>
<td>10.18</td>
</tr>
<tr>
<td></td>
<td>wind speed=</td>
<td>wind speed=</td>
<td>wind speed=</td>
<td>wind speed=</td>
</tr>
<tr>
<td></td>
<td>35.19</td>
<td>36.95</td>
<td>38.71</td>
<td>40.47</td>
</tr>
<tr>
<td></td>
<td>wave height=</td>
<td>wave height=</td>
<td>wave height=</td>
<td>wave height=</td>
</tr>
<tr>
<td></td>
<td>10.69</td>
<td>10.69</td>
<td>10.69</td>
<td>10.69</td>
</tr>
<tr>
<td></td>
<td>wind speed=</td>
<td>wind speed=</td>
<td>wind speed=</td>
<td>wind speed=</td>
</tr>
<tr>
<td></td>
<td>35.19</td>
<td>36.95</td>
<td>38.71</td>
<td>40.47</td>
</tr>
<tr>
<td></td>
<td>wave height=</td>
<td>wave height=</td>
<td>wave height=</td>
<td>wave height=</td>
</tr>
<tr>
<td></td>
<td>11.20</td>
<td>11.20</td>
<td>11.20</td>
<td>11.20</td>
</tr>
<tr>
<td></td>
<td>wind speed=</td>
<td>wind speed=</td>
<td>wind speed=</td>
<td>wind speed=</td>
</tr>
<tr>
<td></td>
<td>35.19</td>
<td>36.95</td>
<td>38.71</td>
<td>40.47</td>
</tr>
<tr>
<td></td>
<td>wave height=</td>
<td>wave height=</td>
<td>wave height=</td>
<td>wave height=</td>
</tr>
<tr>
<td></td>
<td>11.71</td>
<td>11.71</td>
<td>11.71</td>
<td>11.71</td>
</tr>
</tbody>
</table>

The sensitivity analysis was performed using the coupled model as described previously due to its more accurate results and shear stresses were neglected as they have a minimal effect on the overall stress.

Figure 36 graphically shows the results of the sensitivity analysis and the trend lines that result. The figures show that as wind speed and wave height increase, the average stress at the tower base increases.

It also shows that there is a linear relationship between wind speed and average stress and wave height and average stress.

One observation of note is that the slope of the lines in the stress vs. wave height graph is greater than the slope of the line in stress vs. wind speed. This signifies that the wave height causes a greater change in stress than the wind speed does. This is further justified in Table 29 and Table 30 which define the slope and y intercept parameters for a linear fit of each line where it can be seen that the linear slopes for graphs of wave height vs. stress are almost twice as big as those for wind speed vs. stress.
Figure 36: Sensitivity Analysis Average Stress vs. Wind and Wave Results

Table 29: Polyfit Parameters Wave Height vs Stress

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Slope</th>
<th>Intercept (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>35.19</td>
<td>3643</td>
<td>38298</td>
</tr>
<tr>
<td>36.95</td>
<td>2376</td>
<td>55149</td>
</tr>
<tr>
<td>38.72</td>
<td>3131</td>
<td>49909</td>
</tr>
<tr>
<td>40.47</td>
<td>3061</td>
<td>54126</td>
</tr>
</tbody>
</table>

Table 30: Polyfit Parameters, Wind Speed vs Stress

<table>
<thead>
<tr>
<th>Wave Height (m)</th>
<th>Slope</th>
<th>Intercept (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.18</td>
<td>1912</td>
<td>8168</td>
</tr>
<tr>
<td>10.69</td>
<td>1713</td>
<td>17073</td>
</tr>
<tr>
<td>11.2</td>
<td>1679</td>
<td>20076</td>
</tr>
<tr>
<td>11.71</td>
<td>1828</td>
<td>15968</td>
</tr>
</tbody>
</table>
The percent change in stress compared to the original input conditions was also calculated and can be seen in Table 31. It agrees with results found in the using the graphs and linear fit in that the change in wave height has a greater effect on the stress than a change in wind speed does.

**Table 31: Percentage Change in Stress for Change in Input Conditions**

<table>
<thead>
<tr>
<th>Percentage Change in Wave Height</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage Change in Wind Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.00</td>
<td>3.41</td>
<td>5.82</td>
<td>7.45</td>
</tr>
<tr>
<td>5</td>
<td>6.15</td>
<td>6.67</td>
<td>8.97</td>
<td>10.77</td>
</tr>
<tr>
<td>10</td>
<td>8.95</td>
<td>11.09</td>
<td>13.40</td>
<td>15.28</td>
</tr>
<tr>
<td>15</td>
<td>14.03</td>
<td>15.34</td>
<td>17.48</td>
<td>20.25</td>
</tr>
</tbody>
</table>

Table 31 shows, that while, there is an increase in stress as wind speed increases, the model simulation is not significantly sensitive to a change in wind speed. For a wind speed increase of 15%, the average stress at the tower base only increased by 7.45%. The simulation appears to be more sensitive to changes in wave height. For a 15% change in wave height, the average tower base stress increased by 14.03%. The stress appears to increase at the same rate as wave height. This can be explained by the implementation of the forces in the model. Mooring forces caused by waves and currents are implemented as external forces calculated through an external DLL that calculates water kinematics. Wind speeds are directly used to calculate wind shear within the HAWC2 program. Furthermore, as the wave height increases it results in more nonlinearity in the model (Karimirad, 2013).

A fatigue analysis was also done for the sensitivity study. This is seen in Figure 37 which shows the linear damage accumulation at the tower base for all the sensitivity load cases. Similar to the average stress results, as the wind speed and wave height increase, the fatigue damage also increases. However, the relationship does not appear to be linear. This is due to the transfer functions between the base and the tower and their nonlinear relationship. There appears to be an increasing trend as wave height increases but no significant trend as wind speed increases.
As stated in Chapter 5.6, certain input conditions for previous results do not represent the most realistic simulations that a wind turbine would experience and resulted in the tower yielding that is seen in Chapter 6.1.2, where the maximum results exceed the approximated yield stress. As a result, a new set of simulations was run using new conditions, previously described in Chapter 5.6, which results in the load cases shown in Table 32. These results include changes in the yaw angle of the turbine and the assumption that the turbine is consistently oriented in the maximum wind direction. In addition, a clearer picture of the wind turbine orientation and wind and wave orientation can be seen in Figure 38. For new results it was assumed that the turbine was orientated in the direction of the maximum wind direction as opposed to original results which had the turbine facing towards the origin. These load cases were simulated, and new results are described in the following subsections, including differences and similarities between original and new results.
## Table 32: Load Case Nomenclature for Revised Simulations

<table>
<thead>
<tr>
<th>Wind Direction (deg)</th>
<th>Mean Water Level (m)</th>
<th>Wave Direction (deg)</th>
<th>Yaw Angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wdir300_mwl0_wvdir0_yaw0</td>
<td>300</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>wdir300_mwl-4.32_wvdir0_yaw0</td>
<td>300</td>
<td>-4.32</td>
<td>0</td>
</tr>
<tr>
<td>wdir300_mwl0.795_wvdir0_yaw0</td>
<td>300</td>
<td>0.795</td>
<td>0</td>
</tr>
<tr>
<td>wdir300_mwl0_wvdir46.11_yaw0</td>
<td>300</td>
<td>0</td>
<td>163.89</td>
</tr>
<tr>
<td>wdir300_mwl-4.32_wvdir46.11_yaw0</td>
<td>300</td>
<td>-4.32</td>
<td>163.89</td>
</tr>
<tr>
<td>wdir300_mwl0.795_wvdir46.11_yaw0</td>
<td>300</td>
<td>0.795</td>
<td>163.89</td>
</tr>
<tr>
<td>wdir300_mwl0_wvdir0_yaw8</td>
<td>300</td>
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<td>0</td>
</tr>
<tr>
<td>wdir300_mwl-4.32_wvdir0_yaw8</td>
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</tr>
<tr>
<td>wdir300_mwl0.795_wvdir0_yaw8</td>
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<td>0.795</td>
<td>0</td>
</tr>
<tr>
<td>wdir300_mwl0_wvdir46.11_yaw8</td>
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<td>163.89</td>
</tr>
<tr>
<td>wdir300_mwl-4.32_wvdir46.11_yaw8</td>
<td>300</td>
<td>-4.32</td>
<td>163.89</td>
</tr>
<tr>
<td>wdir300_mwl0.795_wvdir46.11_yaw8</td>
<td>300</td>
<td>0.795</td>
<td>163.89</td>
</tr>
<tr>
<td>wdir300_mwl0_wvdir0_yawneg8</td>
<td>300</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>wdir300_mwl-4.32_wvdir0_yawneg8</td>
<td>300</td>
<td>-4.32</td>
<td>0</td>
</tr>
<tr>
<td>wdir300_mwl0.795_wvdir0_yawneg8</td>
<td>300</td>
<td>0.795</td>
<td>0</td>
</tr>
<tr>
<td>wdir300_mwl0_wvdir46.11_yawneg8</td>
<td>300</td>
<td>0</td>
<td>163.89</td>
</tr>
<tr>
<td>wdir300_mwl-4.32_wvdir46.11_yawneg8</td>
<td>300</td>
<td>-4.32</td>
<td>163.89</td>
</tr>
<tr>
<td>wdir300_mwl0.795_wvdir46.11_yawneg8</td>
<td>300</td>
<td>0.795</td>
<td>163.89</td>
</tr>
</tbody>
</table>

### Figure 38: Turbine Orientation with Wind and Wave Directions

Wind Rose

Wind Direction

46.11 deg

Wave Direction

Wind Direction

Wave Direction

46.11 deg

Wave Direction
6.4.1 Coupled Analysis

The coupled analysis was performed as it was in Chapter 6.1, using the new loading conditions. Certain trends stayed consistent for both new and revised results, while others changed. As expected, one trend that stayed consistent was that combined design stress in the tower base far exceeds that of the tower top and the fatigue damage at the tower base, making the tower base yielding the controlling factor in design. In addition, the moments about the x-axis create the largest stresses experienced at the tower bottom followed by moment about the y-axis and axial forces. This is also expected because of the input directions of the wind and waves. Having the turbine oriented in the direction of maximum wind as seen in Figure 38, creates a large back and forth motion which causes a large fore-aft moment and stress. However, the wave directionality not directly aligned with the axis which causes a secondary side to side moment and a stress about the y axis. Shear stress was also found to be significantly less than normal stress, as it was previously and as a result was neglected going forward.

Main differences in trends appear when considering the maximum and average total design stress results at the tower base. Figure 39 shows the tower base average combined normal stresses for all revised load combinations. As seen, the tower base stress is greatest for load combination wdir300_mwl432_wvdir46_yaw8. which has an average combined stress of 59,623 kPa. When the yaw is at +8°, the stresses appear to be the greatest followed by the yaw at 0°. The lowest stresses are produced when the yaw is at -8°. The yaw direction appears to have the greatest effect on the stress results, compared to the mean water level and wave direction. This differs from the original results in that there is a clear trend that appear when the yaw angle is changed. Whereas original results showed that wind directionality had only a slight effect on the average stresses. In addition, a second trend that appears clear in the revised results is that when the mean water level is 4.32 m above sea level, it produces higher stresses. As expected, this is because the highest observed sea level creates more stress from the waves at the tower base. This trend can also be seen in the original results.
The biggest difference in original and revised results comes from the maximum combined stress results, which were found to be exceeding yield in the original loading scenarios. Table 33 presents the maximum combined design stresses of the revised loading conditions normalized to the approximated yield stress of $3.55 \times 10^5$ kPa. As shown, all load cases fall significantly below the approximated yield stress of the tower. The worst case loading condition, \texttt{wdir309_mwl0_wvdir0_yaw0}, produces a maximum stress magnitude at the tower base of 156,4477 kPa which represents only 44.1% of the approximated yield stress.
Table 33: Revised Maximum Combined Design Stresses Normalized to Yield Stress

<table>
<thead>
<tr>
<th>Condition</th>
<th>σ</th>
<th>τ</th>
</tr>
</thead>
<tbody>
<tr>
<td>'wdir300_mwl0795_wvdir0_yaw0'</td>
<td>0.391</td>
<td>0.032</td>
</tr>
<tr>
<td>'wdir300_mwl0795_wvdir46_yaw0'</td>
<td>0.391</td>
<td>0.029</td>
</tr>
<tr>
<td>'wdir300_mwl0_wvdir0_yaw0'</td>
<td><strong>0.441</strong></td>
<td>0.028</td>
</tr>
<tr>
<td>'wdir300_mwl0_wvdir46_yaw0'</td>
<td>0.393</td>
<td>0.028</td>
</tr>
<tr>
<td>'wdir300_mwl1432_wvdir0_yaw0'</td>
<td>0.412</td>
<td>0.029</td>
</tr>
<tr>
<td>'wdir300_mwl1432_wvdir46_yaw0'</td>
<td>0.398</td>
<td>0.029</td>
</tr>
<tr>
<td>'wdir300_mwl0795_wvdir0_yaw-8'</td>
<td>0.380</td>
<td><strong>0.035</strong></td>
</tr>
<tr>
<td>'wdir300_mwl0795_wvdir46_yaw-8'</td>
<td>0.382</td>
<td>0.030</td>
</tr>
<tr>
<td>'wdir300_mwl0_wvdir0_yaw-8'</td>
<td>0.374</td>
<td>0.033</td>
</tr>
<tr>
<td>'wdir300_mwl0_wvdir46_yaw-8'</td>
<td>0.393</td>
<td>0.033</td>
</tr>
<tr>
<td>'wdir300_mwl1432_wvdir0_yaw-8'</td>
<td>0.363</td>
<td>0.034</td>
</tr>
<tr>
<td>'wdir300_mwl1432_wvdir46_yaw-8'</td>
<td>0.376</td>
<td>0.030</td>
</tr>
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<td>'wdir300_mwl0795_wvdir0_yaw8'</td>
<td>0.433</td>
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<td>0.421</td>
<td>0.027</td>
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<tr>
<td>'wdir300_mwl0_wvdir46_yaw8'</td>
<td>0.430</td>
<td>0.027</td>
</tr>
<tr>
<td>'wdir300_mwl1432_wvdir0_yaw8'</td>
<td>0.428</td>
<td>0.029</td>
</tr>
<tr>
<td>'wdir300_mwl1432_wvdir46_yaw8'</td>
<td>0.428</td>
<td>0.029</td>
</tr>
</tbody>
</table>

The reason for this large discrepancy between original and revised results is because of the input conditions used for the original results. The way that the conditions were inputted into the software simulation resulted in the turbine being subjected to motions that it is not supposed to experience in realistic scenarios, even extreme conditions. For example, the original wind directionality inputs caused the turbine to bend and twist in extreme ways. In addition, using the average wave period input with maximum wave height input caused the turbine base to experience very quick repeated wave loading with a high wave height, a scenario that it is not likely to experience in its lifetime. These conditions were revised to represent more realistic climate conditions that the turbine would experience for a 50-year storm and results indicate that the combined stress does not exceed yield.

6.4.2 Coupled vs. Uncoupled Analysis

Using a baseline loading scenario (wdir300_mwl0_wvdir0_yaw0), an uncoupled analysis was performed to determine the effects of coupling on the simulation. Similar trends appeared in the revised loading scenario with some small differences. For example, Figure 40 shows a similar image to Figure 35 in
comparing the uncoupled and coupled stress time histories. Revised results show that the uncoupled stresses exceed coupled stresses. However, the zoomed in image from 500 seconds to 550 second shows that coupled and uncoupled results appear more in sync. Uncoupled simulations are able to capture the variability associated with FOWTs and the peak stresses they experience. However, the coupled analysis has consistently smaller stress values. This can be attributed to the nonlinear nature of the analysis as described with original results. Adding separate wind and wave analyses together does not account for the nonlinear behavior that occurs when a FOWT experiences wind and wave loads together, which appears to produce a damping effect on the tower base. This reinforces the conclusion that uncoupled analyses are adequate for preliminary design, but final design should include a coupled analysis to account for the nonlinear behavior of a FOWT tower.

Figure 40: Revised Coupled vs. Uncoupled Stress Time History
A comparison of uncoupled and coupled results can also be seen in Table 34 which shows maximum and average results for all axial and bending stresses. As expected, the uncoupled analysis showed that the stress caused by the moment about the x had the most significant effect on the results. However, for the uncoupled analysis, the axial stress appears to have a more significant effect than the stress caused by the y axis and tended to be almost 2x larger than the coupled analysis axial stress. This can be attributed to the nonlinear nature of the analysis and further proves that an uncoupled analysis is adequate for preliminary design, however, a coupled analysis is necessary for final design to prevent over-designing.

Table 34: Revised Coupled vs. Uncoupled Stress Results

<table>
<thead>
<tr>
<th></th>
<th>Coupled Analysis</th>
<th>Uncoupled Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Average Values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>σ x (kPa)</td>
<td>1.95E+04</td>
<td>3.32E+04</td>
</tr>
<tr>
<td>σ y (kPa)</td>
<td>8.66E+03</td>
<td>9.04E+03</td>
</tr>
<tr>
<td>σ axial (kPa)</td>
<td>8.47E+03</td>
<td>1.70E+04</td>
</tr>
<tr>
<td>σ combined (kPa)</td>
<td>3.66E+04</td>
<td>5.92E+04</td>
</tr>
<tr>
<td><strong>Maximum Values</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>σ x (kPa)</td>
<td>7.92E+04</td>
<td>7.84E+04</td>
</tr>
<tr>
<td>σ y (kPa)</td>
<td>4.15E+04</td>
<td>4.30E+04</td>
</tr>
<tr>
<td>σ axial (kPa)</td>
<td>9.64E+03</td>
<td>1.78E+04</td>
</tr>
<tr>
<td>σ combined (kPa)</td>
<td>9.72E+04</td>
<td>1.06E+05</td>
</tr>
</tbody>
</table>

6.4.3 Sensitivity Study

The sensitivity study was also performed with the revised loading conditions and produced similar results to the original loading conditions. Figure 41 again presents the sensitivity trend results and shows that the stress changes linearly. The stresses appear to change slightly more with wave height than wind speed, but the difference is not as evident as it was using the original loading scenarios. This was explained in Chapter 6.3 as a result of how loading is applied to the model. The waves and currents cause mooring line forces which are implemented through an external DLL whereas wind speed is directly inputted into the model and used to calculate wind shear.
Figure 41: Revised Sensitivity Analysis Average Stress vs. Wind and Wave Results

Table 35 further shows that the model simulation is not significantly affected by changes in wind speed or wave height. For a 15% change in wind speed, the stress only changes by about 2%. Similarly for wave height, a 15% change in wave height causes a 3% change in stress. This differs from original results which showed that the stress increased at the same rate as wave height. This was likely due to the short dominant wave period that was revised in Table 35 results.

Table 35: Revised Percentage Change in Stress for Change in Input Conditions

<table>
<thead>
<tr>
<th>Percentage Change in Wind Speed</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.00</td>
<td>0.63</td>
<td>1.58</td>
<td>2.25</td>
</tr>
<tr>
<td>5</td>
<td>0.95</td>
<td>1.42</td>
<td>2.33</td>
<td>2.96</td>
</tr>
<tr>
<td>10</td>
<td>1.88</td>
<td>2.47</td>
<td>3.29</td>
<td>4.00</td>
</tr>
<tr>
<td>15</td>
<td>2.97</td>
<td>3.67</td>
<td>4.47</td>
<td>4.95</td>
</tr>
</tbody>
</table>
Revised results show that under realistic environmental conditions, the stress changes an similar amount for changes in wind speed and wave height. It also suggests that the model is not extremely sensitive to these changes. Though not in the scope of this research, it is important to consider the model sensitivity during final design to ensure that it accurately matches the sensitivity of the structure.
CHAPTER 7: CONCLUSIONS

7.1 Summary of Findings

Over the past 10 years, the push for more renewable energy sources to replace fossil fuels has led to a dramatic increase in wind energy systems around the globe. The Offshore Wind Market Report 2022 predicts that the offshore wind industry will continue to exponentially grow over the next decade with the global cumulative potential generating capacity, jumping 50,623 MW in 2022 to more than 170,000 MW by 2027 (Musial et al., 2022). As space close to shore becomes scarce and turbine capacity becomes larger, it becomes uneconomical to build fixed bottom wind turbines and FOWT become the main generator of wind energy. However, FOW is still a relatively new industry, and this comes with certain challenges that must be addressed. The main challenge is the more severe climate conditions that are experienced further from shore and the durability concerns this causes. High winds coupled with wave sensitivity, and mooring forces result in a very complex structure that is subjected to more corrosion and stress conditions that typical land based and fixed bottom wind turbines (McMorland et al., 2022).

Many studies have been conducted in the past decade on the performance of FOWT under a variety of climate conditions. However, much of past research is focused on the platform response under fatigue loading or model-to-model comparison. Few studies have focused on the response of the tower, specifically for fatigue and extreme operational conditions. The research presented in this paper utilizes the IEA 15 MW FOWT model with a semi-submersible platform from Allen et al. (2020) and Gaertner et al. (2020) to obtain time domain response of the turbine tower under extreme loading conditions.

First, extreme climate conditions were calculated using data obtained from NOAA Buoy Station 44005 in the Gulf of Maine. The Weibull Distribution was used to describe the variation in wind speed, wind gust speed, and wave heights for the site and the extreme 50-year storm conditions were calculated. The Power Law was then used with the extreme wind speed to obtain the wind speed at the hub height of the turbine. Wind and wave directionality was found using a wind/ wave rose and current and mean water level conditions from Gómez et al. (2015) were used for implementation of current data into the model.
Climate conditions were entered into the nonlinear aero-servo-hydro-elastic code, HAWC2, to simulate a FOWT subject to extreme coupled wind and wave conditions. In addition, parked strength load case DLC 6.1, based on IEC 61400-3 design requirements was used for analysis. This load case defines the wind turbine in an idling condition subject to 50-year extreme storm climate conditions. The load case was run for 108 combinations of wind direction, wave direction, and mean sea level and average and maximum stress results were obtained from the tower base and tower top.

Results found the stresses at the base of the tower far exceed the stresses at the top of the tower. This is because the turbine tower act similarly to a cantilever beam with a distributed wind load applied along its length and concentrated point loads at the end or tower top, together these creates the maximum moment and shear at the tower base and a much smaller shear and moment at the tower top. In addition, it was found that the shear at the tower top is greater than the normal stress at the tower top. This is also due to the application of the loading on the tower. While the normal stress at the tower top will be smaller, there is a greater magnitude of wind shear force applied to the top of the tower. The top of the tower is also allowed more torsion than the base because it is not a fixed constraint. Because the tower base stresses far exceed the tower top stresses, the tower base is the constraining location that was investigated in more depth.

Looking more depth into tower base results, it was determined that the moment about the x axis created the largest stresses at the tower base followed by moment about the y axis and axial forces. This is due to the input direction of the wind and wave conditions. Wind speed coming from the southwest and the waves coming from southeast create a large back and forth movement on the turbine tower, causing a large fore aft moment to occur. However, because the wind and wave conditions are not implemented exactly along the axis, a secondary side-to-side moment is also created which causes the stress in the y direction.

Another interesting result of note was that the load cases where the wind direction is 308º clockwise from true North produce average results that are slightly lower than load cases where the wind direction is 292º clockwise from true North. The maximum results agreed with this observation and showed this difference
more clearly. This can also be attributed to the misalignment of the wind and waves. When the wave and waves are more closely aligned it produces larger stresses in the turbine.

Maximum results also presented large stresses at the tower base that in multiple instances exceeded the approximated allowable yield stress of the tower. Load case wdir292_mwl0795_wvdir193 and wdir292_mwl432_wvdir193 both produce maximum tower base stresses above the yield stress. Other load cases produce stresses that come close to yielding as well.

A fatigue analysis was also completed for the each of the 18 load cases and found that all accumulated fatigue damage to be less than the maximum value of 1 based on the Palmgren-Miner rule, rainflow counting, and the S-N curve. The total damage accumulation for all load cases appears to be small and the yielding described is likely the controlling factor in design of the turbine tower.

For the worst-case fatigue loading scenario, uncoupled wind and uncoupled wave analyses were performed to compare to the coupled analysis of that same load case. Wind loading conditions appear to have a much more significant effect on the tower base than wave loading does. This is expected as the wind loading is applied to the top of the tower and creates a much larger moment at the base than hydrodynamic loading that is applied at the base. Results indicated that the uncoupled analysis produced 1.5x to 2.0x higher results than the coupled analysis, which indicated that an uncoupled analysis is acceptable for preliminary design of FOWT but a coupled analysis is needed for final design to ensure accurate results.

Finally, a sensitivity study was completed to determine how the model reacts to changes in wind speed and wave heights. It was concluded that there was a linear relationship between wind speed and average stress and wave height and average stress. However, the simulation appears to be more sensitive to changes in wave height than wind speed. The stress appears to increase at the same rate as the wave height but about half the rate for wind speed.

After further investigation of the results and inputs, 108 new simulations were run to represent more realistic ocean and wind conditions. These revised results were analyzed and compared to the original and showed that many trends remained the same. The most significant difference was in the maximum design
stress at the tower base. Using the revised climate conditions, the tower does not appear to be yielding for any loading scenario. In fact, the worst case design normal stress represented only 44.1% of the approximated yield stress. The most likely reason for this large discrepancy is way that the conditions were inputted into the software simulation. The original inputs resulted in the turbine being subjected to motions and loading that it is not supposed to experience in realistic scenarios, even extreme conditions, while revised input conditions represented a more realistic 50-year storm.

Revised results from the uncoupled vs. couple analysis yielded similar results to the original conditions, as did the sensitivity study. This further proves that an uncoupled analysis is adequate for preliminary design, but a coupled analysis is necessary for final design. In addition, the HAWC2 model simulation code was proven to not show significant changes in stress for changes in wind speed. Through the revised input conditions, it was found that increases in wind speed and wave height created a smaller change in stress than originally thought.

**7.2 Further Research**

Results of this study indicate that for 50-year extreme environmental conditions, the tower base yielding stresses are the controlling design factor compared to shear stress and fatigue. However, a more in-depth study of construction materials should be considered in future work to increase the strength and durability of the tower. In addition, a deeper study into the tower properties could be performed to optimize the tower for best performance. This would help to ensure that yielding does not occur and the FOWT uses materials most efficiently for a cost-effective design while still being able to withstand extreme loading conditions.

This study shows the fatigue analysis of the tower base and determines that fatigue is not the controlling factor in tower design. A deeper look into the design details and stress concentrations in the tower may be able to expand on this conclusion. This would involve a detailed finite element model of the tower base and a look into the connection detail classes that exist in the tower. This study would help to further
knowledge of how the turbine tower performs under fatigue loading and what type of design welding detail achieves best results for FOWT.
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Jonkman, Jason, Emmanuel Branlard, Matthew Hall, Greg Hayman, Andrew Platt, and Amy Robertson. 2020. “Implementation of Substructure Flexibility and Member-Level Load Capabilities for Floating Offshore Wind Turbines in OpenFAST.” NREL/TP-5000-76822, 1665796, MainId:10466.

https://doi.org/10.2172/1665796.


https://doi.org/10.1002/we.2701.

http://tools.windenergy.dtu.dk/Pdap/downloads/.


“Station 44005 (LLNR 820) - GULF OF MAINE - 78 NM East of Portsmouth, NH.” *National Data Buoy Center (NDBC)*, National Oceanic and Atmospheric Administration, 12 Dec. 2022, 


APPENDIX

A.1 Supplemental Tables and Figures

Figure 42A: Cross Sectional Properties Definitions for HAWC2 .st File
### Table 36A: Roughness Parameter and Power-Law Exponent for Different Terrain Types (DNV-RP-C205, 2014)

<table>
<thead>
<tr>
<th>Terrain Type</th>
<th>Roughness Parameter $z_0$</th>
<th>Power-Law Exponent $\alpha$</th>
</tr>
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<tbody>
<tr>
<td>Plane ice</td>
<td>0.00001 to 0.0001</td>
<td></td>
</tr>
<tr>
<td>Open Sea without waves</td>
<td>0.0001</td>
<td></td>
</tr>
<tr>
<td>Open Sea with waves</td>
<td>0.0001 to 0.01</td>
<td>0.12</td>
</tr>
<tr>
<td>Coastal Areas with onshore wind</td>
<td>0.001 to 0.01</td>
<td></td>
</tr>
<tr>
<td>Snow Surface</td>
<td>0.001 to 0.006</td>
<td></td>
</tr>
<tr>
<td>Open Country without significant buildings and vegetation</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Mown Grass</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Fallow Field</td>
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<td></td>
</tr>
<tr>
<td>Long Grass, rocky ground</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Cultivated Land with scattered buildings</td>
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<td>0.16</td>
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<td>Pasture Land</td>
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</tr>
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<td>Forest and Suburbs</td>
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<tr>
<td>City Centers</td>
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### Table 37A: Naming Convention for Original Models Run and Turbulence Seeds

<table>
<thead>
<tr>
<th>Turbulence Seed Numbers</th>
<th>Wind Direction Input (deg)</th>
<th>Mean Water Level Input (m)</th>
<th>Wave Direction Input (deg)</th>
</tr>
</thead>
<tbody>
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<td>1001-1006</td>
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<td>0</td>
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<td>1101-1106</td>
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<tr>
<td>1201-1206</td>
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<td>0.795</td>
<td>0</td>
</tr>
<tr>
<td>1011-1016</td>
<td>292</td>
<td>0</td>
<td>133.9</td>
</tr>
<tr>
<td>1111-1116</td>
<td>292</td>
<td>-4.32</td>
<td>133.9</td>
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<td>1021-1026</td>
<td>292</td>
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<td>-4.32</td>
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<tr>
<td>2101-2106</td>
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<tr>
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<td>2011-2016</td>
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<td>308</td>
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**Total Simulations Done:** 108
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<th>x</th>
<th>y</th>
<th>E</th>
<th>G</th>
<th>l1</th>
<th>l2</th>
<th>k</th>
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<th>A</th>
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</table>

**Table 3.4: Tower Geometric Properties**
### Table 39A: Maximum Total Stress Results Before Safety Factor and Normalization to Yield

<table>
<thead>
<tr>
<th></th>
<th>σ (kPa)</th>
<th>τ(kPa)</th>
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<tbody>
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<td>1.61E+04</td>
</tr>
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<td>1.57E+04</td>
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<td>2.32E+05</td>
<td>1.46E+04</td>
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<td>1.33E+04</td>
</tr>
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<td>wdir292_mwl0_wvdir193</td>
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<td>1.39E+04</td>
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<td>wdir292_mwl432_wvdir0</td>
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<td>2.34E+05</td>
<td>1.44E+04</td>
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<td>1.62E+04</td>
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<td>wdir308_mwl0795_wvdir133</td>
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</table>

### Table 40A: Average Total Stress Results Before Safety Factor and Normalization to Yield

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<th>τ(kPa)</th>
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<td>4.55E+03</td>
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<td>4.64E+03</td>
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<td><strong>4.75E+03</strong></td>
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<td>4.32E+03</td>
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### Table 41A: Cumulative Fatigue Damage Results for Sensitivity Analysis

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</tr>
</tbody>
</table>

### A.2 MATLAB Code for Climate Analysis

```matlab
%Wind Speed Code
%Oct 12, 2022
%Programer: Ailish Bozzo
%Input File: rawdata.xlsx
clc;

%% IMPORTING ALL YEAR DATA
data1982=readmatrix('rawdata.xlsx','Sheet','1982');
data1983=readmatrix('rawdata.xlsx','Sheet','1983');
data1984=readmatrix('rawdata.xlsx','Sheet','1984');
data1985=readmatrix('rawdata.xlsx','Sheet','1985');
data1986=readmatrix('rawdata.xlsx','Sheet','1986');
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data1999=readmatrix('rawdata.xlsx','Sheet','1999');
data2001=readmatrix('rawdata.xlsx','Sheet','2001');
data2002=readmatrix('rawdata.xlsx','Sheet','2002');
data2003=readmatrix('rawdata.xlsx','Sheet','2003');
```
data2004 = readmatrix('rawdata.xlsx', 'Sheet', '2004');
data2005 = readmatrix('rawdata.xlsx', 'Sheet', '2005');
data2006 = readmatrix('rawdata.xlsx', 'Sheet', '2006');
data2007 = readmatrix('rawdata.xlsx', 'Sheet', '2007');
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data2009 = readmatrix('rawdata.xlsx', 'Sheet', '2009');
data2010 = readmatrix('rawdata.xlsx', 'Sheet', '2010');
data2011 = readmatrix('rawdata.xlsx', 'Sheet', '2011');
data2012 = readmatrix('rawdata.xlsx', 'Sheet', '2012');
data2014 = readmatrix('rawdata.xlsx', 'Sheet', '2014');
data2015 = readmatrix('rawdata.xlsx', 'Sheet', '2015');
data2016 = readmatrix('rawdata.xlsx', 'Sheet', '2016');
data2017 = readmatrix('rawdata.xlsx', 'Sheet', '2017');
data2018 = readmatrix('rawdata.xlsx', 'Sheet', '2018');
data2019 = readmatrix('rawdata.xlsx', 'Sheet', '2019');
data2020 = readmatrix('rawdata.xlsx', 'Sheet', '2020');
data2021 = readmatrix('rawdata.xlsx', 'Sheet', '2021');

data2011; data2012; data2013; data2014; data2015; data2016; data2017; data2018; data2019; data2020; data2021];

[r, c] = size(dataall);  \%puts all data imported in one variable

for j = 1:c;
    for i = 1:r;
        if dataall(i, j) == 99.0;
            dataall(i, j) = "NaN";
        elseif dataall(i, j) == 999;
            dataall(i, j) = "NaN";
        else
            dataall(i, j) = dataall(i, j);
        end
    end
end

\% WIND SPEED DATA

gustfactor = 1 + (0.137 * log(4.9/4.9)) - (0.047 * log(8/10));

for i = 1:r;
    wspd(i, 1) = dataall(i, 1);  \%Year in column 1
    wspd(i, 2) = dataall(i, 2);  \%Month in column 2
    wspd(i, 3) = dataall(i, 3);  \%Day in column 3
    wspd(i, 4) = dataall(i, 4);  \%Hour in column 4
    wspd(i, 5) = dataall(i, 7);  \%8 minute averaged wind speed in column 5
    wspd(i, 6) = dataall(i, 7) ./ gustfactor;  \%10 minute averaged wind speed in column 6
end;

wspdclean = rmmissing(wspd);  \%takes out all rows with NaN to create a clean matrix

save wspd.mat wspd;  \%saves yearly stats as .mat to use in wind rose code

\% YEARLY STATS

years = unique(wspdclean(:, 1));  \%finds all unique years in clean data
NumYears = length(years);  \%determines how many years there are in the data

for k = 1:NumYears  \%creates a loop cycling through the clean data to find yearly stats
    year = years(k, 1);
    yearloc = find(wspdclean(:, 1) == year);
    yeardata = wspdclean(yearloc, :);

    wspdyearstat(k, 1) = year;  \%puts year in column 1
    wspdyearstat(k, 2) = mean(yeardata(:, 5));  \%yearly average 8 minute in column 2
    wspdyearstat(k, 3) = max(yeardata(:, 5));  \%yearly max 8 minute in column 3
    wspdyearstat(k, 4) = mean(yeardata(:, 6));  \%yearly average 10 minute
    wspdyearstat(k, 5) = max(yeardata(:, 6));  \%yearly max 10 minute
end
figure('Name','Yearly Average Wind Speed over Time'); %creates a figure of yearly averages
plot(wspdyearstat(:,1),wspdyearstat(:,4)); %over all years evaluated
hold on;
plot(wspdyearstat(:,1),wspdyearstat(:,5)); %adds max yearly to graph
title('Yearly Wind Speed over Time','FontName','Times New Roman','FontSize',12);
xlabel('years','FontName','Times New Roman','FontSize',12);
ylabel('10 minute Wind Speed (m/s)','FontName','Times New Roman','FontSize',12);
legend('average','maximum','FontName','Times New Roman','FontSize',12);
legend('boxoff');

Overallavg_year=mean(wspdyearstat(:,4)); %calculates the overall average of the yearly data
save avgwspd.mat wspdyearstat; %saves yearly stats as .mat to use in wind rose code

MONTHLY STATS

months= unique(wspdclean(:,2)); %finds all the unique months in the clean data
NumMonths=length(months);

for k=1:NumMonths %creates a loop cycling through yearly data to find monthly stats
    monthk=months(k,1);
    monthkloc=find(wspdclean(:,2)==monthk);
    monthkdata=wspdclean(monthkloc,:);
    monthstat(k,1)=monthk; %puts month in column 1
    monthstat(k,2)=mean(monthkdata(:,6)); %monthly average
    monthstat(k,3)=max(monthkdata(:,6)); %monthly max
end

figure('Name','Monthly Wind Speed over 20 Years'); %creates a figure of monthly averages
over years evaluated
plot(monthstat(:,1),monthstat(:,2));
hold on;
plot(monthstat(:,1),monthstat(:,3)); %adds monthly max to graph
title('Monthly Average and Maximum Wind Speed over Time');
xlabel('Month');
ylabel('Wind Speed (m/s)');
legend('average wind speed','max wind speed');

ESTIMATION OF WIND SPEED AT CERTAIN HEIGHTS USING POWER AND LOG RULE FOR ORIGINAL CONDITIONS
% VERIFY THIS WITH NOAA CHARTS AND DATA %
height=[4;4.9;5;10;20;30;40;50;60;65;70;80;90;100;110;120;130;140;150;200]; %different heights to
evaluate the function at
height0=4.9; %height of orginal measurement
alpha=0.14; %constant for power rule
z00=0.0002; %constant for log rule
wspd0yr=Overallavg_year; %orginal average measurement speed
wspd0m=Overallavg_month; %orginal average measurement speed

wspdwr_yr=wspd0yr.*(height/height0).^alpha; %power law profile
wspdlog_yr=wspd0yr.*(log(height./z00)/log(height0./z00)); %log profile

wspdwr_m=wspd0m.*(height/height0).^alpha; %power law profile
wspdlog_m=wspd0m.*(log(height./z00)/log(height0./z00)); %log profile

figure('Name','Power and Log Rule for Original Data'); %creates graph of estimations
should add NOAA map data to find most accurate one
plot(wspdwr_yr,height);
hold on;
plot(wspdlog_yr,height);
% hold on;
% plot(wspdwr_m,height);
% hold on;
% plot(wspdlog_m,height);
legend('Power Law Profile ';'Log Profile';'Location';'southeast';'FontName';'Times New Roman';'FontSize';12);%     , 'Power Law Profile for Monthly Average','Log Profile for Monthly Average');
ylabel('Height of Turbine (m);'FontName';'Times New Roman';'FontSize';12);
xlabel('Estimated 10 minute Average Wind Speed (m/s);'FontName';'Times New Roman';'FontSize';12);
title('Power and Log Rule for Original Data;'FontName';'Times New Roman';'FontSize';12);
legend('boxoff');

%% WEIBULL DISTRIBUTION FUNCTION FOR EXTREME VALUES AT ORIGINAL HEIGHT USING ALL DATA
Allstat=nonzeros(wspdclean(:,6)); %creates vector of all the data that is not zero for the distribution
[parmHat,parmCI] = wblfit(Allstat); %fits the data to the Weibull Distribution and outputs the 95% confidence interval for the parameter estimates
A_all=parmHat(1,1); %scale parameter
B_all=parmHat(1,2); %shape parameter
min_all=min(Allstat); %minimum of the data
max_all=max(Allstat); %maximum of the data
figure; %graphs the pdf weibull fit of the data using the scale and shape parameters that were found
yyaxis right
x_all=linspace(min_all,max_all);
plot(x_all,wblpdf(x_all,A_all,B_all),'LineWidth',3)
xlabel('Wind Speed (m/s);'FontName';'Times New Roman';'FontSize';12)
ylabel('Probability Density Function (pdf);'FontName';'Times New Roman';'FontSize';12)
title('Weibull Fit Probability Distribution Function at 4.9 meters;'FontName';'Times New Roman';'FontSize';12)

yyaxis left
histogram(Allstat,132); %graphs the data in a histogram
xaxis('Name','Wind Speed (m/s);'FontName';'Times New Roman';'FontSize';12)
ylabel('Number of Occurances;'FontName';'Times New Roman';'FontSize';12)
[N,edges]=histcounts(Allstat);
title('Histogram of all Wind Speed Data in m/s;'FontName';'Times New Roman';'FontSize';12)

figure; %graphs the cdf weibull fit of the data using the scale and shape parameters that were found
yyaxis right
x_all=linspace(min_all,max_all);
plot(x_all,wblcdf(x_all,A_all,B_all))
xlabel('Wind Speed (m/s);'FontName';'Times New Roman';'FontSize';12)
ylabel('Cumulative Distribution Function (cdf);'FontName';'Times New Roman';'FontSize';12)
title('Weibull Fit Cumulative Distribution Function 4.9 meters;'FontName';'Times New Roman';'FontSize';12)

%% WEIBULL DISTRIBUTION FUNCTION FOR EXTREME VALUES AT ORIGINAL HEIGHT USING YEAR MAX
wspdyearstatnonzero=nonzeros(wspdyearstat(:,5)); %creates vector of all the data that is not zero for the distribution
[parmHat,parmCI] = wblfit(wspdyearstatnonzero); %fits the data to the Weibull Distribution and outputs the 95% confidence interval for the parameter estimates
A_year=parmHat(1,1); %scale parameter
B_year=parmHat(1,2); %shape parameter
min_year=min(wspdyearstatnonzero); %minimum of the data
max_year=max(wspdyearstatnonzero); %maximum of the data
figure('Name','Weibull Fit Probability Distribution Function of Yearly Averages');%graphs the pdf weibull fit of the data using the scale and shape parameters that were found
yyaxis right
x_year=linspace(min_year,max_year);
plot(x_year,wblpdf(x_year,A_year,B_year),'LineWidth',3)
xlabel('Wind Speed (m/s)')
ylabel('Probability Density Function (pdf)')
title('Weibull Fit Probability Distribution Function of Yearly Averages at 4.9 meters')

yyaxis left
histogram(wspdyearstat(:,5),6); %graphs the data in a histogram
xlabels('Wind Speed (m/s)');
ylabels('Number of Occurances');
[N,edges]=histcounts(wspdyearstat(:,5));
title('Histogram of Yearly Wind Speed Data in m/s at 4.9 meters')

figure('Name','Weibull Fit Cumulative Distribution Function of Yearly Averages at 4.9 meters');
%graphs the cdf weibull fit of the data using the scale and shape parameters that were found
x_year=linspace(min_year,max_year);
plot(x_year,wblcdf(x_year,A_year,B_year)),%,'DisplayName','A=, B=')
xlabels('Wind Speed (m/s)')
ylabels('Cumulative Distribution Function (cdf)')
title('Weibull Fit Cumulative Distribution Function of Yearly Averages at 4.9 meters')

%% EXTREME CONDITIONS AT ORIGINAL HEIGHT Using Weibull Distribution and YEARLY MAX

figure;
wblplot(wspdyearstat(:,5))
xlabels('Extreme Wind Speed (m/s)')
ylabels('Probability')

averagemax=mean(wspdyearstat(:,5))

storm100yr = wblinv(0.99,A_year,B_year);
storm50yr = wblinv(0.98,A_year,B_year);
storm10yr = wblinv(0.9,A_year,B_year);

%% ESTIMATION OF WIND SPEED AT CERTAIN HEIGHTS USING POWER AND LOG RULE FOR EXTREME CONDITIONS

Turbineheight=[150]; %hub height of turbine
height0=4.9; %height of orginal measurement
alphaextreme=0.11; %constant for power rule
z00=0.0002; %constant for log rule

wspd0extreme=[storm10yr;storm50yr;storm100yr]; %extreme conditions at original height -> Get data from weibull distribution for 10,50,100 yr storm

pwrextreme=wspd0extreme.*(Turbineheight/height0).^alphaextreme;%power law profile

logextreme=wspd0extreme.*(log(Turbineheight./z00)/log(height0./z00));%log profile

%% Subplot Histograms

figure; %graphs the pdf weibull fit of the data using the scale and shape parameters that were found
subplot(1,2,1)
yyaxis right
x_all=linspace(min_all,max_all);
plot(x_all,wblpdf(x_all,A_all,B_all),'LineWidth',3)
xlabels('Wind Speed (m/s)','FontName','Times New Roman','FontSize',12)
ylabels('Probability Density Function (pdf)','FontName','Times New Roman','FontSize',12)

yyaxis left
histogram(Allstat,132); %graphs the data in a histogram
xlabels('Wind Speed (m/s)','FontName','Times New Roman','FontSize',12);
ylabels('Number of Occurances','FontName','Times New Roman','FontSize',12);

[N,edges]=histcounts(Allstat);
title('All Wind Speed Data','FontName','Times New Roman','FontSize',12)

subplot(1,2,2)
yyaxis right
x_year=linspace(min_year,max_year);
plot(x_year,wblpdf(x_year,A_year,B_year),'LineWidth',3)
xlabels('Wind Speed (m/s)')
ylabels('Probability Density Function (pdf)')

yyaxis left
histogram(wspdyearstat(:,5),6); %graphs the data in a histogram
xlabels('Wind Speed (m/s)');
ylabel('Number of Occurances');
[N,edges]=histcounts(wspdyearstat(:,5));
title('Yearly Maximum Wind Speed Data','FontName','Times New Roman','FontSize',12)

% Wind and Wave Rose Code
% Oct 12, 2022
% Programer: Ailish Bozzo
% Input File: wspd.mat
% wdir.mat
% wvht.mat
% wvdir.mat

clear all;
close all;
clc;

%% LOADING YEARLY AVERAGES FROM WIND AND WAVE CODES
load wspd.mat;
load wdir.mat;
load wvht.mat;
load wvdir.mat;

windspeeddirection(:,1)=wspd(:,6);
windspeeddirection(:,2)=wdir(:,5);

% windspeeddirection=[wspd(:,6);wdir(:,5)];
windspeddirectionclean=rmmissing(windspeeddirection);
waveheightdirection=[wvht(:,5),wvdir(:,5)];
waveheightdirectionclean=rmmissing(waveheightdirection);

% WIND ROSE
wind_rose(windspeeddirectionclean(:,2),windspeeddirectionclean(:,1));

% WAVE ROSE
wave_rose(waveheightdirectionclean(:,2),waveheightdirectionclean(:,1));

A.3 HAWC2 Main Simulation Code

; UMaine-Semi-floater IEA 15 MW Reference Wind Turbine.
;
; Note! This file links to external htc files that contain
; values for the WTG system.
;
; *-----------------------------------------------------------------------------------------------------------------------------
; SET UP SIMULATION PROPERTIES
begin simulation:
time_stop [time stop]; ; length of simulation in seconds;
solvertype 1; (newmark) ; 1= dense newmark (default) 2= sparse newmark (faster and recommended);
on_no_convergence continue ; continue if convergence is not obtained at a time step;
convergence_limits 1E3 1.0 1E-7 ; convergence limit to be obtained [residual on internal-external forces, residual on increment, residual on constraint equation];
logfile ./log/[Case id].log ; log file path to check for errors;
visualization ./visualization/[Case id].hdf5 ; visualization file path;
begin newmark;
deltat 0.01 ; time increments in seconds
end newmark;
end simulation;

;-----------------------------------------------------------------------------------------------------------------------------
SET UP OUTPUT FILES FOR STRUCTURAL PROPERTIES

begin new_htc_structure;
  beam_output_file_name ./bodyout/[Case id].dat;  writes initial conditions
  body_output_file_name ./bodyout/[Case id].dat;  body locations correct?
  body_eigenanalysis_file_name ./bodyout/[Case id].dat;  damping correct?
  struct_inertia_output_file_name ./bodyout/[Case id].dat;  CM locations correct?
  structure_eigenanalysis_file_name ./bodyout/[Case id].dat;  full-system frequencies?

DEFINE STRUCTURAL INPUTS

begin main_body;
  name ifb ;
  type timoschenko ;
  nbodies 1 ;
  node_distribution c2_def ;
  damping_posdef 0.0 0.0 0.0 0.0 0.0 0.0 ;
  begin timoschenko_input ;
    filename ./data/IEA_15MW_RWT_Dummy_st.dat;  points to file where distributed beam input
data is listed
    set 1 1 ;
  end timoschenko_input;
  begin c2_def ;
    nsec 2 ;
    sec 1 0.0e+00 0.0e+00 0.0e+00 0.0e+00 ;
    sec 2 0.0e+00 0.0e+00 0.0e+00 0.0e+00 ;
  end c2_def ;
end main_body ;

begin main_body;  tower
  name tower ;
  type timoschenko ;
  nbodies 1 ;
  node_distribution c2_def ;
  damping_posdef 0.0 0.0 0.0 1.12E-02 1.10E-02 1.194E-04 ;
  begin timoschenko_input ;
    filename ./data/IEA_15MW_RWT_UMaineSemi_Tower_st.dat;  tuned to 0.95% damping ratio on 1st FA/SS (tower
root fixed)
    set 1 1 ;
  end timoschenko_input;
  begin c2_def ;
    nsec 11 ;
    sec 1 0 0 0.0000e+00 0 ;
    sec 2 0 0 -1.3000e+01 0 ;
    sec 3 0 0 -2.6000e+01 0 ;
    sec 4 0 0 -3.9000e+01 0 ;
    sec 5 0 0 -5.2000e+01 0 ;
    sec 6 0 0 -6.5000e+01 0 ;
    sec 7 0 0 -7.8000e+01 0 ;
sec 8 0 0 -9.1000e+01 0 ;
sec 9 0 0 -1.0400e+02 0 ;
sec 10 0 0 -1.1700e+02 0 ;
sec 11 0 0 -1.2958e+02 0 :
end c2_def ;
end main_body ;
;
continue_in_file ./data/IEA_15MW_RWT_WTG_bodies_noFPM.htc ; ;body definitions are continued in
data folder
;-----------------------------------------------------------------------------------------------------------------------------

;floater
-----------------------------------------------------------------------------------------------------------------------------

DEFINE FLOATING PLATFORM
begin ext_sys ;
module  ESYSWamit ;
name    floater ;
dll     'ESYSWamit.dll';
ndata 28 ;
;qtf] ndata 29 ;
data  WAMIT_FILE './HydroData/IEA-15-240-RWT-UMaineSemi';
data  time_step 0.01 ;
data  GRAVITY 9.80665 ;
data  DENSITY 1025.0 ;
data  MASS    1.7838E+07 ;
data  COG     0.0 0.0 14.94 ;
data  BUOY    2.03111e+08 ;
data  COB_XY  0.0 0.0 ;
data  RIJ_COG 2 2 26.479 ;
data  RIJ_COG 3 3 36.425 ;
data  INI_POS 0 0 0 ;
data  INIT_ROT 0 0 180 ;
data  IRF_TIME_SPAN 60.0 ;
data  WAVE_DIR -180.0 ;
;    data  DUMP_FILE_PREFIX umaine ;
data  DIFFRACTION_METHOD irf_1 ;
;[qtf] data  INCLUDE_QTF 1 1 3.14 ;
data  QUADDRAG 1 1 9.23E+05 ;
data  QUADDRAG 1 5 -8.92E+06 ;
data  QUADDRAG 2 2 9.23E+05 ;
data  QUADDRAG 2 4 8.92E+06 ;
data  QUADDRAG 3 3 2.30E+06 ;
data  QUADDRAG 4 2 8.92E+06 ;
data  QUADDRAG 4 4 1.68E+10 ;
data  QUADDRAG 5 1 -8.92E+06 ;
data  QUADDRAG 5 5 1.68E+10 ;
data  QUADDRAG 6 6 4.80E+10 ;
data  END ;
end ext_sys ;
;-----------------------------------------------------------------------------------------------------------------------------

;mooring
;-----------------------------------------------------------------------------------------------------------------------------

DEFINE MOORING LINES
; continue_in_file ./data/IEA_15MW_RWT_UMaineSemi_mooring_system_init.htc ;
continue_in_file ./data/IEA_15MW_RWT_UMaineSemi_mooring_system.htc ;
;-----------------------------------------------------------------------------------------------------------------------------
DEFINE BODY ORIENTATION
begin orientation;
; begin base; ;orientation of the base
mbdy_ifb ; ;name of body which the next body is attached to
inipos 0.0 0.0 -15.0 ; ;initial position in global coordinates [x,y,z]
mbdy_eulerpar 1.0 0.0 0.0 0.0 ; ;rotation given as euler parameters directly [r0,r1,r2,r3]
end base ;
;
begin relative; ;orientation relative to the base
mbdy1_ifb 1 ; ;main body which the next main body is attached to [name, node#]
mbdy2_tower 1 ; ;next main body [name,node#]
mbdy2_eulerang 0.0 0.0 0.0 ; ;same as global: zTT down, yTT downwind ;euler angle rotations
[x,y,z]
end relative;
continue_in_file ./data/IEA_15MW_RWT_WTG_orientation.htc; ;orientation is continued in separate file
;
end orientation;
;
DEFINE MAIN BODY CONSTRAINTS
begin constraint;
;
begin dll;
ID 0.0 0.0 15.0 ;
dll 'ESYSWamit.dll' ;
init cstr_h2_esyswamit_init ;
update cstr_h2_esyswamit_update ;
neq 6 ;
nbodies 1 ;
nesys 1 ;
mbdy_node ifb 0 ;
esys_node floater 0 ;
end dll;
;
; begin fix0 ;
; mbdy ifb ;
; disable_at 50;
; end fix0 ;
;
begin fix1 ; ;fix a given node on one main body to another main body
mbdy1 ifb 1 ; ;[main body 1, node number of main body]
mbdy2 tower 1 ; ;[main body 2, node number of main body 2]
end fix1 ;
continue_in_file ./data/IEA_15MW_RWT_WTG_constraint.htc;
continue_in_file ./data/IEA_15MW_RWT_UMaineSemi_mooring_constraint.htc;
;
end constraint;
;
end new_htc_structure;
;
DEFINE WIND CLIMATE
begin wind;
density 1.225;  ; density of wind
wsp [Windspeed];  ; mean wind speed (m/s) AT HUB HEIGHT
tint [TI];  ; turbulence intensity ratio
horizontal_input 1; 0=false, 1=true input is defined in global coordinates with horizontal axis
windfield_rotations [wdir] 0.0 0.0;  ; yaw, tilt, rotation  ; rotation in global coordinates, all zero
means wind is in global y direction only
center_pos0 0.0 0.0 -150;  ; center of turb box[x,y,z] global coordinates
shear_format 3 [shear_exp]; 0=none, 1=constant, 2=log, 3=power, 4=linear
turb_format [tu_model]; 0=none, 1=mann, 2=flex
tower_shadow_method 3; 0=none, 1=potential flow, 2=jet, 3=potential_2 (flow where shadow source is moved and rotated with tower coordinates)
scale_time_start [t0];  ; start time for the turbulence scaling, stop time is determined by the simulation length
wind_ramp_factor 0.0 [t0] [wsp factor] 1.0;  [tstart, tstop, % start, % stop]  ; calculates a factor that is multiplied to the wind speed vectors
[gust] iec_gust [gust_type] [G_A] [G_phi0] [G_t0] [G_T];
;
create_turb_parameters 29.4 1.0 3.7 [tu_seed] 1.0;  L, alfaeps, gamma, seed, highfreq compensation [length scale, 1.0 in normal practice, seed number, high frequency compensation (1=point velocity only represent local value closest to anemometer measurements]
filename_u ./simulation_iec/iec_turb/[Turb base name]u.bin;
filename_v ./simulation_iec/iec_turb/[Turb base name]v.bin;
filename_w ./simulation_iec/iec_turb/[Turb base name]w.bin;
box_dim_u 8192 [turb_dx];  [number of grid points, length between grid points]
box_dim_v 32 4.679999948E+00;
box_dim_w 32 4.679999948E+00;
std_scaling 1.0 0.8 0.5;  [ratio to u-direction (1.0), ratio to v-direction (0.8), ratio to w-direction (0.5)] ALL AT DEFAULT
end mann;
;
begin tower_shadow_potential_2; included if potential flow tower shadow model is chosen
tower_mbdy_link tower;  ; name of main body to which the shadow source is linked
nsec 2;  ; number of datasets specified by the radius command
radius 0.0 5.00;  ; radius at base [z coordinate, tower radius at z coordinate]
radius 129.495 3.25;  ; radius at top
end tower_shadow_potential_2;
end wind;
;
begin aerodrag;  ; tower drag
begin aerodrag_element;  ; aerodynamic drag calculation points are set up for a given main body
mbdy_name tower;  ; name of main body which aerodynamic calculation points are linked
aerodrag_sections uniform 11;  ; [distribution method, number of calculation points]
nsec 3;  ; number of second defined below
sec 0.0 0.6 10.00;  ; tower bottom [distance along main_body c2_def_line, drag coefficient, width of structure(diameter)]
sec 117.000 0.6 10.00;
sec 129.495 0.6 6.50;  ; tower top
end aerodrag_element;
;
begin aerodrag_element;  ; nacelle drag
mbdy_name shaft;
aerodrag_sections uniform 2;
nsec 2;
sec 0.0 0.8 10.0;
sec 11.13604196165944 0.8 10.0;
end aerodrag_element;
end aerodrag;

continue_in_file ./data/IEA_15MW_RWT_WTG_aero.htc;

-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
DEFINE WATER CLIMATE
begin hydro;
  ;calculates hydrodynamic forces using Morison's Formula
  begin water_properties;
    rho 1025; density of water
    gravity 9.80665; gravity acceleration
    mwl [mwl]; mean water level in global z coordinates
    mudlevel 200.0; mud level in global z coordinates
    wave_direction [wvdir]; wave direction in degrees forward from the right looking towards the wind at default conditions
    ; current 2 0.5 0.1429 0; type(0=none,1=constant,2=power law), velocity at mean water level, type parameter (alpha), current direction. ALREADY ACCOUNTED FOR IN STREAM FUNCTION
    water_kinematics_dll wkin_dll.dll waves/[wave_case].inp ; [relative path the water kinematics dll, dll input file]
  end water_properties;
end hydro;

-----------------------------------------------------------------------------------------------------------------------------
-----------------------------------------------------------------------------------------------------------------------------
BEGIN LINK TO DLLS THAT DEFINE CONTROLLERS, EXTERNAL FORCES, ETC.
begin dll;

begin type2_dll; dtu basic controller
  name dtu_we_controller ;
  filename ./control/dtu_we_controller.dll ;
  dll_subroutine_init init_regulation_advanced ;
  dll_subroutine_update update_regulation ;
  arraysizes_init 100 1;
  arraysizes_update 100 100;
  begin init ;
    ; Overall parameters
    constant 1 15000.0 ; Rated power [kW]
    constant 2 0.524 ; Minimum rotor (LSS) speed [rad/s]
    constant 3 0.792 ; Rated rotor (LSS) speed [rad/s]
    constant 4 21586451.33303 ; Maximum allowable generator torque [Nm]
    constant 5 100.0 ; Minimum pitch angle, theta_min [deg], if |theta_min|>90, then a table of <wsp,theta_min> is read ; from a file named 'wptable.n', where n=int(theta_min)
    constant 6 90.0 ; Maximum pitch angle [deg]
    constant 7 2.0 ; Maximum pitch velocity operation [deg/s]
    constant 8 0.15915 ; Frequency of generator speed filter [Hz]
    constant 9 0.7 ; Damping ratio of speed filter [-]
    constant 10 1.01 ; Frequency of free-free DT torsion mode [Hz], if zero no notch filter used
    ; Partial load control parameters
    constant 11 0.302217E+08 ; Optimal Cp tracking K factor [Nm/(rad/s)^2],
      Qg=K*Omega^2, K=eta*0.5*rho*A*Cp_opt*R^3/lambda_opt^3
    constant 12 0.112427E+09 ; Proportional gain of torque controller [Nm/(rad/s)]
    constant 13 0.201829E+08 ; Integral gain of torque controller [Nm/rad]
    constant 14 0.0 ; Differential gain of torque controller [Nm/(rad/s)^2]
    ; Full load control parameters
    constant 15 0 ; Generator control switch [1=constant power, 0=constant torque]
constant 16 0.640241E+00 ; Proportional gain of pitch controller [rad/(rad/s)]
constant 17 0.862019E+01 ; Integral gain of pitch controller [rad/rad]
constant 18 0.0 ; Differential gain of pitch controller [rad/(rad/s^2)]
constant 19 0.4e-08 ; Proportional power error gain [rad/W]
constant 20 0.4e-08 ; Integral power error gain [rad/(Ws)]
constant 21 11.95434 ; Coefficient of linear term in aerodynamic gain scheduling, KK1 [deg]
constant 22 720.25183 ; Coefficient of quadratic term in aerodynamic gain scheduling, KK2 [deg^2] &
; (if zero, KK1 = pitch angle at double gain)
constant 23 1.5 ; Relative speed for double nonlinear gain [-]
; Cut-in simulation parameters
constant 24 -1 ; Cut-in time [s], no cut-in is simulated if zero or negative
constant 25 1.0 ; Time delay for soft start of torque [1/1P]
; Cut-out simulation parameters
constant 26 -1 ; Shut-down time [s], no shut-down is simulated if zero or negative
constant 27 5.0 ; Time of linear torque cut-out during a generator assisted stop [s]
constant 28 1 ; Stop type [1=normal, 2=emergency]
constant 29 1.0 ; Time delay for pitch stop after shut-down signal [s]
constant 30 2.0 ; Maximum pitch velocity during initial period of stop [deg/s]
constant 31 3.0 ; Time period of initial pitch stop phase [s] (maintains pitch speed specified in constant 30)
constant 32 2.0 ; Maximum pitch velocity during final phase of stop [deg/s]
; Expert parameters (keep default values unless otherwise given)
constant 33 2.0 ; Time for the maximum torque rate = Maximum allowable generator torque/(constant 33 +
0.01s) [s]
constant 34 2.0 ; Upper angle above lowest minimum pitch angle for switch [deg], if equal then hard switch
constant 35 95.0 ; Percentage of the rated speed when the torque limits are fully opened [%]
constant 36 2.0 ; Time constant of 1st order filter on wind speed used for minimum pitch [1/1P]
constant 37 1.0 ; Time constant of 1st order filter on pitch angle used for gain scheduling [1/1P]
; Drivetrain damper
constant 38 0.0 ; Proportional gain of active DT damper [Nm/(rad/s)], requires frequency in input 10
; Over speed
constant 39 50.0 ; Overspeed percentage before initiating turbine controller alarm (shut-down) [%]
; Additional non-linear pitch control term (not used when all zero)
constant 40 0.0 ; Rotor speed error scaling factor [rad/s]
constant 41 0.0 ; Rotor acceleration error scaling factor [rad/s^2]
constant 42 0.0 ; Pitch rate gain [rad/s]
; Storm control command
constant 43 28.0 ; Wind speed 'Vstorm' above which derating of rotor speed is used [m/s]
constant 44 28.0 ; Cut-out wind speed (only used for derating of rotor speed in storm) [m/s]
; Safety system parameters
constant 45 50.0 ; Overspeed percentage before initiating safety system alarm (shut-down) [%]
constant 46 2.0 ; Max low-pass filtered tower top acceleration level [m/s^2]
; Turbine parameter
constant 47 240.0 ; Nominal rotor diameter [m]
; Parameters for rotor inertia reduction in variable speed region
constant 48 0.0 ; Proportional gain on rotor acceleration in variable speed region [Nm/(rad/s^2)] (not used when zero)
; Parameters for alternative partial load controller with PI regulated TSR tracking
constant 49 9.0 ; Optimal tip speed ratio [-] (only used when K=constant 11 = 0 otherwise Qg=K*Omega^2 is used)
; Parameters for adding aerodynamic drivetrain damping on gain scheduling
constant 50 0.0 ; Aerodynamic DT damping coefficient at the operational point of zero pitch angle
[Nm/(rad/s)] (not used when zero)
constant 51 0.0 ; Coefficient of linear term in aerodynamic DT damping scheduling, KK1 [deg]
constant 52 0.0 ; Coefficient of quadratic term in aerodynamic DT damping scheduling, KK2 [deg^2]
; Torque exclusion zone
constant 53 0.0 ; Exclusion zone: Lower speed limit [rad/s] (Default 0 used if zero)
constant 54 0.0 ; Exclusion zone: Generator torque at lower limit [Nm] (Default 0 used if zero)
constant 55 0.0 ; Exclusion zone: Upper speed limit [rad/s] (if <= 0 then exclusion zone functionality is inactive)
constant 56 0.0 ; Exclusion zone: Generator torque at upper limit [Nm] (Default 0 used if zero)
constant 57 0.0 ; Time constant of reference switching at exclusion zone [s] (Default 0 used if zero)

; DT torsion mode damper
constant 58 0.0 ; Frequency of notch filter [Hz] (Default 10 x input 10 used if zero)
constant 59 0.0 ; Damping of BP filter [-] (Default 0.02 used if zero)
constant 60 0.0 ; Damping of notch filter [-] (Default 0.01 used if zero)
constant 61 0.0 ; Phase lag of damper [s] => max 40*dt (Default 0 used if zero)

; Fore-aft Tower mode damper
constant 62 0.0 ; Frequency of BP filter [Hz] (Default 10 used if zero)
constant 63 0.0 ; Frequency of notch filter [Hz] (Default 10 used if zero)
constant 64 0.0 ; Damping of BP filter [-] (Default 0.02 used if zero)
constant 65 0.0 ; Damping of notch filter [-] (Default 0.01 used if zero)
constant 66 0.0 ; Gain of damper [-] (Default 0 used if zero)
constant 67 0.0 ; Phase lag of damper [s] => max 40*dt (Default 0 used if zero)
constant 68 0.0 ; Time constant of 1st order filter on PWR used for fore-aft Tower mode damper GS [Hz] (Default 10 used if zero)
constant 69 0.0 ; Lower PWR limit used for fore-aft Tower mode damper GS [-] (Default 0 used if zero)
constant 70 0.0 ; Upper PWR limit used for fore-aft Tower mode damper GS [-] (Default 0 used if zero)

; Side-to-side Tower mode filter
constant 71 0.0 ; Frequency of Tower side-to-side notch filter [Hz] (Default 100 used if zero)
constant 72 0.0 ; Damping of notch filter [-] (Default 0.01 used if zero)
constant 73 0.0 ; Max low-pass filtered tower top acceleration level before initiating safety system alarm (shut-down) [m/s^2] (Default 1.1 x input 46 used if zero)
constant 74 0.0 ; Time constant of 1st order filter on tower top acceleration [1/1P] (Default 1 used if zero)

; Pitch deviation monitor parameters
constant 75 1005020 ; Parameters for pitch deviation monitoring. The format is 1,nnn,mmm ; where 'nnn' [s] is the period of the moving average and 'mmm' is threshold of the deviation [0.1 deg] (functionality is inactive if value <$ 1,000,000)

; Gear ratio
constant 76 1.0 ; Gear ratio used for the calculation of the LSS rotational speeds and the HSS generator torque reference [-] (Default 1 if zero)

end init ;

begin output ;
    general time ; [s]
    constraint bearing1 shaft_rot 1 only 2 ; Drivetrain speed [rad/s]
    constraint bearing2 pitch1 1 only 1 ; [rad]
    constraint bearing2 pitch2 1 only 1 ; [rad]
    constraint bearing2 pitch3 1 only 1 ; [rad]
    wind free_wind 1 0.0 0.0 -150 ; Global coordinates at hub height
dll type2_dll generator_servo inpvec 2 ; Elec. power from generator servo .dll
dll type2_dll generator_servo inpvec 8 ; Grid state flag from generator servo .dll
mbdy state acc towertop 1 1.0 global only 1 ; Tower top x-acceleration [m/s^2]
mbdy state acc towertop 1 1.0 global only 2 ; Tower top y-acceleration [m/s^2]
end output;
end type2_dll;

begin type2_dll; generator servo
    name generator_servo ;
    filename ./control/generator_servo.dll ;
dll subroutine_init init_generator_servo ;
dll subroutine_update update_generator_servo ;
arraysizes_init 100 1 ;
arraysizes_update 100 100;
begin init;
    constant 1 20.0 ; Frequency of 2nd order servo model of generator-converter system [Hz]
    constant 2 0.9 ; Damping ratio 2nd order servo model of generator-converter system [-]
    constant 3 21586451.33303 ; Maximum allowable LSS torque (pull-out torque) [Nm]
    constant 4 0.9655 ; Generator efficiency [-]
    constant 5 1.0 ; Gearratio [-]
    constant 6 0.0 ; Time for half value in softstart of torque [s]
    constant 7 -1 ; Time for grid loss [s] (never if lower than zero)
end init;

begin output;
    general time ; Time [s]
    dll type2_dll dtu_we_controller inpvec 1 ; Electrical torque reference [Nm]
    constraint bearing1 shaft_rot 1 only 2 ; Generator LSS speed [rad/s]
    mbdy momentvec shaft 1 1 shaft only 3 ; Shaft moment [kNm] (Qshaft)
end output;

begin actions;
    mbdy moment_int shaft 1 -3 shaft connector 2 ; Generator LSS torque [Nm]
end actions;
end type2_dll;

begin type2_dll; mechanical brake
    name mech_brake;
    filename ./control/mech_brake.dll;
    dll_subroutine_init init_mech_brake;
    dll_subroutine_update update_mech_brake;
    arraysizes_init 100 1;
    arraysizes_update 100 100;
begin init;
    constant 1 12951870.799818 ; Fully deployed maximum brake torque [Nm] (0.6*max torque)
    constant 2 100.0 ; Parameter alpha used in Q = tanh(omega*alpha), typically 1e2/Omega_nom
    constant 3 0.5 ; Delay time for before brake starts to deploy [s]
    constant 4 0.6 ; Time for brake to become fully deployed [s]
end init;

begin output;
    general time ; Time [s]
    constraint bearing1 shaft_rot 1 only 2 ; Generator LSS speed [rad/s]
    dll type2_dll dtu_we_controller inpvec 25 ; Command to deploy mechanical disc brake [0,1]
end output;

begin actions;
    mbdy moment_int shaft 1 -3 shaft connector 2 ; Brake LSS torque [Nm]
end actions;
end type2_dll;

begin type2_dll; pitch servo
    name servo_with_limits;
    filename ./control/servo_with_limits.dll;
    dll_subroutine_init init_servo_with_limits;
    dll_subroutine_update update_servo_with_limits;
    arraysizes_init 100 1;
    arraysizes_update 100 100;
begin init;
constant 1 3 ; Number of blades [-]
constant 2 1.0 ; Frequency of 2nd order servo model of pitch system [Hz]
constant 3 0.7 ; Damping ratio 2nd order servo model of pitch system [-]
constant 4 2.0 ; Max. pitch speed [deg/s]
constant 5 15.0 ; Max. pitch acceleration [deg/s^2]
constant 6 0.0 ; Min. pitch angle [deg]
constant 7 90.0 ; Max. pitch angle [deg]
constant 8 -1 ; Time for pitch runaway [s]
constant 9 -1 ; Time for stuck blade 1 [s]
constant 10 0.0 ; Angle of stuck blade 1 [deg] (if > 90 deg then blade is stuck at instantaneous angle)
end init;
begin output;
    general time ; Time [s]
dll type2_dll dtu_we_controller inpvec 2 ; Pitch1 demand angle [rad]
dll type2_dll dtu_we_controller inpvec 3 ; Pitch2 demand angle [rad]
dll type2_dll dtu_we_controller inpvec 4 ; Pitch3 demand angle [rad]
dll type2_dll dtu_we_controller inpvec 26 ; Flag for emergency pitch stop [0=off/1=on]
end output;

begin actions;
    constraint bearing2 angle pitch1 ; Angle pitch1 bearing [rad]
    constraint bearing2 angle pitch2 ; Angle pitch2 bearing [rad]
    constraint bearing2 angle pitch3 ; Angle pitch3 bearing [rad]
end actions;

end type2_dll;

begin type2_dll; tower-blade-tip distance
name towerclearance_mblade;
filename ./control/towerclearance_mblade.dll;
dll subroutine_init initialize;
dll subroutine_update update;
arraysizes_init 3 1;
arraysizes_update 15 6;
begin init ; Variables passed into initialization function
    constant 1 5.00 ; Tower radius at tower bottom [m]
    constant 2 3.25 ; Tower radius at tower top [m]
    constant 3 3 ; Number of points to check [-]
end init;
begin output; Variables passed into update function
    mbdy state pos tower 1 0.0 global ; [1,2,3] global coordinates of tower base
    mbdy state pos tower 9 1.0 global ; [4,5,6] global coordinates of tower top
    mbdy state pos blade1 19 1.0 global ; [7,8,9] global coordinates of point 1 (blade 1 tip)
    mbdy state pos blade2 19 1.0 global ; [10,11,12] global coordinates of point 2 (blade 2 tip)
    mbdy state pos blade3 19 1.0 global ; [13,14,15] global coordinates of point 3 (blade 3 tip)
end output;
end type2_dll;

;-----------------------------------------------------------------------------------------------------------------------------
;-----------------------------------------------------------------------------------------------------------------------------
;-----------------------------------------------------------------------------------------------------------------------------
;-----------------------------------------------------------------------------------------------------------------------------
;-----------------------------------------------------------------------------------------------------------------------------

;-------------------------------------------------- DEFINE WHICH SENSORS/ PARAMETERS TO BE SAVED IN OUTPUT FILES
begin output;
    filename ./iec_res/[Case id];
data_format [out_format]; General time series data format
    buffer 9999 ; buffer size in terms of time steps
time [t0] [time stop];
general time; time output
constraint bearing1 shaft_rot 2; angle and angle velocity
constraint bearing2 pitch1 5; angle and angular velocity
constraint bearing2 pitch2 5; angle and angular velocity
constraint bearing2 pitch3 5; angle and angular velocity
aero omega; rotational speed of rotor (rad/s)
aero torque; integrated aerodynamic forces of all blades to rotor torsion (kNm)
aero power; integrated aerodynamic forces of all blades to rotor torsion multiplied by rotor speed (kW)
aero thrust; integrated aerodynamic force of all blades to rotor thrust (kN)
wind free_wind 1 0.0 0.0 -150; local wind at fixed position: coo (1=global,2=non-rotation rotor coo.), pos x, pos y, pos z

; Moments about local coordinate system:
; [main_body name, element number, node number on element (1 or 2), main_body name of which coordinate system is used for output]
mbdy momentvec tower 1 1 tower # tower base bending moment; ; ---SENSOR 17-19---
mbdy momentvec tower 9 2 tower # tower yaw bending moment; ; ---SENSOR 20-22---
mbdy momentvec towertop 1 1 towertop # tower top bending moment; ; ---SENSOR 23-25---
mbdy momentvec shaft 1 1 shaft # main bearing bending moment; ; ---SENSOR 26-28---
mbdy momentvec blade1 1 1 blade1 # blade 1 root bending moment; ; ---SENSOR 29-31---
mbdy momentvec blade2 1 1 blade2 # blade 2 root bending moment; ; ---SENSOR 32-34---
mbdy momentvec blade3 1 1 blade3 # blade 3 root bending moment; ; ---SENSOR 35-37---

; Moments about global coordinate system:
; [main_body name, element number, node number on element (1 or 2), main_body name of which coordinate system is used for output]
mbdy momentvec tower 1 1 global # tower base bending moment; ; ---SENSOR 17-19---
mbdy momentvec tower 9 2 global # tower yaw bearing bending moment; ; ---SENSOR 20-22---
mbdy momentvec towertop 1 1 global # tower top bending moment; ; ---SENSOR 23-25---
mbdy momentvec shaft 1 1 global # main bearing bending moment; ; ---SENSOR 26-28---

; Forces on local coordinate system:
mbdy forcevec tower 1 1 tower # tower base shear force; ; ---SENSOR ---
mbdy forcevec tower 9 2 tower # tower yaw bearing force; ; ---SENSOR ---
mbdy forcevec towertop 1 1 towertop # tower top shear force; ; ---SENSOR ---
mbdy forcevec shaft 1 1 shaft # main bearing shear force; ; ---SENSOR ---

; Forces on global coordinate system:
mbdy forcevec tower 1 1 global # tower base shear force; ; ---SENSOR ---
mbdy forcevec tower 9 2 global # tower yaw bearing force; ; ---SENSOR ---
mbdy forcevec towertop 1 1 global # tower top shear force; ; ---SENSOR ---
mbdy forcevec shaft 1 1 global # main bearing shear force; ; ---SENSOR ---

; Displacements and accelerations
mbdy state pos tower 1 1.0 global only 1 # Tower top FA displ; ; [pos vel acc acg, main_body name, element number, relative distance from node 1 to 2, main_body element used for output(global)]
mbdy state pos tower 1 1.0 global only 2 # Tower top SS displ;
mbdy state acc tower 1 1.0 global only 1 # Tower top FA acc;
mbdy state acc tower 1 1.0 global only 2 # Tower top SS acc;
mbdy state pos towertop 1 1.0 global only 1 # Tower top FA displ;
mbdy state pos towertop 1 1.0 global only 2 # Tower top SS displ;
mbdy state acc towertop 1 1.0 global only 1 # Tower top FA acc;
mbdy state acc towertop 1 1.0 global only 2 # Tower top SS acc;
mbdy state pos tower 1 1.0 global only 1 #Tower Bottom FA displ;
mbdy state pos tower 1 1.0 global only 2 #Tower Bottom SS displ;
mbdy state acc tower 1 1.0 global only 1 #Tower Bottom FA acc;
mbdy state acc tower 1 1.0 global only 2 #Tower Bottom SS acc;
mbdy state pos blade1 9 1.0 blade1 # blade 1 tip pos;
mbdy state pos blade2 9 1.0 blade2 # blade 2 tip pos;
mbdy state pos blade3 9 1.0 blade3 # blade 3 tip pos;
mbdy state pos blade1 9 1.0 global # gl blade 1 tip pos;

Angles and Orientations
mbdy statevec_new tower default tower elastic -1.2958e+02 1.0 0.0 0.0 #tower top movement;
mbdy statevec_new tower default tower elastic 0.0 1.0 0.0 0.0 #tower bottom movement;
mbdy statevec_new tower c2def tower elastic -1.2958e+02 1.0 0.0 0.0 #tower top movement;
mbdy statevec_new tower c2def tower elastic 0.0 1.0 0.0 0.0 #tower bottom movement;
mbdy state_rot proj_ang towertop 1 1.0 global only 3 #tower top twist projection angle;
mbdy state_rot proj_ang tower 9 1.0 global only 3 #tower bottom twist projection angle;
mbdy state_rot proj_ang tower 1 1.0 global only 3 #tower bottom twist projection angle;
mbdy state_rot eulerang_xyx towertop 1 1.0 global only 3 #tower top twist projection angle;
mbdy state_rot eulerang_xyx tower 9 1.0 global only 3 #tower top twist projection angle;
mbdy state_rot eulerang_xyx tower 1 1.0 global only 3 #tower bottom twist projection angle;
mbdy state_rot axisangle towertop 1 1.0 global only 3 #tower top twist projection angle;
mbdy state_rot axisangle tower 9 1.0 global only 3 #tower top twist projection angle;
mbdy state_rot axisangle tower 1 1.0 global only 3 #tower bottom twist projection angle;

- Monitor Aerodynamics -;
aero windspeed 3 1 1 72.5;
aero alfa 1 72.5; angle of attack in x-y local aerodynamic plane [blade number, radius]
aero alfa 2 72.5;
aero alfa 3 72.5;
aero cl 1 72.5; instantaneous life coefficient [blade number, radius]
aero cl 2 72.5;
aero cl 3 72.5;
aero cd 1 72.5; instantaneous drag coefficient [blade number, radius]
aero cd 2 72.5;
aero cd 3 72.5;

; DLL outputs and into HAWC2
; dll type2_dll dtu_we_controller inpvec 1 # Generator torque reference [Nm];
; [reference name, inpvec, channel number in or out going array]
dll type2_dll dtu_we_controller inpvec 2 # Pitch angle reference of blade 1 [rad];
dll type2_dll dtu_we_controller inpvec 3 # Pitch angle reference of blade 2 [rad];
dll type2_dll dtu_we_controller inpvec 4 # Pitch angle reference of blade 3 [rad];
dll type2_dll dtu_we_controller inpvec 5 # Power reference [W];
dll type2_dll dtu_we_controller inpvec 6 # Filtered wind speed [m/s];
dll type2_dll dtu_we_controller inpvec 7 # Filtered rotor speed [rad/s];
dll type2_dll dtu_we_controller inpvec 8 # Filtered rotor speed error for torque [rad/s];
dll type2_dll dtu_we_controller inpvec 9 # Bandpass filtered rotor speed [rad/s];
dll type2_dll dtu_we_controller inpvec 10 # Proportional term of torque controller [Nm];
dll type2_dll dtu_we_controller inpvec 11 # Integral term of torque controller [Nm];
 dll type2_dll dtu_we_controller inpvec 12 # Minimum limit of torque [Nm];
 dll type2_dll dtu_we_controller inpvec 13 # Maximum limit of torque [Nm];
 dll type2_dll dtu_we_controller inpvec 14 # Torque limit switch based on pitch [-];
 dll type2_dll dtu_we_controller inpvec 15 # Filtered rotor speed error for pitch [rad/s];
 dll type2_dll dtu_we_controller inpvec 16 # Power error for pitch [W];
 dll type2_dll dtu_we_controller inpvec 17 # Proportional term of pitch controller [rad];
 dll type2_dll dtu_we_controller inpvec 18 # Integral term of pitch controller [rad];
 dll type2_dll dtu_we_controller inpvec 19 # Minimum limit of pitch [rad];
 dll type2_dll dtu_we_controller inpvec 20 # Maximum limit of pitch [rad];
 dll type2_dll dtu_we_controller inpvec 21 # Torque reference from DT damper [Nm];
 dll type2_dll dtu_we_controller inpvec 22 # Status signal [-];
 dll type2_dll dtu_we_controller inpvec 23 # Total added rate [rad/s];
 dll type2_dll dtu_we_controller inpvec 24 # Filtered Mean pitch for gain sch [rad];
 dll type2_dll dtu_we_controller inpvec 25 # Flag for mechanical brake [0=off/1=on];
 dll type2_dll dtu_we_controller inpvec 26 # Flag for emergency pitch stop [0=off/1=on];
 dll type2_dll dtu_we_controller inpvec 27 # LP filtered acceleration level [m/s^2];
 dll type2_dll dtu_we_controller inpvec 31 # Monitored average of reference pitch [rad];
 dll type2_dll dtu_we_controller inpvec 32 # Monitored ave. of actual pitch (blade 1) [rad];

 dll type2_dll generator_servo inpvec 1  # Mgen LSS [Nm];
 dll type2_dll generator_servo inpvec 2  # Pelec [W];
 dll type2_dll generator_servo inpvec 3  # Mframe [Nm];
 dll type2_dll generator_servo inpvec 4  # Mgen HSS [Nm];
 dll type2_dll generator_servo inpvec 8  # Grid flag [0=run/1=stop];

 dll type2_dll mech_brake inpvec 3 1 # Brake torque [Nm];

 dll type2_dll servo_with_limits inpvec 1 # pitch 1 [rad];
 dll type2_dll servo_with_limits inpvec 2 # pitch 2 [rad];
 dll type2_dll servo_withLimits inpvec 3 # pitch 3 [rad];

 dll type2_dll towerclearance_mblade inpvec 1 # Bltip tow min d [m];

 HydroDynamic output
 water_surface 0.0 0.0; water surface at base point
 end output;

 exit;

---

### A.5 Post Processing Analysis Codes

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Stress Maximum and Average Results
%Nov 9, 2022
%Programer: Ailish Bozzo
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
close all
clear all
clc

T=table2array(TowerProperties(1,"Var11"));
I=table2array(TowerProperties(1,"Var13"));
A=table2array(TowerProperties(1,"Var16"));
ri=table2array(TowerProperties(1,"Var5"));
```

% and y the same for circular cross section
k = table2array(TowerProperties(1, "Var14")); \% and y the same for circular cross section
r = 10/2;
r2 = r - (82.954/1000);
Q = 2/3 * ((r^3) - (r2^3));
b = 2 * (r - r2);

\\% Material Properties
E_steel = (table2array(TowerProperties(11, "Var9")))/1000; \% in kPa
G_steel = table2array(TowerProperties(11, "Var10"));

\\% LOADING RESULTS
\\% Adding All results Folders to the Path and Importing Variables
BasePath = 'C:\HAWC2\iec_res';
DirList = dir(BasePath);
DirList = DirList([DirList.isdir]); \% Folders only
DirList = DirList(3:length(DirList),:);
for iDir = 1:numel(DirList);
    aDir = fullfile(BasePath, DirList(iDir).name);
    fprintf('Processing: %s
', aDir);
    addpath(aDir);
    folder = DirList(iDir,1).name;
    Names(iDir,1) = string(folder);
    string1 = 'C:\HAWC2\iec_res\';
    string2 = folder;
    string3 = '\timeseries.mat';
    path = convertContainedStringsToChars(append(string1, string2, string3));
    files = dir([path]);
    for i = 1:size(files,1);
        filename = files(i,1).name;
        load(fullfile);
    end
end
Names = categorical(Names);

\\% MAX TOWER BASE BENDING STRESS MAGNITUDES in KILO PASCALS MC/I
\\% Mx MAGNITUDE
BaseBendingMx(:,1) = abs((timeseries_292_0795_0(:,2)*r)/I);
BaseBendingMx(:,2) = abs((timeseries_292_0795_133(:,2)*r)/I);
BaseBendingMx(:,3) = abs((timeseries_292_0795_193(:,2)*r)/I);
BaseBendingMx(:,4) = abs((timeseries_292_0_0(:,2)*r)/I);
BaseBendingMx(:,5) = abs((timeseries_292_0_133(:,2)*r)/I);
BaseBendingMx(:,6) = abs((timeseries_292_0_193(:,2)*r)/I);
BaseBendingMx(:,7) = abs((timeseries_292_432_0(:,2)*r)/I);
BaseBendingMx(:,8) = abs((timeseries_292_432_133(:,2)*r)/I);
BaseBendingMx(:,9) = abs((timeseries_292_432_193(:,2)*r)/I);
BaseBendingMx(:,10) = abs((timeseries_308_0795_0(:,2)*r)/I);
BaseBendingMx(:,11) = abs((timeseries_308_0795_133(:,2)*r)/I);
BaseBendingMx(:,12) = abs((timeseries_308_0795_193(:,2)*r)/I);
BaseBendingMx(:,13) = abs((timeseries_308_0_0(:,2)*r)/I);
BaseBendingMx(:,14) = abs((timeseries_308_0_133(:,2)*r)/I);
BaseBendingMx(:,15) = abs((timeseries_308_0_193(:,2)*r)/I);
BaseBendingMx(:,16) = abs((timeseries_308_432_0(:,2)*r)/I);
BaseBendingMx(:,17) = abs((timeseries_308_432_133(:,2)*r)/I);
BaseBendingMx(:,18) = abs((timeseries_308_432_193(:,2)*r)/I);
BaseBendingMxMax = transpose(max(BaseBendingMx(:, :, :)));

\\% My MAGNITUDE
BaseBendingMy(:,1) = abs((timeseries_292_0795_0(:,3)*r)/I);
BaseBendingMy(:,2) = abs((timeseries_292_0795_133(:,3)*r)/I);
BaseBendingMy(:,3) = abs((timeseries_292_0795_193(:,3)*r)/I);
BaseBendingMy(:,4)=abs((timeseries_292_0_0(:,3)*r)/I);
BaseBendingMy(:,5)=abs((timeseries_292_0_133(:,3)*r)/I);
BaseBendingMy(:,6)=abs((timeseries_292_0_193(:,3)*r)/I);
BaseBendingMy(:,7)=abs((timeseries_292_432_0(:,3)*r)/I);
BaseBendingMy(:,8)=abs((timeseries_292_432_133(:,3)*r)/I);
BaseBendingMy(:,9)=abs((timeseries_292_432_193(:,3)*r)/I);
BaseBendingMy(:,10)=abs((timeseries_308_0795_0(:,3)*r)/I);
BaseBendingMy(:,11)=abs((timeseries_308_0795_133(:,3)*r)/I);
BaseBendingMy(:,12)=abs((timeseries_308_0795_193(:,3)*r)/I);
BaseBendingMy(:,13)=abs((timeseries_308_0_0(:,3)*r)/I);
BaseBendingMy(:,14)=abs((timeseries_308_0_133(:,3)*r)/I);
BaseBendingMy(:,15)=abs((timeseries_308_0_193(:,3)*r)/I);
BaseBendingMy(:,16)=abs((timeseries_308_432_0(:,3)*r)/I);
BaseBendingMy(:,17)=abs((timeseries_308_432_133(:,3)*r)/I);
BaseBendingMy(:,18)=abs((timeseries_308_432_193(:,3)*r)/I);
BaseBendingMyMax= transpose(max(BaseBendingMy(:,:)));%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

BaseBendingMz(:,1)=abs((timeseries_292_0795_0(:,4)*r)/Ip);
BaseBendingMz(:,2)=abs((timeseries_292_0795_133(:,4)*r)/Ip);
BaseBendingMz(:,3)=abs((timeseries_292_0795_193(:,4)*r)/Ip);
BaseBendingMz(:,4)=abs((timeseries_292_0_0(:,4)*r)/Ip);
BaseBendingMz(:,5)=abs((timeseries_292_0_133(:,4)*r)/Ip);
BaseBendingMz(:,6)=abs((timeseries_292_0_193(:,4)*r)/Ip);
BaseBendingMz(:,7)=abs((timeseries_292_432_0(:,4)*r)/Ip);
BaseBendingMz(:,8)=abs((timeseries_292_432_133(:,4)*r)/Ip);
BaseBendingMz(:,9)=abs((timeseries_292_432_193(:,4)*r)/Ip);
BaseBendingMz(:,10)=abs((timeseries_308_0795_0(:,4)*r)/Ip);
BaseBendingMz(:,11)=abs((timeseries_308_0795_133(:,4)*r)/Ip);
BaseBendingMz(:,12)=abs((timeseries_308_0795_193(:,4)*r)/Ip);
BaseBendingMz(:,13)=abs((timeseries_308_0_0(:,4)*r)/Ip);
BaseBendingMz(:,14)=abs((timeseries_308_0_133(:,4)*r)/Ip);
BaseBendingMz(:,15)=abs((timeseries_308_0_193(:,4)*r)/Ip);
BaseBendingMz(:,16)=abs((timeseries_308_432_0(:,4)*r)/Ip);
BaseBendingMz(:,17)=abs((timeseries_308_432_133(:,4)*r)/Ip);
BaseBendingMz(:,18)=abs((timeseries_308_432_193(:,4)*r)/Ip);
BaseBendingMzMax= transpose(max(BaseBendingMz(:,:)));%

%% MAX TOWER BASE AXIAL STRESS MAGNITUDES IN KILO PASCALS F/A

BaseAxial(:,1)=abs((timeseries_292_0795_0(:,10)/A));
BaseAxial(:,2)=abs((timeseries_292_0795_133(:,10)/A));
BaseAxial(:,3)=abs((timeseries_292_0795_193(:,10)/A));
BaseAxial(:,4)=abs((timeseries_292_0_0(:,10)/A));
BaseAxial(:,5)=abs((timeseries_292_0_133(:,10)/A));
BaseAxial(:,6)=abs((timeseries_292_0_193(:,10)/A));
BaseAxial(:,7)=abs((timeseries_292_432_0(:,10)/A));
BaseAxial(:,8)=abs((timeseries_292_432_133(:,10)/A));
BaseAxial(:,9)=abs((timeseries_292_432_193(:,10)/A));
BaseAxial(:,10)=abs((timeseries_308_0795_0(:,10)/A));
BaseAxial(:,11)=abs((timeseries_308_0795_133(:,10)/A));
BaseAxial(:,12)=abs((timeseries_308_0795_193(:,10)/A));
BaseAxial(:,13)=abs((timeseries_308_0_0(:,10)/A));
BaseAxial(:,14)=abs((timeseries_308_0_133(:,10)/A));
BaseAxial(:,15)=abs((timeseries_308_0_193(:,10)/A));
BaseAxial(:,16)=abs((timeseries_308_432_0(:,10)/A));
BaseAxial(:,17)=abs((timeseries_308_432_133(:,10)/A));
BaseAxial(:,18)=abs((timeseries_308_432_193(:,10)/A));

BaseAxialMax= transpose(max(BaseAxial(:,::)));

%% COMBINED STRESS (AXIAL PLUS BENDING)
for i=1:width(BaseBendingMx);
    for j=1:length(BaseBendingMx);
        CombinedStress(j,i)= BaseBendingMx(j,i) + BaseBendingMy(j,i) +BaseAxial(j,i);
    end
    CombineStressMax(1,i)=max(CombinedStress(:,i));
    CombineStressAverage(1,i)=mean(CombinedStress(:,i));
end

CombineStressMaxTable=transpose(CombineStressMax);
CombineStressAverageTable=transpose(CombineStressAverage);

figure;
y=(CombineStressMax*1.35);
x=categorical({'\sigma_{total}'});
b_prop=bar(x,y,0.8);
ylabel('Normal Stress Magnitude (kN/m^2)');
legend(Names(3:20),'Location','eastoutside');
legend('boxoff')
title('Tower Base Maximum Normal Stress');
ylim([0 4.5*10^5]);
yticks([0:5*10^4:4.5*10^5]);
for k=1:length(b_prop)
    xtips1 = b_prop(k).XEndPoints;
ytips1 = b_prop(k).YEndPoints;
    labels1 = string(round(b_prop(k).YData,0));
    text(xtips1,ytips1,labels1,'HorizontalAlignment','left','Rotation',90,...
          'VerticalAlignment','middle')
end
fontname(gcf,"Times New Roman");
fontsize(gcf,12,"points");

figure;
y=(CombineStressAverage*1.35);
x=categorical({'\sigma_{total}'});
b_prop=bar(x,y,0.8);
ylabel('Normal Stress Magnitude (kN/m^2)');
legend(Names(3:20),'Location','eastoutside');
legend('boxoff')
title('Tower Base Average Normal Stress');
ylim([0 1.5*10^5]);
yticks([0:1*10^4:1.5*10^5]);
for k=1:length(b_prop)
    xtips1 = b_prop(k).XEndPoints;
ytips1 = b_prop(k).YEndPoints;
    labels1 = string(round(b_prop(k).YData,0));
    text(xtips1,ytips1,labels1,'HorizontalAlignment','left','Rotation',90,...
          'VerticalAlignment','middle')
end
fontname(gcf,"Times New Roman");
fontsize(gcf,12,"points");

%% SHEAR STRESS IN KILO PASCALS VQ/IT
Fx MAGNITUDE
BaseShear(:,1)=abs((timeseries_292_0795_0(:,8)*Q)/((I*b)));  
BaseShear(:,2)=abs((timeseries_292_0795_133(:,8)*Q)/((I*b)));  
BaseShear(:,3)=abs((timeseries_292_0795_193(:,8)*Q)/((I*b)));  
BaseShear(:,4)=abs((timeseries_292_0_0(:,8)*Q)/((I*b)));  
BaseShear(:,5)=abs((timeseries_292_0_133(:,8)*Q)/((I*b)));  
BaseShear(:,6)=abs((timeseries_292_0_193(:,8)*Q)/((I*b)));  
BaseShear(:,7)=abs((timeseries_292_432_0(:,8)*Q)/((I*b)));  
BaseShear(:,8)=abs((timeseries_292_432_133(:,8)*Q)/((I*b)));  
BaseShear(:,9)=abs((timeseries_292_432_193(:,8)*Q)/((I*b)));  
BaseShear(:,10)=abs((timeseries_308_0795_0(:,8)*Q)/((I*b)));  
BaseShear(:,11)=abs((timeseries_308_0795_133(:,8)*Q)/((I*b)));  
BaseShear(:,12)=abs((timeseries_308_0795_193(:,8)*Q)/((I*b)));  
BaseShear(:,13)=abs((timeseries_308_0_0(:,8)*Q)/((I*b)));  
BaseShear(:,14)=abs((timeseries_308_0_133(:,8)*Q)/((I*b)));  
BaseShear(:,15)=abs((timeseries_308_0_193(:,8)*Q)/((I*b)));  
BaseShear(:,16)=abs((timeseries_308_432_0(:,8)*Q)/((I*b)));  
BaseShear(:,17)=abs((timeseries_308_432_133(:,8)*Q)/((I*b)));  
BaseShear(:,18)=abs((timeseries_308_432_193(:,8)*Q)/((I*b)));  
BaseShearMax= transpose(max(BaseShear(:,::)));

Fy MAGNITUDE
BaseSheary(:,1)=abs((timeseries_292_0795_0(:,9)*Q)/((I*b)));  
BaseSheary(:,2)=abs((timeseries_292_0795_133(:,9)*Q)/((I*b)));  
BaseSheary(:,3)=abs((timeseries_292_0795_193(:,9)*Q)/((I*b)));  
BaseSheary(:,4)=abs((timeseries_292_0_0(:,9)*Q)/((I*b)));  
BaseSheary(:,5)=abs((timeseries_292_0_133(:,9)*Q)/((I*b)));  
BaseSheary(:,6)=abs((timeseries_292_0_193(:,9)*Q)/((I*b)));  
BaseSheary(:,7)=abs((timeseries_292_432_0(:,9)*Q)/((I*b)));  
BaseSheary(:,8)=abs((timeseries_292_432_133(:,9)*Q)/((I*b)));  
BaseSheary(:,9)=abs((timeseries_292_432_193(:,9)*Q)/((I*b)));  
BaseSheary(:,10)=abs((timeseries_308_0795_0(:,9)*Q)/((I*b)));  
BaseSheary(:,11)=abs((timeseries_308_0795_133(:,9)*Q)/((I*b)));  
BaseSheary(:,12)=abs((timeseries_308_0795_193(:,9)*Q)/((I*b)));  
BaseSheary(:,13)=abs((timeseries_308_0_0(:,9)*Q)/((I*b)));  
BaseSheary(:,14)=abs((timeseries_308_0_133(:,9)*Q)/((I*b)));  
BaseSheary(:,15)=abs((timeseries_308_0_193(:,9)*Q)/((I*b)));  
BaseSheary(:,16)=abs((timeseries_308_432_0(:,9)*Q)/((I*b)));  
BaseSheary(:,17)=abs((timeseries_308_432_133(:,9)*Q)/((I*b)));  
BaseSheary(:,18)=abs((timeseries_308_432_193(:,9)*Q)/((I*b)));  
BaseShearxMax= transpose(max(BaseSheary(:,::)));

COMBINED SHEAR STRESS
for i=1:width(BaseShearx);  
    for j=1:length(BaseShearx);  
        CombinedShear(j,i)= BaseShearx(j,i) + BaseSheary(j,i) + BaseBendingMz(j,i);  
    end  
    CombineShearMax(1,i)=max(CombinedShear(:,i));  
    CombineShearAverage(1,i)=mean(CombinedShear(:,i));  
end

CombineShearMaxTable=transpose(CombineShearMax);  
CombineShearAverageTable=transpose(CombineShearAverage);
figure;  
y=CombineShearMax;
x=categorical({'\tau_{total}'});

b_prop=bar(x,y,0.8);
ylabel('Shear Stress Magnitude (kN/m^2)');
legend(Names(3:20), 'Location', 'eastoutside');
legend('boxoff')
title('Tower Base Maximum Shear Stress');
ylim([0 1.6*10^4]);
yticks([0:1*10^3:1.6*10^4]);

for k=1:length(b_prop)
  xtips1 = b_prop(k).XEndPoints;
ytips1 = b_prop(k).YEndPoints;
  labels1 = string(round(b_prop(k).YData,0));
  text(xtips1,ytips1,labels1, 'HorizontalAlignment', 'left', 'Rotation', 90,...
       'VerticalAlignment', 'middle')
end

fontname(gcf, "Times New Roman");
fontsize(gcf, 12, "points");

figure;
y=CombineShearAverage;
x=categorical({'\tau_{total}'});

b_prop=bar(x,y,0.8);
ylabel('Shear Stress Magnitude (kN/m^2)');
legend(Names(3:20), 'Location', 'eastoutside');
legend('boxoff')
title('Tower Base Average Shear Stress');
ylim([0 4.5*10^3]);
yticks([0:0.5*10^3:4.5*10^3]);

for k=1:length(b_prop)
  xtips1 = b_prop(k).XEndPoints;
ytips1 = b_prop(k).YEndPoints;
  labels1 = string(round(b_prop(k).YData,0));
  text(xtips1,ytips1,labels1, 'HorizontalAlignment', 'left', 'Rotation', 90,...
       'VerticalAlignment', 'middle');
end

fontname(gcf, "Times New Roman");
fontsize(gcf, 12, "points");

%% SAVE STRESS TIME HISTORIES TO FOLDER

save BaseAxial BaseAxial;
save BaseBendingMx BaseBendingMx;
save BaseBendingMy BaseBendingMy;
save BaseBendingMz BaseBendingMz;
save CombinedStress CombinedStress;
save BaseShearx BaseShearx;
save BaseSheary BaseSheary;
save CombinedShear CombinedShear;

%% COMPARING X,Y,Z, AXIAL STRESSES FOR WORST CASE

AverageStresses=1.35*[mean(BaseBendingMx(:,9)) , mean(BaseBendingMy(:,9)) ,
  mean(BaseBendingMz(:,9)) , mean(BaseAxial(:,9)), mean(BaseShearx(:,9)) ,mean(BaseSheary(:,9))];

figure;
xavg=categorical({'\sigma_x', '\sigma_y', '\tau_{z}', '\sigma_{axial}', '\tau_{x}', '\tau_{y}'},
  stressavgbar=bar(xavg,AverageStresses,0.8);
ylabel('Stress Magnitude (kPa)');
title('Tower Base Average Stresses Comparison for wdir292_mwl432_wvdir193');
ylim([0 7*10^4])
yticks([0:10000:7*10^4])

for k=1:length(stressavgbar)
xtips1 = stressavgbar(k).XEndPoints;
ytips1 = stressavgbar(k).YEndPoints;
labels1 = string(round(stressavgbar(k).YData,0));
text(xtips1,ytips1,labels1,'HorizontalAlignment','left','Rotation',90,...
'VerticalAlignment','middle')
end
top fontname(gcf,"Times New Roman");
fontsize(gcf,12,"points");

%% TOP COMBINED STRESS FOR COMPARISON WITH BOTTOM USING WORST CASE

I_top=table2array(TowerProperties(10,"Var11")); %x and y the same for circular cross
section
Ip_top=table2array(TowerProperties(10,"Var13"));
A_top=table2array(TowerProperties(10,"Var16"));
r1_top=table2array(TowerProperties(10,"Var5")); %x and y the same for circular cross
section
k_top=table2array(TowerProperties(10,"Var14")); %x and y the same for circular cross
section

r_top=6.5/2;
r2_top=r_top-(41.06/1000);
Q_top=2/3*((r_top^3)-(r2_top^3));
b_top=2*(r_top-r2_top);

TopStress(:,1)=abs((timeseries_292_432_193(:,5)*r_top)/I_top); % x bend
TopStress(:,2)=abs((timeseries_292_432_193(:,6)*r_top)/I_top); % y bend
TopStress(:,3)=abs((timeseries_292_432_193(:,7)*r_top)/Ip_top); % z bend
TopStress(:,4)=abs((timeseries_292_432_193(:,13)/A_top)); % axial
TopStress(:,5)=abs((timeseries_292_432_193(:,11)*Q_top)/((I_top*b_top))); % x shear
TopStress(:,6)=abs((timeseries_292_432_193(:,12)*Q_top)/((I_top*b_top))); % y shear

TopStress(:,7)=TopStress(:,1)+TopStress(:,2)+TopStress(:,4); %Combined Stress
TopStress(:,8)=TopStress(:,5)+TopStress(:,6)+TopStress(:,3); % Combined Shear

TopAverages=1.35*mean(TopStress(:,:));
TopvBottom=[TopAverages(:,1:6);AverageStresses];
TopvBottomCombined=[TopAverages(:,7),TopAverages(:,8);1.35*CombineStressAverageTable(9,1),
CombineShearAverageTable(9,1)];

figure;
x_topvbottom=categorical({'\sigma_{x}','\sigma_{y}','\tau_{z}','\sigma_{axial}','\tau_{x}','\tau_{y}'});
stresstopvbottombar=bar(x_topvbottom,TopvBottom,0.8);
ylabel('Stress Magnitude (kPa)');
legend('Top Stress','Base Stress','Location','northeast');
legend('boxoff');
tilt('Average Stress Tower Top vs Tower Bottom for wdir292_mwl432_wvdir193');
stitresstopvbottombar(2).FaceColor = [0.6350 0.0780 0.1840];
ylim([0 0.7*10^5])
yticks([0:20000:0.7*10^5])
for k=1:length(stresstopvbottombar)
    xtips1 = stresstopvbottombar(k).XEndPoints;
ytips1 = stresstopvbottombar(k).YEndPoints;
    labels1 = string(round(stresstopvbottombar(k).YData,0));
text(xtips1,ytips1,labels1,'HorizontalAlignment','left','Rotation',90,...
'VerticalAlignment','middle')
end
fontname(gcf,"Times New Roman");
fontsize(gcf,12,"points");

figure;
x_topvbottomcombine=categorical({'\tau_{combined}','\sigma_{combined}'});
stresstopvbottomcombinebar=bar(x_topvbottomcombine,TopvBottomCombined,0.8);
ylabel('Stress Magnitude (kPa)');
legend('Base Stress','Top Stress','Location','northeast');
legend('boxoff');
tilt('Average Stress Tower Top vs Tower Bottom for wdir292_mwl432_wvdir193');
stressbottomcombinebar(2).FaceColor = [0.6350 0.0780 0.1840];
ylim([0 1.3e10^5])
yticks([0:20000:1.3e10^5])
for k=1:length(stressbottomcombinebar)
    xtips1 = stressbottomcombinebar(k).XEndPoints;
    ytips1 = stressbottomcombinebar(k).YEndPoints;
    labels1 = string(round(stressbottomcombinebar(k).YData,0));
    text(xtips1,ytips1,labels1,'HorizontalAlignment','left','Rotation',90,...
    'VerticalAlignment','middle')
end
fontname(gcf,"Times New Roman");
fontsize(gcf,12,"points");

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Stress Maximum and Average Results
%Nov 9, 2022
%Programer: Ailish Bozzo
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
close all
clear all
tlc

TOWER PROPERTIES
TowerProperties=readtable('IEA_15MW_RWT_UMaineSemi_Tower_st.dat');
I=table2array(TowerProperties(1,"Var11");  % and y the same for circular cross section
Ip=table2array(TowerProperties(1,"Var13");
A=table2array(TowerProperties(1,"Var16");
ri=table2array(TowerProperties(1,"Var5");  % and y the same for circular cross section
k=table2array(TowerProperties(1,"Var14");

r=10/2;
r2=r-(82.954/1000);
Q=2/3*(r^3)-(r2^3);
b=2*(r-r2);

Material Properties
E_steel=(table2array(TowerProperties(11,"Var9")))/1000; % in kPA
G_steel=table2array(TowerProperties(11,"Var10");

LOADING RESULTS
BasePath = 'C:\HAWC2\iec_res';
DirList = dir(BasePath);
DirList = DirList((DirList.isdir);  % Folders only
DirList=DirList(3:length(DirList),:);
for iDir = 1:numel(DirList);
    aDir = fullfile(BasePath, DirList(iDir).name);
    fprintf('Processing: %s
', aDir);
    addpath(aDir);
    folder= DirList(iDir,1).name;
    Names(iDir,1)=string(folder);
    string1='C:\HAWC2\iec_res \';
    string2=folder;
    string3='\timeseries.mat';
    path= convertContainedStringsToChars(append(string1,string2,string3));
    files = dir([path]);
    for i=1:size(files,1);
        filename=files(i,1).name;
        load([filename]);
    end
end
Names=categorical(Names);

TOWER BASE BENDING STRESS MAGNITUDES in KILO PASCALS MC/I

BaseBendingMx(:,i)=abs((timeseries_292_0795_0(:,2)*r)/I);
BaseBendingMx(:,2)=abs((timeseries_292_0795_133(:,2)*r)/I);
BaseBendingMx(:,3)=abs((timeseries_292_0795_193(:,2)*r)/I);
BaseBendingMx(:,4)=abs((timeseries_292_0_0(:,2)*r)/I);
BaseBendingMx(:,5)=abs((timeseries_292_0_133(:,2)*r)/I);
BaseBendingMx(:,6)=abs((timeseries_292_0_193(:,2)*r)/I);
BaseBendingMx(:,7)=abs((timeseries_292_432_0(:,2)*r)/I);
BaseBendingMx(:,8)=abs((timeseries_292_432_133(:,2)*r)/I);
BaseBendingMx(:,9)=abs((timeseries_292_432_193(:,2)*r)/I);
BaseBendingMx(:,10)=abs((timeseries_308_0795_0(:,2)*r)/I);
BaseBendingMx(:,11)=abs((timeseries_308_0795_133(:,2)*r)/I);
BaseBendingMx(:,12)=abs((timeseries_308_0795_193(:,2)*r)/I);
BaseBendingMx(:,13)=abs((timeseries_308_0_0(:,2)*r)/I);
BaseBendingMx(:,14)=abs((timeseries_308_0_133(:,2)*r)/I);
BaseBendingMx(:,15)=abs((timeseries_308_0_193(:,2)*r)/I);
BaseBendingMx(:,16)=abs((timeseries_308_432_0(:,2)*r)/I);
BaseBendingMx(:,17)=abs((timeseries_308_432_133(:,2)*r)/I);
BaseBendingMx(:,18)=abs((timeseries_308_432_193(:,2)*r)/I);

BaseBendingMxMax = transpose(max(BaseBendingMx(:,::)));

BaseBendingMy(:,1)=abs((timeseries_292_0795_0(:,3)*r)/I);
BaseBendingMy(:,2)=abs((timeseries_292_0795_133(:,3)*r)/I);
BaseBendingMy(:,3)=abs((timeseries_292_0795_193(:,3)*r)/I);
BaseBendingMy(:,4)=abs((timeseries_292_0_0(:,3)*r)/I);
BaseBendingMy(:,5)=abs((timeseries_292_0_133(:,3)*r)/I);
BaseBendingMy(:,6)=abs((timeseries_292_0_193(:,3)*r)/I);
BaseBendingMy(:,7)=abs((timeseries_292_432_0(:,3)*r)/I);
BaseBendingMy(:,8)=abs((timeseries_292_432_133(:,3)*r)/I);
BaseBendingMy(:,9)=abs((timeseries_292_432_193(:,3)*r)/I);
BaseBendingMy(:,10)=abs((timeseries_308_0795_0(:,3)*r)/I);
BaseBendingMy(:,11)=abs((timeseries_308_0795_133(:,3)*r)/I);
BaseBendingMy(:,12)=abs((timeseries_308_0795_193(:,3)*r)/I);
BaseBendingMy(:,13)=abs((timeseries_308_0_0(:,3)*r)/I);
BaseBendingMy(:,14)=abs((timeseries_308_0_133(:,3)*r)/I);
BaseBendingMy(:,15)=abs((timeseries_308_0_193(:,3)*r)/I);
BaseBendingMy(:,16)=abs((timeseries_308_432_0(:,3)*r)/I);
BaseBendingMy(:,17)=abs((timeseries_308_432_133(:,3)*r)/I);
BaseBendingMy(:,18)=abs((timeseries_308_432_193(:,3)*r)/I);

BaseBendingMyMax = transpose(max(BaseBendingMy(:,::)));

BaseBendingMz(:,1)=abs((timeseries_292_0795_0(:,4)*r)/Ip);
BaseBendingMz(:,2)=abs((timeseries_292_0795_133(:,4)*r)/Ip);
BaseBendingMz(:,3)=abs((timeseries_292_0795_193(:,4)*r)/Ip);
BaseBendingMz(:,4)=abs((timeseries_292_0_0(:,4)*r)/Ip);
BaseBendingMz(:,5)=abs((timeseries_292_0_133(:,4)*r)/Ip);
BaseBendingMz(:,6)=abs((timeseries_292_0_193(:,4)*r)/Ip);
BaseBendingMz(:,7)=abs((timeseries_292_432_0(:,4)*r)/Ip);
BaseBendingMz(:,8)=abs((timeseries_292_432_133(:,4)*r)/Ip);
BaseBendingMz(:,9)=abs((timeseries_292_432_193(:,4)*r)/Ip);
BaseBendingMz(:,10)=abs((timeseries_308_0795_0(:,4)*r)/Ip);
BaseBendingMz(:,11)=abs((timeseries_308_0795_133(:,4)*r)/Ip);
BaseBendingMz(:,12)=abs((timeseries_308_0795_193(:,4)*r)/Ip);
BaseBendingMz(:,13)=abs((timeseries_308_0_0(:,4)*r)/Ip);
BaseBendingMz(:,14)=abs((timeseries_308_0_133(:,4)*r)/Ip);
BaseBendingMz(:,15)=abs((timeseries_308_0_193(:,4)*r)/Ip);
BaseBendingMz(:,16)=abs((timeseries_308_432_0(:,4)*r)/Ip);
BaseBendingMz(:,17)=abs((timeseries_308_432_133(:,4)*r)/Ip);
BaseBendingMz(:,18)=abs((timeseries_308_432_193(:,4)*r)/Ip);

BaseBendingMzMax= transpose(max(BaseBendingMz(:,13:
BaseAxial(:,1)=abs((timeseries_292_0795_0(:,10)/A));
BaseAxial(:,2)=abs((timeseries_292_0795_133(:,10)/A));
BaseAxial(:,3)=abs((timeseries_292_0795_193(:,10)/A));
BaseAxial(:,4)=abs((timeseries_292_0_0(:,10)/A));
BaseAxial(:,5)=abs((timeseries_292_0_133(:,10)/A));
BaseAxial(:,6)=abs((timeseries_292_0_193(:,10)/A));
BaseAxial(:,7)=abs((timeseries_292_432_0(:,10)/A));
BaseAxial(:,8)=abs((timeseries_292_432_133(:,10)/A));
BaseAxial(:,9)=abs((timeseries_292_432_193(:,10)/A));
BaseAxial(:,10)=abs((timeseries_308_0795_0(:,10)/A));
BaseAxial(:,11)=abs((timeseries_308_0795_133(:,10)/A));
BaseAxial(:,12)=abs((timeseries_308_0795_193(:,10)/A));
BaseAxial(:,13)=abs((timeseries_308_0_0(:,10)/A));
BaseAxial(:,14)=abs((timeseries_308_0_133(:,10)/A));
BaseAxial(:,15)=abs((timeseries_308_0_193(:,10)/A));
BaseAxial(:,16)=abs((timeseries_308_432_0(:,10)/A));
BaseAxial(:,17)=abs((timeseries_308_432_133(:,10)/A));
BaseAxial(:,18)=abs((timeseries_308_432_193(:,10)/A));

BaseAxialMax= transpose(max(BaseAxial(:,13:
end

CombinedStressMaxTable=transpose(CombineStressMax);
CombineStressAverageTable=transpose(CombineStressAverage);

figure;
y=(CombineStressMax*1.35);
x=categorical({'\(\sigma_{\text{total}}\)'});
b_prop=bar(x,y,0.8);
ylabel('Normal Stress Magnitude (kN/m^2)');
legend(Names(3:20),'Location','eastoutside');
legend('boxoff')
title('Tower Base Maximum Normal Stress');
ylim([0 4.5*10^5]);
yticks([0:5*10^4:4.5*10^5]);
for k=1:length(b_prop)
    xtips1 = b_prop(k).XEndPoints;
ytips1 = b_prop(k).YEndPoints;
labels1 = string(round(b_prop(k).YData,0));
text(xtips1,ytips1,labels1,'HorizontalAlignment','left','Rotation',90,...
end

figure;
y=(CombineStressAverage*1.35);
x=categorical({'\sigma_{total}'});
b_prop=bar(x,y,0.8);
ylabel('Normal Stress Magnitude (kN/m^2)');
legend(Names(3:20), 'Location', 'eastoutside');
legend('boxoff')
title('Tower Base Average Normal Stress');
ylim([0 1.5*10^5]);
yticks([0:1.*10^4:1.5*10^5]);
for k=1:length(b_prop)
    xtips1 = b_prop(k).XEndPoints;
ytips1 = b_prop(k).YEndPoints;
    labels1 = string(round(b_prop(k).YData,0));
    text(xtips1, ytips1, labels1, 'HorizontalAlignment', 'left', 'Rotation', 90, ...
        'VerticalAlignment', 'middle')
end

fontname(gcf, "Times New Roman");
fontsize(gcf, 12, "points");

%% SHEAR STRESS IN KILO PASCALS VQ/IT

BaseShearx(:,1)=abs((timeseries_292_0795_0(:,8)*Q)/((I*b)));
BaseShearx(:,2)=abs((timeseries_292_0795_133(:,8)*Q)/((I*b)));
BaseShearx(:,3)=abs((timeseries_292_0795_193(:,8)*Q)/((I*b)));
BaseShearx(:,4)=abs((timeseries_292_0_0(:,8)*Q)/((I*b)));
BaseShearx(:,5)=abs((timeseries_292_0_133(:,8)*Q)/((I*b)));
BaseShearx(:,6)=abs((timeseries_292_0_193(:,8)*Q)/((I*b)));
BaseShearx(:,7)=abs((timeseries_292_432_0(:,8)*Q)/((I*b)));
BaseShearx(:,8)=abs((timeseries_292_432_133(:,8)*Q)/((I*b)));
BaseShearx(:,9)=abs((timeseries_292_432_193(:,8)*Q)/((I*b)));
BaseShearx(:,10)=abs((timeseries_308_0795_0(:,8)*Q)/((I*b)));
BaseShearx(:,11)=abs((timeseries_308_0795_133(:,8)*Q)/((I*b)));
BaseShearx(:,12)=abs((timeseries_308_0795_193(:,8)*Q)/((I*b)));
BaseShearx(:,13)=abs((timeseries_308_0_0(:,8)*Q)/((I*b)));
BaseShearx(:,14)=abs((timeseries_308_0_133(:,8)*Q)/((I*b)));
BaseShearx(:,15)=abs((timeseries_308_0_193(:,8)*Q)/((I*b)));
BaseShearx(:,16)=abs((timeseries_308_432_0(:,8)*Q)/((I*b)));
BaseShearx(:,17)=abs((timeseries_308_432_133(:,8)*Q)/((I*b)));
BaseShearx(:,18)=abs((timeseries_308_432_193(:,8)*Q)/((I*b)));
BaseShearxMax= transpose(max(BaseShearx(:, :)));

BaseSheary(:,1)=abs((timeseries_292_0795_0(:,9)*Q)/((I*b)));
BaseSheary(:,2)=abs((timeseries_292_0795_133(:,9)*Q)/((I*b)));
BaseSheary(:,3)=abs((timeseries_292_0795_193(:,9)*Q)/((I*b)));
BaseSheary(:,4)=abs((timeseries_292_0_0(:,9)*Q)/((I*b)));
BaseSheary(:,5)=abs((timeseries_292_0_133(:,9)*Q)/((I*b)));
BaseSheary(:,6)=abs((timeseries_292_0_193(:,9)*Q)/((I*b)));
BaseSheary(:,7)=abs((timeseries_292_432_0(:,9)*Q)/((I*b)));
BaseSheary(:,8)=abs((timeseries_292_432_133(:,9)*Q)/((I*b)));
BaseSheary(:,9)=abs((timeseries_292_432_193(:,9)*Q)/((I*b)));
 BaseShearyMax= transpose(max(BaseSheary(:, :)));
BaseSheary(:,10)=abs((timeseries_308_0795_0(:,9)*Q)/((I*b)));  
BaseSheary(:,11)=abs((timeseries_308_0795_133(:,9)*Q)/((I*b)));  
BaseSheary(:,12)=abs((timeseries_308_0795_193(:,9)*Q)/((I*b)));  
BaseSheary(:,13)=abs((timeseries_308_0_0(:,9)*Q)/((I*b)));  
BaseSheary(:,14)=abs((timeseries_308_0_133(:,9)*Q)/((I*b)));  
BaseSheary(:,15)=abs((timeseries_308_0_193(:,9)*Q)/((I*b)));  
BaseSheary(:,16)=abs((timeseries_308_432_0(:,9)*Q)/((I*b)));  
BaseSheary(:,17)=abs((timeseries_308_432_133(:,9)*Q)/((I*b)));  
BaseSheary(:,18)=abs((timeseries_308_432_193(:,9)*Q)/((I*b)));  
BaseShearXMax= transpose(max(BaseSheary(:,,:)));  

%% COMBINED SHEAR STRESS  
for i=1:width(BaseShearx);  
    for j=1:length(BaseShearx);  
    CombinedShear(j,i)= BaseShearX(j,i) + BaseSheary(j,i) + BaseBendingMz(j,i);  
    end  
    CombineShearMax(1,i)=max(CombinedShear(:,i));  
    CombineShearAverage(1,i)=mean(CombinedShear(:,i));  
end  
CombineShearMaxTable=transpose(CombineShearMax);  
CombineShearAverageTable=transpose(CombineShearAverage);  

figure;  
y=CombineShearMax;  
x=categorical({'\tau_{total}'});  

b_prop=bar(x,y,0.8);  
ylabel('Shear Stress Magnitude (kN/m^2)');  
legend(Names(3:20), 'Location', 'eastoutside');  
legend('boxoff');  
title('Tower Base Maximum Shear Stress');  
ylim([0 1.6*10^4]);  
yticks([0:1*10^3:1.6*10^4]);  
for k=1:length(b_prop);  
    xtips1 = b_prop(k).XEndpoints;  
    ytips1 = b_prop(k).YEndpoints;  
    labels1 = string(round(b_prop(k).YData,0));  
    text(xtips1,ytips1,labels1, 'HorizontalAlignment', 'left', 'Rotation', 90,...  
         'VerticalAlignment', 'middle');  
end  
fontname(gcf,"Times New Roman");  
fontsize(gcf,12,"points");  

figure;  
y=CombineShearAverage;  
x=categorical({'\tau_{total}'});  

b_prop=bar(x,y,0.8);  
ylabel('Shear Stress Magnitude (kN/m^2)');  
legend(Names(3:20), 'Location', 'eastoutside');  
legend('boxoff');  
title('Tower Base Average Shear Stress');  
ylim([0 4.5*10^3]);  
yticks([0:0.5*10^3:4.5*10^3]);  
for k=1:length(b_prop);  
    xtips1 = b_prop(k).XEndpoints;  
    ytips1 = b_prop(k).YEndpoints;  
    labels1 = string(round(b_prop(k).YData,0));  
    text(xtips1,ytips1,labels1, 'HorizontalAlignment', 'left', 'Rotation', 90,...  
         'VerticalAlignment', 'middle');  
end  
fontname(gcf,"Times New Roman");
SAVE STRESS TIME HISTORIES TO FOLDER

save BaseAxial BaseAxial;
save BaseBendingMx BaseBendingMx;
save BaseBendingMy BaseBendingMy;
save BaseBendingMz BaseBendingMz;
save CombinedStress CombinedStress;
save BaseShearx BaseShearx;
save BaseSheary BaseSheary;

COMPARING X,Y,Z, AXIAL STRESSES FOR WORST CASE

AverageStresses=1.35*[mean(BaseBendingMx(:,9)), mean(BaseBendingMy(:,9)),
mean(BaseBendingMz(:,9)), mean(BaseAxial(:,9)), mean(BaseShearx(:,9)),
mean(BaseSheary(:,9))];

figure;
xavg=categorical({'\sigma_x','\sigma_y','\tau_z','\sigma_{axial}','\tau_x','\tau_y'});
stressavgbar=bar(xavg,AverageStresses,0.8);
ylabel('Stress Magnitude (kPa)');
title('Tower Base Average Stresses Comparison for wdir292_mwl432_wvdir193');
ylim([0 7*10^4]);
yticks([0:10000:7*10^4]);
for k=1:length(stressavgbar)
    xtips1 = stressavgbar(k).XEndPoints;
ytips1 = stressavgbar(k).YEndPoints;
    labels1 = string(round(stressavgbar(k).YData,0));
    text(xtips1,ytips1,labels1,'HorizontalAlignment','left','Rotation',90,...
        'VerticalAlignment','middle');
end

fontname(gcf,"Times New Roman");
fontsize(gcf,12,"points");

TOP COMBINED STRESS FOR COMPARISON WITH BOTTOM USING WORST CASE

I_top=table2array(TowerProperties(10,"Var11"));
% x and y the same for circular cross section
Ip_top=table2array(TowerProperties(10,"Var13"));
A_top=table2array(TowerProperties(10,"Var16"));
ri_top=table2array(TowerProperties(10,"Var5"));
% x and y the same for circular cross section
k_top=table2array(TowerProperties(10,"Var14"));
% x and y the same for circular cross section
r_top=6.5/2;
r2_top=r_top-(41.06/1000);
Q_top=2/3*((r_top^3)-(r2_top^3));
b_top=2*(r_top-r2_top);

TopStress(:,1)=abs((timeseries_292_432_193(:,5)*r_top)/I_top);  % x bend
TopStress(:,2)=abs((timeseries_292_432_193(:,6)*r_top)/I_top);  % y bend
TopStress(:,3)=abs((timeseries_292_432_193(:,7)*r_top)/Ip_top);  % z bend
TopStress(:,4)=abs((timeseries_292_432_193(:,13)/A_top));  % axial
TopStress(:,5)=abs((timeseries_292_432_193(:,11)*Q_top)/((I_top*b_top)));
TopStress(:,6)=abs((timeseries_292_432_193(:,12)*Q_top)/((I_top*b_top)));  % x shear
TopStress(:,7)=TopStress(:,1)+TopStress(:,2)+TopStress(:,4);  % Combined Stress
TopStress(:,8)=TopStress(:,5)+TopStress(:,6)+TopStress(:,3);  % Combined Shear

TopAverages=1.35*mean(TopStress(:,:));
TopvBottom=[TopAverages(:,1:6);AverageStresses];
TopvBottomCombined=[TopAverages(:,7),TopAverages(:,8)];1.35*CombinedStressAverageTable(9,1),
CombineShearAverageTable(9,1);
figure;
x_topvbottom=categorical({'\sigma_{x}','\sigma_{y}','\tau_{z}','\sigma_{axial}','\tau_{x}','\tau_{y}'});
stresstopvbottombar=bar(x_topvbottom,TopvBottom,0.8);
ylabel('Stress Magnitude (kPa)');
legend('Top Stress','Base Stress','Location','northeast');
legend('boxoff');
title('Average Stress Tower Top vs Tower Bottom for wdir292_mwl432_wvdir193');
stresstopvbottombar(2).FaceColor = [0.6350 0.0780 0.1840];
ylim([0 0.7*10^5])
yticks([0:20000:0.7*10^5])
for k=1:length(stresstopvbottombar)
    xtips1 = stresstopvbottombar(k).XEndPoints;
ytips1 = stresstopvbottombar(k).YEndPoints;
    labels1 = string(round(stresstopvbottombar(k).YData,0);
    text(xtips1,ytips1,labels1,'HorizontalAlignment','left','Rotation',90,...
    'VerticalAlignment','middle')
end

figure;
x_topvbottomcombine=categorical({'\tau_{combined}','\sigma_{combined}'});
stresstopvbottomcombinebar=bar(x_topvbottomcombine,TopvBottomCombined,0.8);
ylabel('Stress Magnitude (kPa)');
legend('Base Stress','Top Stress','Location','northeast');
legend('boxoff');
title('Average Stress Tower Top vs Tower Bottom for wdir292_mwl432_wvdir193');
stresstopvbottomcombinebar(2).FaceColor = [0.6350 0.0780 0.1840];
ylim([0 1.3*10^5])
yticks([0:20000:1.3*10^5])
for k=1:length(stresstopvbottomcombinebar)
    xtips1 = stresstopvbottomcombinebar(k).XEndPoints;
ytips1 = stresstopvbottomcombinebar(k).YEndPoints;
    labels1 = string(round(stresstopvbottomcombinebar(k).YData,0));
    text(xtips1,ytips1,labels1,'HorizontalAlignment','left','Rotation',90,...
    'VerticalAlignment','middle')
end

Fatigue Stress Analysis Results
Dec 12, 2022
Programer: Ailish Bozzo

close all
clc

Importing Files
load BaseAxial.mat
load BaseBendingMx.mat
load BaseBendingMy.mat
load BaseBendingMz.mat
load BaseShearx.mat
load BaseSheary.mat
load CombinedShear.mat
load CombinedStress.mat

BasePath = 'C:\HAWC2\iec_res';
DirList = dir(BasePath);
DirList = DirList([DirList.isdir]); % Folders only
DirList=DirList(3:length(DirList),:);

for iDir = 1:numel(DirList);
aDir = fullfile(BasePath, DirList(iDir).name);
fprintf('Processing: %s\n', aDir);
addpath(aDir);

folder = DirList(iDir,1).name;
Names(iDir,1)=string(folder);
end

%% CONVERTING TO MEGA PASCALS
CombinedStress_MPa=CombinedStress/1000;

%% DAMAGE AND FATIGUE RESULTS FUNCTION
% From: https://www.mathworks.com/matlabcentral/fileexchange/94105-fatigue-damage-accumulation
for i=1:size(CombinedStress,1);
    stressdamage(i,1)=Names(i+2,1);
    stressdamage(i,2) = fatdamage(CombinedStress_MPa(:,i), 160);
end

for i=1:size(CombinedStress,1);
    stressdamage2(i,1)=Names(i+2,1);
    stressdamage2(i,2) = fatdamage(CombinedStress_MPa(:,i), 160,"FirstSlope",4,"SecondSlope",6);
% Plain Steel 1
end

for i=1:size(CombinedStress,1);
    stressdamage3(i,1)=Names(i+2,1);
    stressdamage3(i,2) = fatdamage(CombinedStress_MPa(:,i), 160,"FirstSlope",3.5,"SecondSlope",5.5);
% Plain steel 2
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Sensitivity Analysis Results
% Dec 18, 2022
% Programer: Ailish Bozzo
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
close all clear all
clc
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Importing Files from sensitivity analysis
BasePath = 'C:\HAWC2\Sensitivity Analysis\sens_res';
DirList = dir(BasePath);
DirList = DirList([DirList.isdir]); % Folders only
DirList=DirList(3:length(DirList),:);
for iDir = 1:numel(DirList);
    aDir = fullfile(BasePath, DirList(iDir).name);
    fprintf('Processing: %s
', aDir);
    addpath(aDir);
    folder= DirList(iDir,1).name;
    NewNames(iDir,1)=string(folder);
    string1='C:\HAWC2\Sensitivity Analysis\sens_res\';
    string2=folder;
    string3='\timeseries.mat';
    path= convertContainedStringsToChars(append(string1,string2,string3));
    files = dir([path]);
    for i=1:size(files,1);
        filename=files(i,1).name;
        load([filename]);
    end
end
load C:\HAWC2\iec_res\wdir300_mwl0795_wvdir0\timeseries.mat;
time=transpose(0.01:0.01:3600);
Names=['wspd35_wht1018';NewNames];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Tower Properties
TowerProperties= readtable('C:\HAWC2\data\IEA_15MW_RWt_WMainsemi_Tower_st.dat');
I=table2array(TowerProperties(1,"Var11")); % x and y the same for circular cross section
Ip=table2array(TowerProperties(1,"Var13"));
A = table2array(TowerProperties(1, "Var16"));
ri = table2array(TowerProperties(1, "Var5"));  % x and y the same for circular cross section
k = table2array(TowerProperties(1, "Var14"));  % x and y the same for circular cross section
r = 10/2;
r2 = r - (82.954/1000);
Q = 2/3*(r^3 - (r2^3));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Material Properties
E_steel = table2array(TowerProperties(11, "Var9"));  % Modulus of Elasticity in Pascal
G_steel = table2array(TowerProperties(11, "Var10"));  % Shear Modulus in Pascal

%%% Sensitivity Analysis Stress Time Series Calculations
BaseStress_35_1018(:,1) = (timeseries_308_0795_0(:,2)*r)/(I);  % Mx
BaseStress_35_1018(:,2) = (timeseries_308_0795_0(:,3)*r)/(I);  % My
BaseStress_35_1018(:,4) = (timeseries_308_0795_0(:,10)/(A));  % Fz
BaseStress_35_1018(:,5) = abs(BaseStress_35_1018(:,1)) + abs(BaseStress_35_1018(:,2)) + abs(BaseStress_35_1018(:,3)) + abs(BaseStress_35_1018(:,4));  % TOTAL STRESS

BaseStress_35_1069(:,1) = (timeseries_wspd35_wvht1069(:,2)*r)/(I);  % Mx
BaseStress_35_1069(:,2) = (timeseries_wspd35_wvht1069(:,3)*r)/(I);  % My
BaseStress_35_1069(:,4) = (timeseries_wspd35_wvht1069(:,10)/(A));  % Fz
BaseStress_35_1069(:,5) = abs(BaseStress_35_1069(:,1)) + abs(BaseStress_35_1069(:,2)) + abs(BaseStress_35_1069(:,3)) + abs(BaseStress_35_1069(:,4));  % TOTAL STRESS

BaseStress_35_1120(:,1) = (timeseries_wspd35_wvht1120(:,2)*r)/(I);  % Mx
BaseStress_35_1120(:,2) = (timeseries_wspd35_wvht1120(:,3)*r)/(I);  % My
BaseStress_35_1120(:,4) = (timeseries_wspd35_wvht1120(:,10)/(A));  % Fz
BaseStress_35_1120(:,5) = abs(BaseStress_35_1120(:,1)) + abs(BaseStress_35_1120(:,2)) + abs(BaseStress_35_1120(:,3)) + abs(BaseStress_35_1120(:,4));  % TOTAL STRESS

BaseStress_35_1171(:,1) = (timeseries_wspd35_wvht1171(:,2)*r)/(I);  % Mx
BaseStress_35_1171(:,2) = (timeseries_wspd35_wvht1171(:,3)*r)/(I);  % My
BaseStress_35_1171(:,4) = (timeseries_wspd35_wvht1171(:,10)/(A));  % Fz
BaseStress_35_1171(:,5) = abs(BaseStress_35_1171(:,1)) + abs(BaseStress_35_1171(:,2)) + abs(BaseStress_35_1171(:,3)) + abs(BaseStress_35_1171(:,4));  % TOTAL STRESS

BaseStress_37_1018(:,1) = (timeseries_wspd37_wvht1018(:,2)*r)/(I);  % Mx
BaseStress_37_1018(:,2) = (timeseries_wspd37_wvht1018(:,3)*r)/(I);  % My
BaseStress_37_1018(:,4) = (timeseries_wspd37_wvht1018(:,10)/(A));  % Fz
BaseStress_37_1018(:,5) = abs(BaseStress_37_1018(:,1)) + abs(BaseStress_37_1018(:,2)) + abs(BaseStress_37_1018(:,3)) + abs(BaseStress_37_1018(:,4));  % TOTAL STRESS

BaseStress_37_1069(:,1) = (timeseries_wspd37_wvht1069(:,2)*r)/(I);  % Mx
BaseStress_37_1069(:,2) = (timeseries_wspd37_wvht1069(:,3)*r)/(I);  % My
BaseStress_37_1069(:,4) = (timeseries_wspd37_wvht1069(:,10)/(A));  % Fz
BaseStress_37_1069(:,5) = abs(BaseStress_37_1069(:,1)) + abs(BaseStress_37_1069(:,2)) + abs(BaseStress_37_1069(:,3)) + abs(BaseStress_37_1069(:,4));  % TOTAL STRESS

BaseStress_37_1120(:,1) = (timeseries_wspd37_wvht1120(:,2)*r)/(I);  % Mx
BaseStress_37_1120(:,2) = (timeseries_wspd37_wvht1120(:,3)*r)/(I);  % My
BaseStress_37_1120(:,4) = (timeseries_wspd37_wvht1120(:,10)/(A));  % Fz
BaseStress_37_1120(:,5) = abs(BaseStress_37_1120(:,1)) + abs(BaseStress_37_1120(:,2)) + abs(BaseStress_37_1120(:,3)) + abs(BaseStress_37_1120(:,4));  % TOTAL STRESS

BaseStress_37_1171(:,1) = (timeseries_wspd37_wvht1171(:,2)*r)/(I);  % Mx
BaseStress_37_1171(:,2) = (timeseries_wspd37_wvht1171(:,3)*r)/(I);  % My
BaseStress_37_1171(:,4) = (timeseries_wspd37_wvht1171(:,10)/(A));  % Fz
BaseStress_37_1171(:,5) = abs(BaseStress_37_1171(:,1)) + abs(BaseStress_37_1171(:,2)) + abs(BaseStress_37_1171(:,3)) + abs(BaseStress_37_1171(:,4));  % TOTAL STRESS

BaseStress_39_1018(:,1) = (timeseries_wspd39_wvht1018(:,2)*r)/(I);  % Mx
BaseStress_39_1018(:,2) = (timeseries_wspd39_wvht1018(:,3)*r)/(I);  % My
BaseStress_39_1018(:,4) = (timeseries_wspd39_wvht1018(:,10)/(A));  % Fz
BaseStress_39_1018(:,5)=\|BaseStress_39_1018(:,1)\|+\|BaseStress_39_1018(:,2)\|+\|BaseStress_39_1018(:,3)\|+\|BaseStress_39_1018(:,4)\|; \text{%TOTAL STRESS}

BaseStress_39_1069(:,1)=(timeseries_wspd39_wvht1069(:,2)*r)/(I); \text{%Mx}
BaseStress_39_1069(:,2)=(timeseries_wspd39_wvht1069(:,3)*r)/(I); \text{%My}
BaseStress_39_1069(:,4)=(timeseries_wspd39_wvht1069(:,10)/(A)); \text{%Fz}
BaseStress_39_1069(:,5)=\|BaseStress_39_1069(:,1)\|+\|BaseStress_39_1069(:,2)\|+\|BaseStress_39_1069(:,3)\|+\|BaseStress_39_1069(:,4)\|; \text{%TOTAL STRESS}

BaseStress_39_1120(:,1)=(timeseries_wspd39_wvht1120(:,2)*r)/(I); \text{%Mx}
BaseStress_39_1120(:,2)=(timeseries_wspd39_wvht1120(:,3)*r)/(I); \text{%My}
BaseStress_39_1120(:,4)=(timeseries_wspd39_wvht1120(:,10)/(A)); \text{%Fz}
BaseStress_39_1120(:,5)=\|BaseStress_39_1120(:,1)\|+\|BaseStress_39_1120(:,2)\|+\|BaseStress_39_1120(:,3)\|+\|BaseStress_39_1120(:,4)\|; \text{%TOTAL STRESS}

BaseStress_39_1171(:,1)=(timeseries_wspd39_wvht1171(:,2)*r)/(I); \text{%Mx}
BaseStress_39_1171(:,2)=(timeseries_wspd39_wvht1171(:,3)*r)/(I); \text{%My}
BaseStress_39_1171(:,4)=(timeseries_wspd39_wvht1171(:,10)/(A)); \text{%Fz}
BaseStress_39_1171(:,5)=\|BaseStress_39_1171(:,1)\|+\|BaseStress_39_1171(:,2)\|+\|BaseStress_39_1171(:,3)\|+\|BaseStress_39_1171(:,4)\|; \text{%TOTAL STRESS}

BaseStress_40_1018(:,1)=(timeseries_wspd40_wvht1018(:,2)*r)/(I); \text{%Mx}
BaseStress_40_1018(:,2)=(timeseries_wspd40_wvht1018(:,3)*r)/(I); \text{%My}
BaseStress_40_1018(:,4)=(timeseries_wspd40_wvht1018(:,10)/(A)); \text{%Fz}
BaseStress_40_1018(:,5)=\|BaseStress_40_1018(:,1)\|+\|BaseStress_40_1018(:,2)\|+\|BaseStress_40_1018(:,3)\|+\|BaseStress_40_1018(:,4)\|; \text{%TOTAL STRESS}

BaseStress_40_1069(:,1)=(timeseries_wspd40_wvht1069(:,2)*r)/(I); \text{%Mx}
BaseStress_40_1069(:,2)=(timeseries_wspd40_wvht1069(:,3)*r)/(I); \text{%My}
BaseStress_40_1069(:,4)=(timeseries_wspd40_wvht1069(:,10)/(A)); \text{%Fz}
BaseStress_40_1069(:,5)=\|BaseStress_40_1069(:,1)\|+\|BaseStress_40_1069(:,2)\|+\|BaseStress_40_1069(:,3)\|+\|BaseStress_40_1069(:,4)\|; \text{%TOTAL STRESS}

BaseStress_40_1120(:,1)=(timeseries_wspd40_wvht1120(:,2)*r)/(I); \text{%Mx}
BaseStress_40_1120(:,2)=(timeseries_wspd40_wvht1120(:,3)*r)/(I); \text{%My}
BaseStress_40_1120(:,4)=(timeseries_wspd40_wvht1120(:,10)/(A)); \text{%Fz}
BaseStress_40_1120(:,5)=\|BaseStress_40_1120(:,1)\|+\|BaseStress_40_1120(:,2)\|+\|BaseStress_40_1120(:,3)\|+\|BaseStress_40_1120(:,4)\|; \text{%TOTAL STRESS}

BaseStress_40_1171(:,1)=(timeseries_wspd40_wvht1171(:,2)*r)/(I); \text{%Mx}
BaseStress_40_1171(:,2)=(timeseries_wspd40_wvht1171(:,3)*r)/(I); \text{%My}
BaseStress_40_1171(:,4)=(timeseries_wspd40_wvht1171(:,10)/(A)); \text{%Fz}
BaseStress_40_1171(:,5)=\|BaseStress_40_1171(:,1)\|+\|BaseStress_40_1171(:,2)\|+\|BaseStress_40_1171(:,3)\|+\|BaseStress_40_1171(:,4)\|; \text{%TOTAL STRESS}

%% Stress Averages with combined stress

WaveHeights=[10.18,10.69,11.20,11.71];
WindSpeeds=[35.19,36.95,38.72,40.47];

AverageBaseStress(1,1)=mean(BaseStress_35_1018(:,5));
AverageBaseStress(1,2)=mean(BaseStress_35_1069(:,5));
AverageBaseStress(1,3)=mean(BaseStress_35_1120(:,5));
AverageBaseStress(1,4)=mean(BaseStress_35_1171(:,5));
AverageBaseStress(2,1)=mean(BaseStress_37_1018(:,5));
AverageBaseStress(2,2)=mean(BaseStress_37_1069(:,5));
AverageBaseStress(2,3)=mean(BaseStress_37_1120(:,5));
AverageBaseStress(2,4)=mean(BaseStress_37_1171(:,5));
AverageBaseStress(3,1)=mean(BaseStress_39_1018(:,5));
AverageBaseStress(3,2)=mean(BaseStress_39_1069(:,5));
AverageBaseStress(3,3)=mean(BaseStress_39_1120(:,5));
AverageBaseStress(3,4)=mean(BaseStress_39_1171(:,5));
AverageBaseStress(4,1)=mean(BaseStress_40_1018(:,5));
AverageBaseStress(4,2)=mean(BaseStress_40_1069(:,5));
AverageBaseStress(4,3)=mean(BaseStress_40_1120(:,5));
AverageBaseStress(4,4)=mean(BaseStress_40_1171(:,5));
wave height plotting

```matlab
figure;
subplot(2,2,1:2);
x2=categorical(WaveHeights);
bar2=bar(x2,AverageBaseStress,0.8);
ylabel('Stress Magnitude (kPa)');
xlabel('Wave Height (m)');
legend('Wind Speed= 35.19 m/s','Wind Speed= 36.95 m/s','Wind Speed= 38.71 m/s','Wind Speed= 40.47 m/s','Location','northwest');
title('Tower Base Average Stress');
legend('boxoff')
fontname(gcf,"Times New Roman");
fontsize(gcf,12,"points");
ylim([0 1.1*10^5]);
yticks([0:1*10^4:1.1*10^5]);

subplot(2,2,3)
plot(WaveHeights,AverageBaseStress(1,:))
hold on
plot(WaveHeights,AverageBaseStress(2,:))
hold on
plot(WaveHeights,AverageBaseStress(3,:))
hold on
plot(WaveHeights,AverageBaseStress(4,:))

waveslope(1,:)=polyfit(WaveHeights,AverageBaseStress(1,:),1);
waveslope(2,:)=polyfit(WaveHeights,AverageBaseStress(2,:),1);
waveslope(3,:)=polyfit(WaveHeights,AverageBaseStress(3,:),1);
waveslope(4,:)=polyfit(WaveHeights,AverageBaseStress(4,:),1);

windslope(1,:)=polyfit(WindSpeeds,AverageBaseStress(:,1),1);
windslope(2,:)=polyfit(WindSpeeds,AverageBaseStress(:,2),1);
windslope(3,:)=polyfit(WindSpeeds,AverageBaseStress(:,3),1);
windslope(4,:)=polyfit(WindSpeeds,AverageBaseStress(:,4),1);
```

wind speed plotting

```matlab
subplot(2,2,4);
plot(WindSpeeds,AverageBaseStress(:,1))
hold on
plot(WindSpeeds,AverageBaseStress(:,2))
hold on
plot(WindSpeeds,AverageBaseStress(:,3))
hold on
plot(WindSpeeds,AverageBaseStress(:,4))
legend('Wave Height= 10.18 m','Wave Height= 10.69 m','Wave Height= 11.20 m','Wave Height= 11.71 m','Location','northwest');
xlabel('Wind Speed(m/s)')
ylabel('Average Stress (kPa)')
title('Average Combined Stress vs Wind Speed')
legend('boxoff')
fontname(gcf,"Times New Roman");
fontsize(gcf,12,"points");

percentage change from original

```matlab
PercentageChange=(AverageBaseStress-AverageBaseStress(1,1))./AverageBaseStress(1,1).*100;
```
% fatigue assessment of combined stress

CombinedBaseStress_time(:,1)=BaseStress_35_1018(:,5)/1000;
CombinedBaseStress_time(:,2)=BaseStress_35_1069(:,5)/1000;
CombinedBaseStress_time(:,3)=BaseStress_35_1120(:,5)/1000;
CombinedBaseStress_time(:,4)=BaseStress_35_1171(:,5)/1000;

CombinedBaseStress_time(:,5)=BaseStress_37_1018(:,5)/1000;
CombinedBaseStress_time(:,6)=BaseStress_37_1069(:,5)/1000;
CombinedBaseStress_time(:,7)=BaseStress_37_1120(:,5)/1000;
CombinedBaseStress_time(:,8)=BaseStress_37_1171(:,5)/1000;

CombinedBaseStress_time(:,9)=BaseStress_39_1018(:,5)/1000;
CombinedBaseStress_time(:,10)=BaseStress_39_1069(:,5)/1000;
CombinedBaseStress_time(:,11)=BaseStress_39_1120(:,5)/1000;
CombinedBaseStress_time(:,12)=BaseStress_39_1171(:,5)/1000;

CombinedBaseStress_time(:,13)=BaseStress_40_1018(:,5)/1000;
CombinedBaseStress_time(:,14)=BaseStress_40_1069(:,5)/1000;
CombinedBaseStress_time(:,15)=BaseStress_40_1120(:,5)/1000;
CombinedBaseStress_time(:,16)=BaseStress_40_1171(:,5)/1000;

for i=1:width(CombinedBaseStress_time);
    stressdamage(i,1)=Names(i,1);
    stressdamage(i,2) = fatdamage(CombinedBaseStress_time(:,i), 160);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% percentage change from original
stressdamagecalc=str2double(stressdamage(:,2));
PercentageChangeFatigue=(stressdamagecalc-stressdamagecalc(1,1))./stressdamagecalc(1,1).*100;
stressdamagegraph=[stressdamagecalc(1:4),stressdamagecalc(5:8),stressdamagecalc(9:12),stressdamagecalc(13:16)];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% plotting

figure;
x3=categorical(WindSpeeds);
bar3=bar(x3,stressdamagegraph,0.8);
ylabel('Damage Accumulation');
xlabel('Wind Speeds (m/s)');
legend('Wave Height= 10.18 m','Wave Height= 10.69 m','Wave Height= 11.20 m','Wave Height= 11.71 m','Location','northwest');
title('Tower Base Linear Damage Accumulation');
legend('boxoff');
fontname(gcf,"Times New Roman");
fontsize(gcf,12,"points");

figure;
plot(WaveHeights,stressdamagecalc(1:4,1))
hold on
plot(WaveHeights,stressdamagecalc(5:8,1))
hold on
plot(WaveHeights,stressdamagecalc(9:12,1))
hold on
plot(WaveHeights,stressdamagecalc(13:16,1))
legend('WSPD 35.19','WSPD 36.95','WSPD 38.71','WSPD 40.47','Location','eastoutside');
xlabel('Wave Height (m)')
ylabel('Fatigue Damage')
title('Fatigue Damage Change with Wave Height')

figure;
plot(WindSpeeds,stressdamagegraph(1,:))
hold on
plot(WindSpeeds,stressdamagegraph(2,:))
hold on
plot(WindSpeeds,stressdamagegraph(3,:))
hold on
plot(WindSpeeds,stressdamagegraph(4,:))
legend('Wave Height 10.18','Wave Height 10.69','Wave Height 11.20','Wave Height 11.71','Location','eastoutside');
xlabel('Wind Speed (m/s)')
ylabel('Fatigue Damage')
title('Fatigue Damage Change with Wind Speed')