A composite model for evaluating fatigue life of offshore wind turbines equipped with a tuned mass damper

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ABSTRACT: Driven by the need to enhance the energy density of individual units, modern wind turbines have undergone a substantial increase in both turbine scale and power rating, with a growing trend toward offshore construction. However, the corrosive marine environment and challenging conditions typical of offshore locations, coupled with greater self-loads, render modern wind turbines susceptible to fatigue damage.
This study employs a composite model to conduct a local fatigue analysis of a fatigue critical component at the base of the state-of-the-art IEC 15-MW offshore wind turbine tower, specifically to investigate the influence of Tuned Mass Dampers (TMD) on the fatigue life of offshore wind turbines. The composite model utilises a blended modelling approach integrating a holistic multibody dynamic model and a detailed finite element model, leveraging the strengths of both approaches to deliver an efficient and accurate fatigue analysis of the turbine mitigating the inherent weaknesses of each individual model. The multibody dynamic model, fully coupled with 22 degrees of freedom, developed using Kane's Dynamics is employed within this composite model to simulate nominal stress time histories of the wind turbine subjected to environmental loading, considering the effects of both hydrodynamic and aerodynamic loading. The detailed finite element model is constructed to calculate Stress Concentration Factors (SCF) in fatigue-critical locations which can be combined with the nominal stresses generated by the multibody dynamic model to produce local stress time histories. Using these results, a comprehensive fatigue assessment is performed of the 15-MW monopile-based wind turbine, taking into account met-ocean conditions specific to the West Coast of Ireland. This analysis indicates that TMDs have a negative impact on the performance of the turbine in the fore-aft direction which dominates the fatigue loads, resulting in a marginal reduction of the operational lifespan of the wind turbine.

1 INTRODUCTION

The global offshore wind energy industry experienced significant expansion in 2023, which marked the second-highest year of growth, with over 13,000 offshore wind turbines added to the global fleet. The resulting 10.8 GW increase in global capacity contributed to a 24% improvement over 2022 (GWEC 2024, McCoy et al. 2024). This rapid growth is projected to continue, with global offshore wind capacity expected to reach 492 GW by 2035 (McCoy et al. 2024). However offshore wind turbine prices are rising due to increasing interest rates, material costs and supply chain constraints (McCoy et al. 2024). In this context, fatigue analysis plays a critical role in determining the operational lifespan of wind turbine structures, enabling companies to predict accurately how long an asset will be operational and thus profitable.

Fatigue-related failures have become a critical concern in the structural integrity of modern wind turbine support structures (Saini et al. 2016, Igwemezie et al. 2019, Mendes et al. 2021, Liao et al. 2022), with particular attention directed toward the welded joint connecting the turbine tower and transition piece, which has been shown to be highly susceptible to fatigue damage (Dong et al. 2012, Yeter et al. 2015, Do et al. 2015, Huo and Tong 2020, Fu et al. 2020, Zhu et al. 2023).

To mitigate vibration-induced loads and extend structural life, TMDs have gained popularity in wind turbine designs (Murtagh et al. 2008, Lackner and Rotea 2011, Si et al. 2013, Stewart and Lackner 2014). These devices are tuned to the natural frequency of a structure, allowing them to dissipate energy and reduce the vibrational response when displaced. To assess the extent of the device's mitigation capabilities, papers such as (Sun & Jahangiri 2019) employ multibody dynamic models to simulate the wind turbine's global response to environmental loads, capturing the interactions between aerodynamic, hydrodynamic, and structural forces. While these models are effective for evaluating overall system behaviour, they fail to consider the effects of local geometries. To address this, researchers have employed finite element models such as (Huo & Tong 2020) which which consider such local effects. However, constructing finite element models suitable for dynamic simulations for offshore wind turbines often necessitates significant simplifications.

To address this gap, this study develops a composite model to perform a fatigue analysis of the IEA 15-MW fixed-based offshore wind turbine with a TMD installed at the top of the turbine tower. The fatigue analysis is based on a potential site off the West Coast of Ireland. The composite model is comprised of a multibody dynamic model which captures the holistic response of the wind turbine to environmental loading and a finite element model which captures local stress concentrations which arise at geometric discontinuities. The composite model is employed to produce stress time histories at the butt weld of the flange connection specifically designed for the 15-MW wind turbine. Using these stress time histories the lifespan of the wind turbine is estimated using a modified version of NRELs MLife which employs the Palmgren/Miners rule and rainflow counting with bi-linear SN curves to predict the fatigue life allowing the influence of the TMD to be investigated. The fatigue life of the component considering the composite model will then be compared with the traditional approach neglecting the influence of the flange connection.

2 METHODOLOGY

2.1 *Environmental Conditions*

The fatigue analysis in this study is based on a potential site off the West Coast of Ireland. This site is selected due to its significant potential for wind energy generation, benefiting from its position on the Atlantic Ocean and exposure to prevailing south-westerly winds, which result in higher wind speeds compared to sites on the East Coast of Ireland. While these elevated wind speeds enhance the site's power production capacity, they also expose the wind turbine to more severe met-ocean conditions. The combination of higher wind speeds and harsh met-ocean conditions makes wind turbines in such a location more vulnerable to fatigue failure. To evaluate this risk, a detailed fatigue analysis is performed using the composite model with wind and wave data collected from a weather buoy positioned at the site.

This data is provided by the Irish Marine Data Buoy Observation Network (IMDBON) and was assessed between the years of 2019 and 2024 in accordance with the IEC 61400 (IEC 2014) design guidelines and HIPERWIND project recommendations (Vanem et al. 2023). Joint probability distributions were established using the method of bins, adhering to the IEC standard (IEC 2014). Wind speeds (W_s) were binned with a width of 2 m/s, while significant wave heights (H_s) were conditionally binned based on wind speeds with a width of 1 m. Similarly, the peak spectral period (T_p) of the waves were conditionally binned based on significant wave height, using a bin width of 1 second. Based on these observations, twelve discrete wind speeds, ranging from the turbine's cut-in to cut-out wind speeds, were considered. Each wind speed was paired with the most probable met-ocean conditions, characterised by a significant wave height and peak spectral period, to simulate realistic operational scenarios. For the purposes of this work, the wind and waves will be considered to be fully aligned.

Table 1: Environmental conditions simulated

Ws (m/s)	3.8	4.5	7.5	9.7	11.3	12.8
	14.3	17.8	18.6	21.0	22.2	24.1
H_s (m)	1.9	2.1	2.5	3.1	3.9	4.6
	5.4	6.0	6.5	6.5	7.3	6.8
T_p (m)	8.4	10.2	10.2	11.5	11.5	12.3
	13.2	14.0	14.0	14.0	14.8	14.0

2.2 *IEA 15-MW*

The fatigue analysis is carried out on the IEA 15-MW fixed-based offshore wind turbine. This turbine features variable-speed, collective-pitch control and is classified as an IEC Class 1B wind turbine. It is a three-bladed, upwind configuration with a hub height of 150 meters above sea level and a rotor diameter of 240 meters. The turbine is supported by a monopile foundation suitable for deployment in 30-meter-deep waters, extending an additional 45 meters below the seabed. Operating between a cut-in wind speed of 3 m/s and a cut-out wind speed of 25 m/s, the turbine reaches its rated power output at 10.59 m/s. With an annual energy production capacity of 77.4 GWh, demonstrating its substantial contribution to renewable energy generation. Further specifications of the IEC 15-MW wind turbine are provided in (Gaertner, Rinker, Sethuraman, Zahle, Anderson, Barter, Abbas, Meng, Bortolotti, Skrzypinski, et al. 2020)

2.3 *Composite model*

This study employs a composite modelling approach to generate accurate stress time histories at critical locations on the wind turbine structure. The composite model integrates the capabilities of both multibody dynamic simulations and finite element analysis, leveraging the strengths of both methods. The multibody dynamic model simulates environmental loading conditions from wind and waves while incorporating the turbine's control systems using the NREL Reference OpenSource Controller (ROSCO) (Abbas et al. 2021). However, this model alone cannot capture localised stress concentrations arising from geometric discontinuities, such as the flange connection between the tower and the transition piece. To address this limitation, finite element modelling of the turbine is used, calculating SCFs that account for the effects of these local geometries. By combining the stress time histories from the multibody dynamic model with SCFs from the finite element model, comprehensive stress time histories are produced, encompassing both the global structural response and local stress distributions. This integrated approach enables more precise fatigue life assessments of critical wind turbine components, ensuring accurate predictions of operational lifespan. Details regarding the construction of the multibody dynamic model and the finite element model are presented in the subsequent section.

2.4 *Multibody dynamic model*

A Matlab-based non-linear aeroelastic multibody dynamic model is used in this work to produce the stress time histories of the axial and bending stresses occurring at the base of the wind turbine tower under environmental loading. This multibody dynamic model is a holistic model which captures the turbine's operational response to both aerodynamic and hydrodynamic loading. The model is constructed based on Kanes Dynamics (Kane and Levinson 1985) using 22 degrees of freedom to describe the motion of the wind turbine.

The model is constructed using a modular framework enabling the computation of the various environmental and operational forces. The sea conditions are characterised by the significant wave height and peak spectral period of the waves based on the Pierson–Moskowitz spectrum (Pierson Jr and Moskowitz 1964). The wave and current interactions are accounted for using Airy wave theory and finally, the hydrodynamic loads on the turbine tower are calculated using Morison's equation (Morison et al. 1950).

The wind fields used in this model are generated via Turbsim (Jonkman 2009) based on turbulence intensities generated for each wind speed from Wang et al (Wang et al. 2014) as recommended by (IEC 2014). Blade Element Momentum (BEM) theory is used with the Turbsim generated wind fields along with the geometric and aerodynamic properties of the wind turbine blade to generate the corresponding forces imposed by the wind on the blades. The BEM theory combines momentum theory and blade element theory and the resulting equations are solved using a root-finding method proposed by Ning (Ning 2014).

Further details regarding the construction and derivation of the muti-body dynamic model can be found in (Sarkar and Fitzgerald 2021) with further details of the modelling available to interested readers in (Sarkar et al. 2020, Sarkar and Fitzgerald 2020).

2.5 *Tuned mass damper*

A TMD is installed at the top of the turbine tower of the multibody dynamic model. Given the inherent aerodynamic damping provided by the turbine blades in the fore-aft direction (Zhang et al. 2023), the TMD is designed to move exclusively in the side-to-side direction, introducing a 23rd degree of freedom to the dynamic system. A mass of 1% of the first modal mass is selected for the TMD and the optimal damping ratio for the TMD is determined using the expression proposed by (Den Hartog 1985). The TMD is tuned to match the first natural side-to-side frequency of the turbine, optimising its ability to mitigate lateral vibrations. The stiffness and damping characteristics of the TMD are defined using the following equations, where K represents the spring stiffness, c is the viscous damping coefficient, and ζ is the damping ratio:

$$K = \omega^2 m, \qquad c = 2\zeta\omega, \qquad \zeta = \sqrt{\frac{(3\mu)}{8(1+\mu))}} \qquad (1)$$

After incorporating the TMD into the multibody dynamic model, the system was validated through a code-to-code comparison with the National Renewable Energy Laboratory's state-of-the-art offshore wind turbine simulator, OpenFAST. A representative example of the validation results are presented in Figure 1. The comparison demonstrates strong agreement between the 22-degree-of-freedom "MAT: Baseline" and "OF: Baseline" models, as well as between the 23-degree-of-freedom "MAT: TMD" and "OF: TMD" models, confirming the accuracy and reliability of the developed multibody dynamic model.

2.6 *Finite Element Model*

A finite element model of the wind turbine was developed using Abaqus software (Abaqus 2011). The model incorporated a combination of geometric components provided by the IEA and components constructed based on geometric data files provided by the IEA (Gaertner et al. 2020). The turbine model includes detailed representations of critical parts, including the blades, hub, tower, and components of the nacelle including bearings, flanges and the low-speed shaft. For this study, the monopile and transition piece were modelled as a single continuous component as is presented in the provided IEA geometry.

A custom-designed ring flange connection was developed to join the tower and transition piece, following the Petersen/Seidel method outlined in IEC 61400-6 (IEC 2020). The flange was designed to withstand the maximum loads encountered during Damage Load Cases (DLC) 1.3, 1.4, 1.5, 2.3, 3.2, 3.3, 4.1, 4.2, 6.2, 6.3, and 7.1. As shown in Figure 3, the flange features a thickness of 190 mm and is secured with 190 M72 10.9-grade high-strength steel bolts. The modelling of the bolts is considered outside the scope of this work and the two flanges were connected using fixed constraints and thus full surface contact between the mating flanges is assumed.

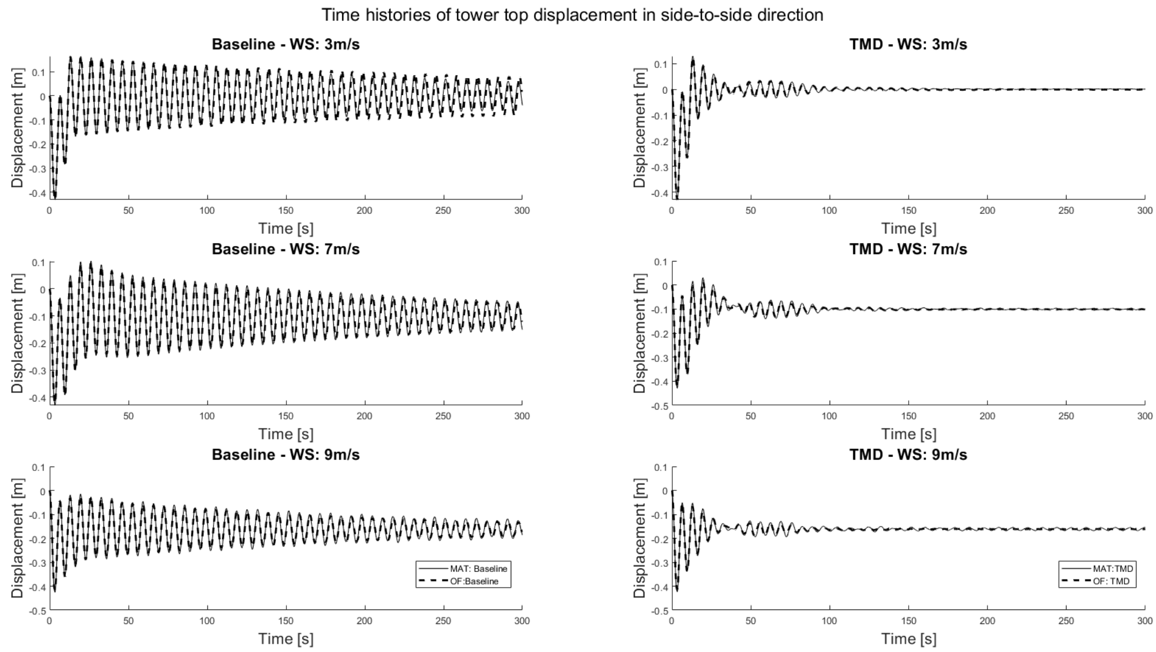

Figure 1: OpenFast vs multibody dynamic model response validation

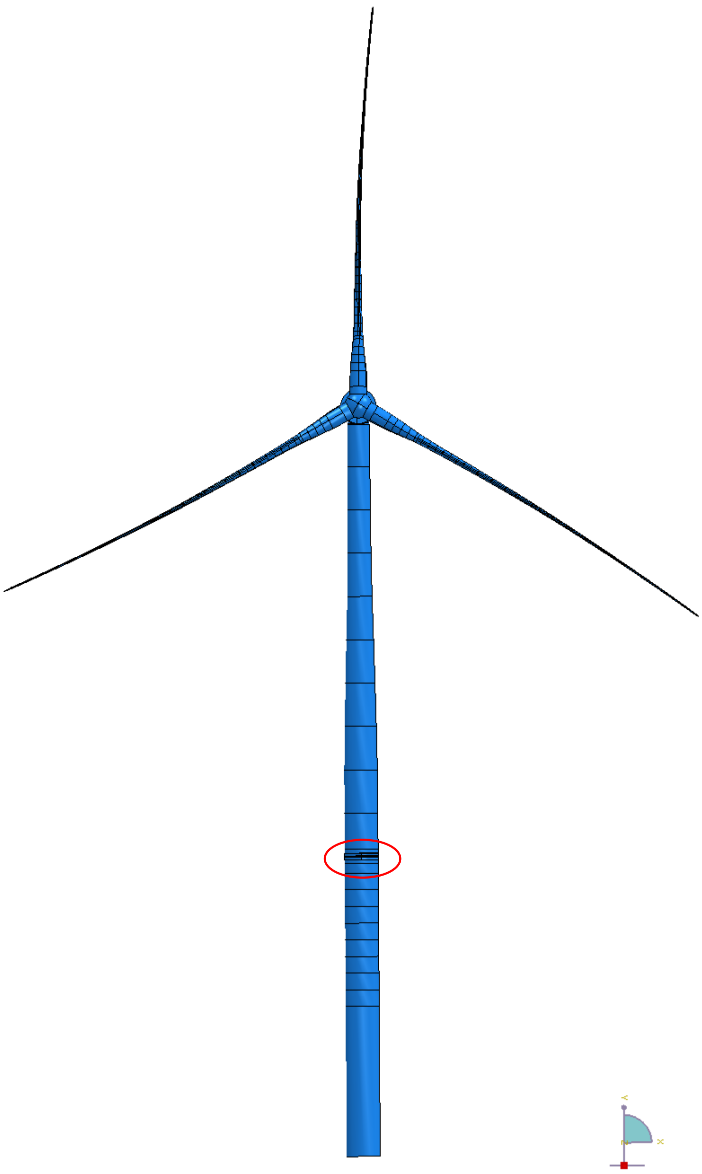

Figure 2: Finite element model of IEA 15-MW wind turbine with the custom ring flange position highlighted

The hub and nacelle components were meshed using C3D8R hexahedral elements and were constructed as rigid components in alignment with the multibody dynamic model. The wind turbine blades, characterised by their complex and variable geometry, were meshed with C3D10 quadratic tetrahedral elements to capture detailed aerodynamic shapes effectively. The tower and monopile/transition piece were meshed with S4R shell elements, which are computationally efficient for large cylindrical structures. To capture localised stress concentrations, the flange and adjacent wall regions of the tower and transition piece were meshed using C3D20R elements known for their strong ability to capture stress concentrations.

To enhance accuracy, local seeding was applied to the region of interest, in this case, the ring flange connection. A mesh convergence analysis was performed to ensure that accurate stress predictions were achieved with the minimal required computational expense. The flange components were meshed with a seed size equal to half of the wall thickness, ensuring at least two elements were present across the wall depth to capture stress gradients effectively. In the bottom section of the turbine tower and the top section of the transition piece, a transition mesh was created using a single bias between the finer flange mesh and the coarser seed size of 0.6 m for the remainder of the tower and monopile/transition piece. The blade, hub, and nacelle components, being of secondary interest for this study, were meshed with a seed length of 1m. The final meshing strategy resulted in a finite element model with over one million elements, balancing computational cost and solution accuracy.

SCFs along the tower wall in close proximity to the flange connection were a key focus of this study. These SCFs were determined by comparing stress dis-

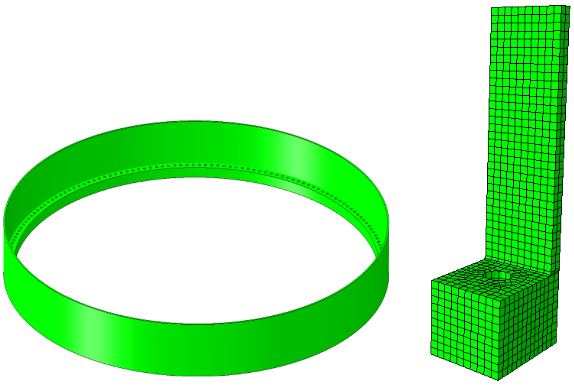

Figure 3: (a) Ring flange (b) Flange segment meshed

tributions in models with and without the flange connection to quantify the localised stress concentration caused by the connection. Given that the turbine tower base experiences both axial and bending loads, SCFs were computed separately for each loading condition. These factors were then applied to the corresponding axial and bending stress time histories, as per the recommendations of the DNV recommended practice guidelines (DNV GL 2016).

2.7 *Fatigue Analysis*

Building on insights from the literature review and documented failures, the fatigue analysis in this work is focused on the butt weld connection of the tower flange connection. The fatigue analysis was conducted in accordance with IEC 61400 (IEC 2014) requiring at least 6 simulations with 600 seconds of usable simulation data for each environmental condition. The fatigue life was estimated using a customised version of NRELs MLife. This analysis calculated the estimated fatigue lifetime based on Palmgren-Miner's rule with the rainflow counting algorithm as specified in Annex G of IEC 61400-1 (IEC 2014).

The fatigue strength of the welded joint was evaluated using a bi-linear SN curve specified in the DNV recommended practice standard (DNV GL 2016). Specifically, the class D curve for butt welds in steel structures exposed to seawater with cathodic protection. By combining this bi-linear S-N curve with the probability distribution derived from the IMDBON buoy data the fatigue life of the wind turbine can be accurately predicted.

3 RESULTS

The total damage that the butt weld experienced over a service life of 20 years can be viewed in Table 2. This table compares the results of the composite model (CM) which considers the local stress concentrations which arise due to the presence of the flange connection against the traditional approach (TA) in which the flange is not considered. Additionally, the case where the TMD device is installed in the composite model is compared with the baseline case.

Table 2: Fatigue damage at 20 years

Damage (D)	TA	CM	CM & TMD
	0.444	0.584	0.592

A comparison between the TA and CM values reveals a 33% increase in fatigue damage due to the presence of the flange connection. Similarly, comparing the results for CM and CM & TMD produces an unexpected outcome as the TMD has a negative impact on the damage experienced by the tower, increasing the fatigue damage by 1.4%. On further inspection of the RMS values of the stresses, the TMD increases the fore-aft bending moments marginally which outweighs the benefits of the TMD in the side-side direction.

Table 3 extends this analysis by comparing the estimated fatigue life based on the traditional approach, the composite model framework, and the composite model with a TMD installed. The results indicate a significant reduction in the fatigue life of the wind turbine of over 10 years when the effects of the flange are considered. Furthermore, the inclusion of the TMD demonstrates an overall negative impact on fatigue life, with a reduction of nearly 6 months compared to the composite model without the TMD.

Table 3: Fatigue life

Lifespan (Years)	TA	CM	CM & TMD
	45.05	34.25	33.78

4 CONCLUSION

This paper performed a fatigue analysis for the IEA 15-MW monopile-based offshore wind turbine for a proposed site off the West Coast of Ireland. Environmental data obtained from the IMDBON for this site was processed and suitable environmental parameters were adopted. A composite model was constructed blending results from a multibody dynamic model and a finite element model. The composite model produced detailed stress time histories for each environmental condition considering the effects of local geometries. A TMD was added to the composite model mitigating the response of the turbine in the side-to-side direction. The results were processed employing an adapted version of NRELs MLife using a bi-linear SN curve obtained from the DNV guidelines.

Two key findings were found in this work. The first key finding is the importance of considering local geometry effects such as the ring flange connection. When neglecting the local stress concentrations which arise due to this feature the fatigue life was overestimated by more than 10 years.

The second key finding relates to the addition of the TMD to the top of the turbine tower. By adding the

TMD, the damage to the wind turbine after 20 years of service was marginally increased stemming from an increase in fore-aft moments which dominate the fatigue life. The addition of the control device was found to reduce the fatigue life by almost 6 months emphasising the value of the composite model in assessing lifetime extension strategies for offshore wind turbines.

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