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Influence of Structural Redundancy on Fatigue Life of Offshore Wind Turbine Jacket Structures

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ABSTRACT

The concept of structural redundancy is implemented in the fatigue analysis of an offshore wind turbine jacket structure. The analyzed jacket is a real life example. Time domain analyses are performed for the most representative design load case. The uni-directional and multi-directional simulations of the offshore wind turbine system are carried out using a coupling of the aero-elastic code and the finite element code. Fatigue analyses are performed using hot spot stress approach and Miner's rule. Comparative studies show that considering structural redundancy leads to expanded fatigue life of the offshore wind turbine jacket structures.

KEY WORDS: Offshore wind turbine; Fatigue Life; Structural redundancy; Hot spot stress; Damage equivalent loads

INTRODUCTION

Offshore wind turbines (OWTs) are typically designed according to respective standards and guidelines for a lifetime of 20-25 years. The design of support structures is usually fatigue-driven since OWTs are exposed to long-term and variable-amplitude loading. Lifetime extension is one of the priorities of wind industry in order to reduce levelized cost of energy (LCOE). However, there is not much experience regarding this issue. DNV-GL (2016) recommends renewed lifetime calculation combined with the assessment through inspection. Ziegler and Muskulus (2016) identified environmental, structural and operational parameters which are important for fatigue lifetime of monopiles and which should be considered in the lifetime extension decision. Fatigue reliability analysis of OWT jacket support structures has been performed by Dong et al. (2012). They observed that allowable cumulative fatigue damage can be increased with the implementation of a relevant inspection strategy.

The aim of this paper is to investigate the influence of structural redundancy on fatigue life of OWT jacket structure. High redundant capacity is an advantage of jackets compared to monopiles and this can be of great interest in order to extend designed lifetime. Nevertheless, this advantage is not made use of in design practice. In this study, the investigation is based on a real-life Senvion 6.2M126 OWT with a jacket structure. Load simulations of the OWT system are performed using the coupled simulation tool ASAS/Flex5. Load case sets are reduced in comparison to what is generally used in design practice. The load-time histories obtained from simulations are post-processed applying rainflow counting (RFC) and damage equivalent loads (DELs) are derived. Based on this, fatigue life of all welded tubular joints within the jacket is estimated using Miner's rule and the structural stress approach. Crack initiation and crack propagation phases are not accounted for and it is assumed that components which reach a cumulative fatigue damage of 1.0 (according to Miner`s rule), fail. These components are considered as non-load carrying and they are released (no load transfer) in the numerical model in further OWT simulations. In order to understand the influence of the loss of the structural component within the jacket structure, several parameters are analyzed: eigenfrequencies, DELs, fatigue damages. Moreover, the most critical joints for fatigue design and potential spots for crack initiation are identified. Wind/wave misalignment and multi-directionality are taken into account as well.

First, the investigated OWT and its respective model are illustrated. Then, load cases that are used for fatigue analyses are presented. Results from fatigue analyses are shown and discussed. Finally, conclusions are drawn based on the results.

FATIGUE ANALYSIS

Welded tubular joints are the critical locations for fatigue damage in the jacket structures. The spots where a fatigue crack is expected to occur are located around the circumference of the intersection between the chord and the brace (at the weld toe, at the brace and at the chord side). These spots are referred to as hot spots. The stresses at these points can be measured experimentally or determined with a finite element (FE) analysis or by using empirical equations. Considering computational efficiency, the hot spot stress (HSS) approach is a reasonable method to be applied in the fatigue design of welded tubular joints of the OWT jacket structures. According to DNV-GL (2014), HSSs has to be evaluated at 8 spots around the circumference of the joint (at the chord and at the brace side) as superposition of normal stresses from axial load, in-plane bending (IPB) and out-of-plane bending (OPB), see Fig. 1.

HSSs which are calculated using empirically based equations can be expressed as follows (Eq. 1):

$$\sigma_{HSS} = SCF \cdot \sigma_{nom} \quad (1)$$

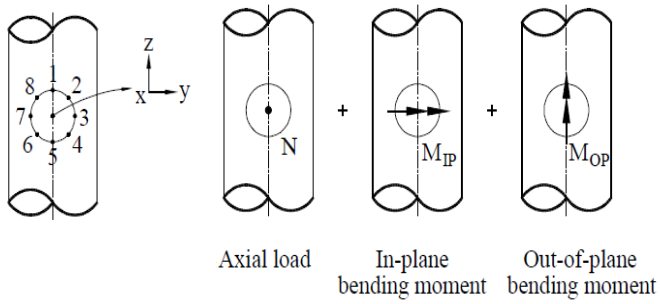


Fig. 1 Inspection points and superposition of stresses in tubular joints (DNV-GL, 2014)

Nominal stresses (σ_{nom}) are determined in the global analysis of the structure while stress concentration factors (SCFs) are dimensionless parameters which depend on the joint configuration, geometrical properties and loading conditions. The empirical equations for calculation of SCFs are recommended by several researchers: Efthymiou (1988), Smedley and Fischer (1991), Kuang et al. (1975). These equations enable calculation of HSSs at the crown (points 1 and 5, see Fig. 3) and at the saddle (points 3 and 7, see Fig. 2) position. HSSs in the other points around the circumference of the joint are determined using a linear interpolation of normal stresses from axial loading at the crown and at the saddle and sinusoidal variation of normal stresses from IPB and OPB.
In this study three different types of tubular joints are investigated, see Fig. 4:

- **Y-joints** represent the connection between jacket braces and jacket legs. They are located at the bottom (Y1) and at the top of the structure (Y5). Y-joints are analyzed as uni-planar and in total, 16 brace to leg welded connections are subject of this study.
- **K-joints** represent the connection between jacket braces and jacket legs as well. Three different K-joint configurations (K2, K3 and K4) are investigated. K-joints are analyzed as uni-planar and the total number of investigated brace to leg welded connections is 48.
- **X-joints** are located in the middle of the X-braces. The jacket structure features four different X-joint configurations (X1, X2, X3 and X4). The total number of investigated welded connections is 16.

Nominal stresses are calculated for all joints based on time series (15 load cases) for axial forces, IPB and OPB moments. The parametric equations developed by Efthymiou (Efthymiou, 1988) are applied to determine HSSs at the crown and at the saddle of the tubular joints. According to DNV-GL (2014), these values are interpolated and HSSs around the circumference of the joints are obtained. For HSSs at the chord and at the brace side, the RFC method is applied to determine the number of cycles (n_i) per stress range ($\Delta\sigma_i$). These stress ranges are used with respective S-N curves in order to determine the number of cycles up to failure (N_i). A linear fatigue damage accumulation is assumed and Miner's rule (Miner, 1945) is employed in order to calculate the fatigue damage (D), (see Eq. 2). The total fatigue damage of the joints is estimated as sum of fatigue damages per load case based on probability of occurrence of load cases over the lifetime. The fatigue life is estimated for each hot spot individually.

$$D = \sum_{i=1}^{n} \frac{n_i}{N_i} \quad (2)$$

The crack initiation and crack growth phases are not considered in this study. It is assumed that complete failure of the joint occurs when a cumulative fatigue damage of 1.0 is reached in one of the hot spots. These joints are considered as non-load carrying and they are released in the numerical model in further simulations and fatigue analyses.

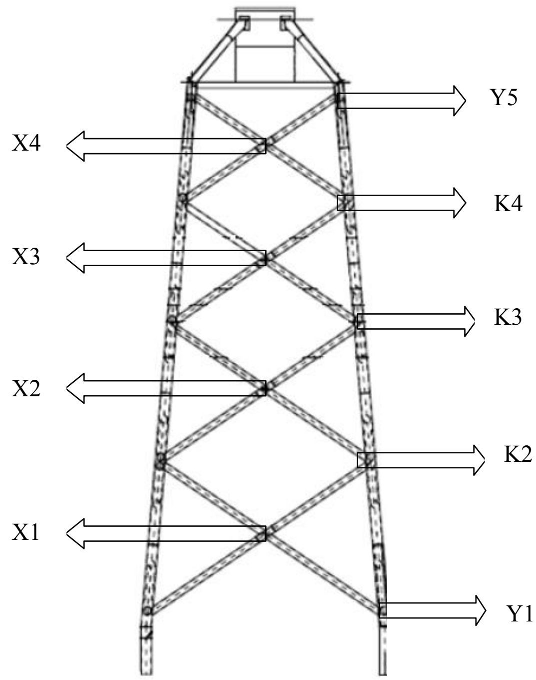


Fig. 2 Positions of the investigated joints

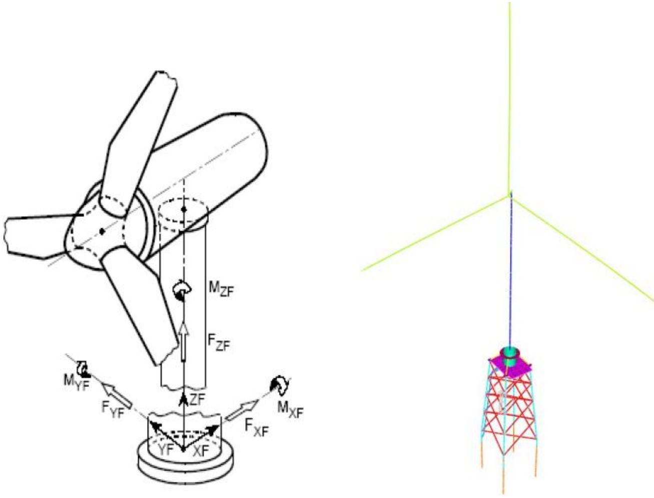
OFFSHORE WIND TURBINE-NUMERICAL MODEL

The investigated OWT is a real-life example from the Thorntonbank project (Phase II). The rotor nacelle assembly (RNA) is a Senvion 6.2M126. Basic parameters of the OWT are given in Table 1. The support structure consists of a four-legged jacket with four levels of X-braces, a transition piece and a tower. The jacket legs are supported by piles and the jacket and the tower are connected through a rigidly modeled transition piece. The total height of the jacket without transition piece is 50.9 m and the hub height is 95 m. The water depth at the site is 27 m.

Table 1. Basic parameters of the Senvion 6.2M126 wind turbine

Parameter	Value
Rated power	6.2 MW
Rotor diameter	126 m
Rated wind speed	13.5 m/s
Hub height	95 m

The following coordinate system (Fig. 3a) is defined for the OWT in this study: The x-axis coincides with the main wind direction. The z-axis passes through the tower centerline with upward direction. The y-axis forms 3-D Cartesian coordinate system with the other two axis.



(a) (b)

Fig. 3 (a) Coordinate system of the OWT (GL, 2012); (b) Coupled ASAS/Flex5 model

All OWT components like blades, nacelle, drive train and turbine tower as well are modeled in the aero-elastic code Flex5, see Øye (1999). For the modeling of the aerodynamic behavior, the blade element momentum theory (BEM) is applied. The control parameters and supervisory functions as well as subsystems like the pitch device are implemented in the Flex5 model. This ensures a realistic behavior of the virtual wind turbine under operating conditions. The jacket structure, the transition piece, soil conditions and wave loading are modeled in the FE tool ASAS. The jacket structure and piles are modeled with beam elements. Tubular joints of the jacket are formed of beam elements rigidly connected at the intersection points of their central axes without consideration of joint flexibilities. This is assumed to be sufficient in this context even if a lot of work has been performed on local joint flexibility of OWT jacket structures, see Schaumann et al. (2008), Kaufer et al. (2010) and Vorpahl (2015). Quadrilateral shell elements are used to model transition piece. Soil conditions are modeled using a set of linear springs per pile along the length.

The numerical model is built-up using a coupling of the Flex5 code and the ASAS code. The coupled ASAS/Flex5 model allows for consideration of the wind and wave loads and their dynamic interactions with the support structure. The coupling between the aero-elastic code Flex5 and the FE-code ASAS is explained by Seidel et al. (2009). The coupled ASAS/Flex5 model used in this study is shown in Fig. 3b.

APPLIED LOADS

Fatigue limit state

A range of load cases needs to be simulated in order to estimate the fatigue life of the OWT. These load cases include all operational states like power production, parked conditions, start-up and shut-down events. In the IEC standard (IEC, 2009), seven load cases are suggested for fatigue limit state analysis. Design load case (DLC) 1.2 is selected in this study since it is the most frequent operation state among all the load cases. In this way, the required OWT simulation load cases are represented accurately enough while the computational effort is limited to a feasible level. Long-term wind and wave statistical data like turbulence intensity distribution, significant wave height and peak-spectral period are taken from the design basis of the Thorntonbank project. The simulation time for each of the 15 wind bins between cut-in and cut-out wind speeds is set to 600 s according to the IEC standard. Initial transients are removed with an additional pre-simulation time of 50 s, which is not included in the results. RFC algorithm is applied to post-process simulation results (load time histories) and to obtain DELs. DELs are calculated for an OWT lifetime of 20 years with an S-N slope of 4 and 2E+8 equivalent load cycles.

Co-directional versus Multi-directional approach

Wind and wave loading vary in magnitude and direction. The directional variations as well as the relative misalignment between wind and wave loading have to be taken into account. The influence of the distributions of wind and wave directions on loads and fatigue life of the support structure is investigated. The wind and wave directional data are based on the design basis of the Thorntonbank project. Twelve different wind sectors are considered. Taking into account the symmetry of the reference jacket structure, the probabilities of opposite sectors are summed up (for example sector N and sector S are summed up into the sector 1) and six different directional sectors are used (Fig. 4).

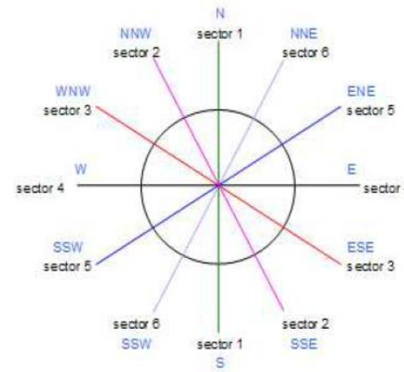


Fig. 4 Wind sectors considered in multi-directional analysis (Certification load assumptions, 2007)

The misalignment of mean wave direction with respect to mean wind direction commonly reaches up to 30% (Peters et al., 1993). Generally, large misalignments occur for smaller wind speeds, while for larger wind speeds wind and wave tend to be more aligned (Fischer et al., 2011). Misalignment effects are investigated for 30° and 90° of misalignment between the wind and wave directions.

SEQUENCE OF SIMULATION

The sequential simulations of the OWT and fatigue analyses of the tubular joints within the jacket are performed in order to implement the structural redundancy concept. Firstly, the OWT system with an undamaged jacket structure is simulated. The Obtained DELs are used for the fatigue life assessment of the jacket structure. The complete fatigue damage of the structural component is assumed after reaching cumulative fatigue damage (D) of 1.0. Crack initiation and crack propagation phases are not accounted for. The failed structural component is considered as non-load carrying and it is released (in this case braces are released from legs) in the FE-model of the jacket structure. All cumulative fatigue damages in non-failed structural components are preserved. Further simulation is performed on the OWT system with a damaged jacket structure. The loss of the load-carrying capacity in a damaged component causes changes of loading paths in the jacket structure. The consequences are changes of DELs and different trends of fatigue damage accumulations. These cumulative fatigue damages are superimposed with those resulting from previous simulation and the following structural component that failed due to fatigue is identified. The repetitive approach like this results in sequential loss of structural components within the jacket. On the one hand, the result is an extended fatigue life. On the other hand, further checks of structural properties like changes of eigenfrequencies, changes of DELs and possibility of the system to withstand extreme loads need to be conducted.

RESULTS AND DISCUSSION

In this section, results of the sequential coupled simulations of the OWT with the jacket support structure for the described load cases (see section Applied Loads) are presented. The influence of structural redundancy on the structural properties and the lifetime extension is presented for the case after the sequential failure of three joints. The changes of DELs and the trends of cumulative fatigue damages are analyzed for all tubular joints within the jacket structure. One K- (4-KIII-4-D2), one Y- (3-YII-5) and one X-joint (II-X4) are selected (see Fig. 5a) and the results for these joints are presented.

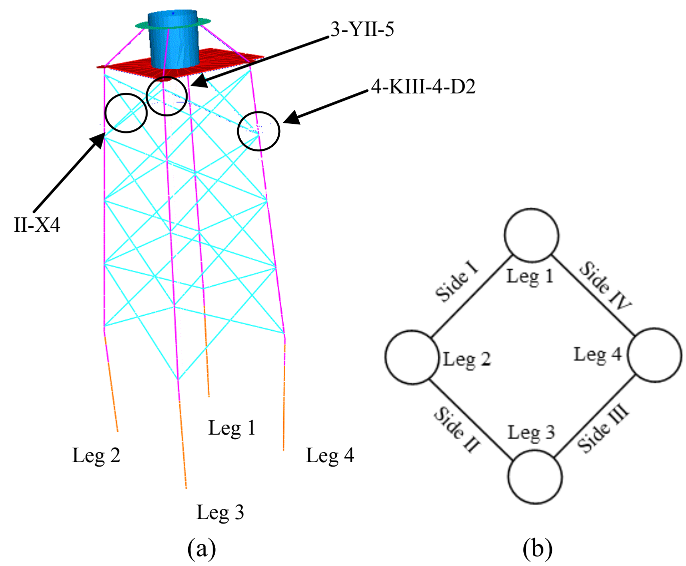


Fig. 5 (a) Positions of K-, Y- and X-joint represented in this study; (b) Definition of the jacket base

The following naming convention of joints is used in this study:

- **K-joints** (e.g. 4-KIII-4-D2)**:** The first number (4 in this case) refers to the jacket leg. KIII designates the joint type (K-joint) and the jacket side (III in this case, see Fig. 5b) to which the joint belongs. The next number (4 in this case, see Fig. 2) shows the height level in the jacket. D1 and D2 designate the downward and the upward orientation of braces respectively (see Fig. 6b).
- **Y-joints** (e.g. 3-YII-5): The first number (3 in this case) refers to the jacket leg. YII designates the joint type (Y-joint) and the jacket side (II in this case, see Fig. 5b) to which joint belongs. The next number (5 in this case, see Fig. 2) shows the height level in the jacket.
- **X-joints** (e.g. II-X4): The first index (II in this case, see Fig. 5b) designates the jacket side to which joint belongs. The bay in which X-joint belongs refers to the second index (X4 in this case, see Fig. 2).

Structural redundancy

The sequential simulations of the OWT system and fatigue analyses of the jacket structure indicate K3-joints as the most suspicious to fatigue damages. All fatigue failures occur at the brace side at the crown or close to the crown (hot spot 11R, see Fig 6b). The positions of failed joints and the sequence of fatigue failures are shown in Fig. 6a. The influence of failures of these three joints is investigated through several parameters: wind/wave misalignments, eigenfrequencies, DELs, trends of cumulative fatigue damages in remaining joints, overall lifetime extension.

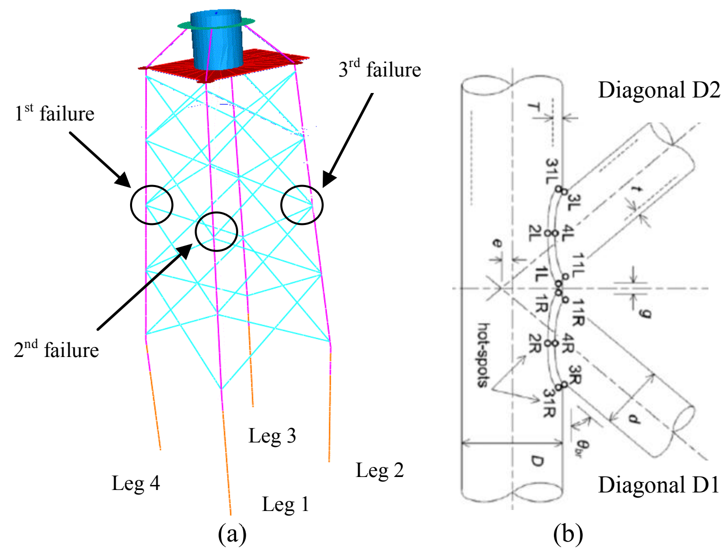


Fig. 6 (a) Positions of the fatigue failures in the jacket taken into account in this study; (b) K-joint, modified from Walbridge (2008)

Wind/wave misalignments

The influence of the distributions of wind- and wave directions on loads of the jacket structure is investigated for the wind speed 10 m/s. The misalignments of 30° and 90° between wind and wave directions are considered. The results of the analyses are shown for the jacket structure with three completely damaged (non-load carrying) joints, see Figure 6a. DELs (axial force, IPB, OPB) are evaluated for the case of co-directional wind/wave and for cases of misalignments of 30° and 90° between wind and wave directions. The absolute differences of DELs are presented for selected K-, Y- and X-joint.

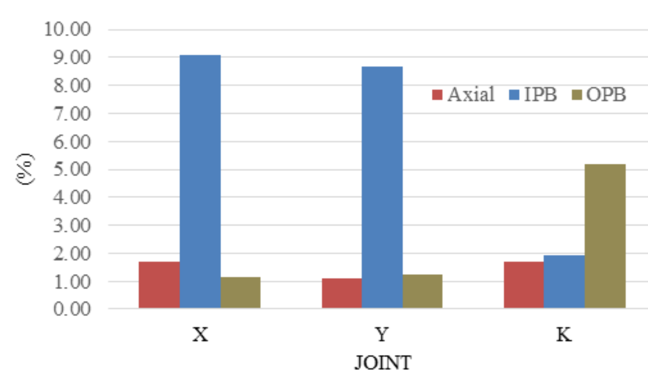


Fig. 7 Absolute differences of DELs for 30° misalignment between wind and wave direction compared to co-directional wind/wave for jacket structure with three completely damaged joints

Figure 7 illustrates the absolute differences of DELs for the case of 30° misalignment between wind and wave direction compared to the case of co-directional wind/wave. It becomes clear from the figure that IPB moments of X- and Y-joint differ around 9 %. On the other hand IPB moment of K-joint is changed for 2 %. DELs of axial forces are slightly affected with the absolute difference of approximately 1-2 %. The differences of OPB moments for X- and Y-joints are in range of 1 % while in case of the K-joint this difference reaches 5%.
In the Fig. 8, absolute differences of DELs for the case of 90° misalignment between wind and wave direction are shown and compared to the case of co-directional wind/wave. In this case, the absolute differences of DELs of X-, Y- and K-joints are in range 1-3 %. The exception is the DEL of OPB moment which differs approximately 5 %.

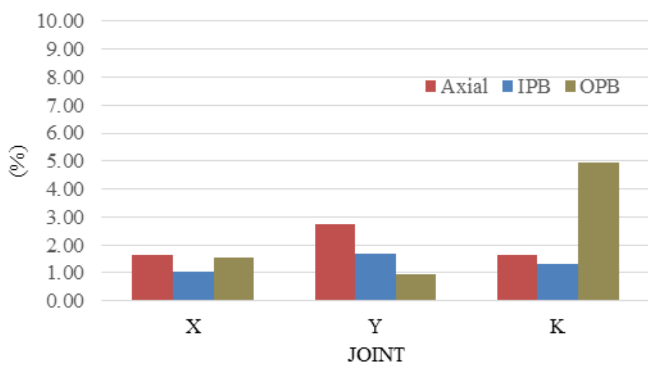


Fig. 8 Absolute differences of DELs for 90° misalignment between wind and wave direction compared to co-directional wind/wave for jacket structure with three completely damaged joints

Deeper insight into DELs of all tubular joints within the damaged jacket shows the small impact of the wind/wave misalignments on results. Comparisons are made for all tubular joints and absolute differences are calculated. In both cases (wind and wave misalignments of 30° and 90°), absolute differences are in range 0-10 %. These values are averaged and shown in Fig. 9

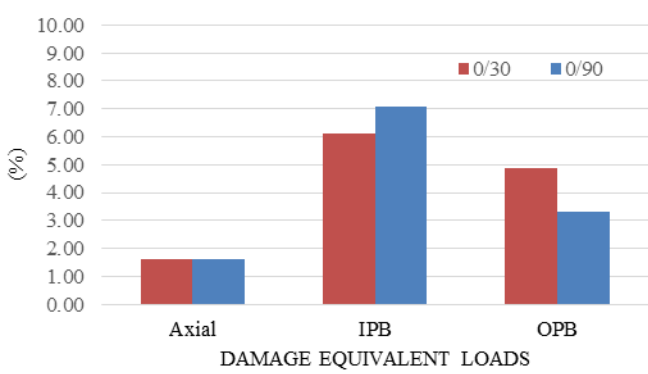


Fig. 9 Averaged absolute differences of DELs of misaligned wind/wave direction compared to co-directional wind/wave for jacket structure with three completely damaged joints

According to the previous results, the wind/wave misalignments show a small impact on DELs in the case of the jacket structure with failed joints (similar results are observed in the case of an undamaged OWT system). Therefore, these effects can be neglected which has a favorable influence on the computational efforts. The negligibility of the wind/wave misalignments and the symmetric property of a four-legged jacket can significantly reduce the number of load combinations. The wind and wave loading impact on a jacket can be analyzed with only 6 co-directional wind/wave combinations instead of 144 possible combinations (12 wind and 12 wave sectors). This approach is used for multidirectional analyses in this study. The reduction flowchart is shown in Fig. 10.

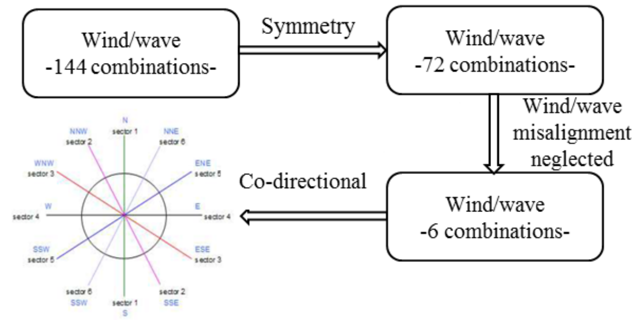


Fig. 10 Reduction of the load combinations for different wind and wave directions

Eigenfrequencies

The eigenfrequencies and the mode shapes are calculated and compared for three different jacket models. The first one represents the undamaged jacket. The second model represents jacket with three completely damaged K-joints (result of sequentially performed OWT simulations and fatigue analyses). The third model is not in agreement with results of the sequentially performed fatigue analyses that show subsequent occurrence of fatigue failures in braces. In this case, it is assumed that fatigue damage occurs in the jacket leg 3 (3-YII-5-joint, see Fig. 5). The aim is to check the influence of the loss of the load carrying capacity in a jacket leg on the eigenfrequencies. There are several reasons for the selection of this joint. This is the only location within the jacket where the highest cumulative fatigue damage (of all control spots in welded connection, see section Fatigue Analysis) occurs at the leg (chord) side. A significant decrease of fatigue life (from 41 years to 35 years) is observed after the sequential fatigue failures of joints (see Fig. 6a). Moreover, according to the probability of wind directions (Design Basis) and OWT simulations, this leg experiences a lot of stress variations (compression/tension) during the OWT lifetime. This is of special interest for already planned investigations which include fracture mechanics based fatigue analyses and effects of load sequences.
The first nine eigenfrequencies from the three jacket models are shown in Fig. 11. It is obvious that the joint loss reduces the stiffness of the jacket and therefore also reduces the magnitudes of the eigenfrequencies. The effect is more conspicuous for the higher eigenmodes.

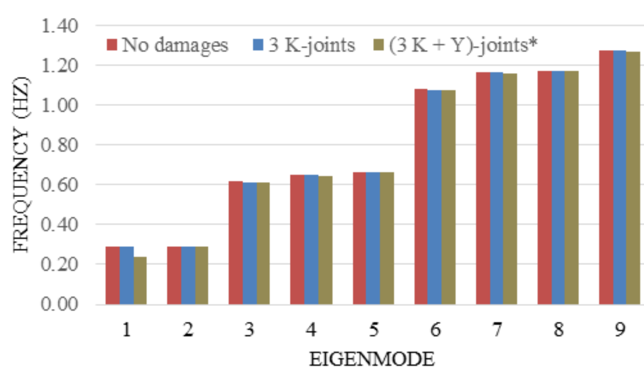


Fig. 11 Eigenfrequencies for the first nine eigenmodes for three different jacket models

An insight to the eigenfrequency differences between the jacket models with damages and the jacket model without damages is shown in Fig. 12. The damages in the braces have no influence on the first global bending modes. But, the damage in the jacket leg reduces the eigenfrequency associated with the first global bending mode by approximately 20 %. For the higher eigenmodes, eigenfrequency differences are in a range of 5-35 % and the influence of the damage in the jacket leg on the eigenfrequencies is significantly smaller. To summarize, fatigue failures at the brace side reduce the eigenfrequencies in higher eigenmodes.

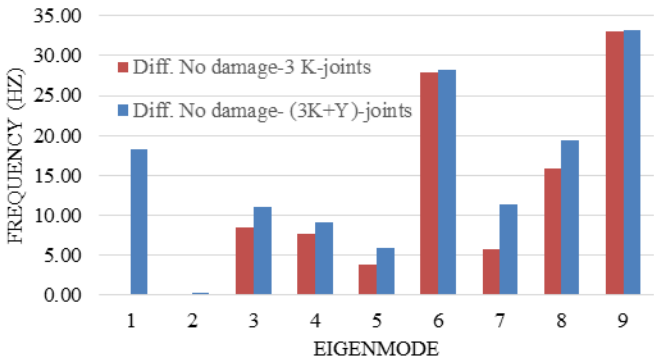


Fig. 12 Eigenfrequency differences between the jacket models with joint failures and the undamaged jacket model

Damage equivalent loads

Jackets are highly redundant structural systems. The damage or the exceeding of the capacity in a structural member does not lead to an immediate structural collapse. The failure of the joint causes a load redistribution within the jacket. The load redistribution has an impact on the further fatigue damage accumulation in remaining joints. Differences of DELs resulted from the joints losses are presented in this paper for the selected K-, Y- and X-joint. The comparisons are made between the undamaged jacket and the jacket which experience sequential failure of three joints (see Fig. 6a).
Figure 13 provides an insight to the absolute differences of the DELs between these two cases.

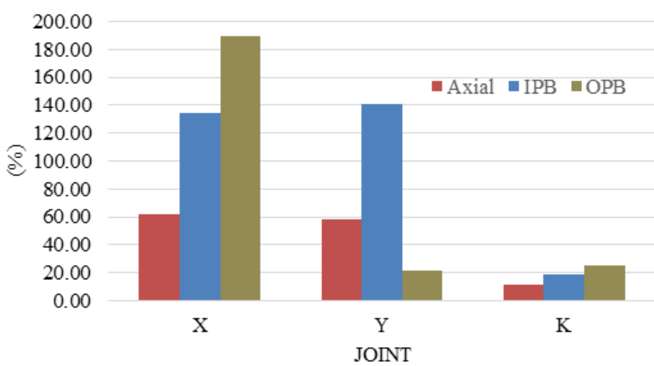


Fig. 13 Absolute differences of DELs between the jacket model with three completely damaged joints and the undamaged jacket model

The highest absolute differences occur in the X-joint. The OPB moment is increased by approximately four times (200 %). In case of the Y- and the K-joint, differences are around 20 % (increasing in the case of Y-joint and decreasing in the case of K-joint). A significant increase of IPB moments of around 140 % is observed for the X- and the Y- joint. In case of the K-joint, IPB moments are reduced by 20 %. The DELs of the axial forces in the X- and the Y-joint are 60 % higher in the jacket model with three completely damaged joints compared to the undamaged jacket model. On the other hand, the DEL of the axial force is reduced around 10% in the K-joint. Loads redistributions and changes of DELs due to joints losses highly affect further trends of fatigue damage accumulations. These effects are underlined in the next sections.

Trends of cumulative fatigue damages

The load redistribution due to joint failure influences the trend of further fatigue damage accumulations within the remaining jacket components. These changes are presented for the three selected joints (K-, Y- and X-joint) when the first, the second, and the third failure in the jacket occur. The sequential OWT simulations and the fatigue analyses are performed for uni-directional wind/wave loads acting on the conservatively positioned four-legged jacket (commonly used in the design of the OWTs jacket structures), see Fig. 14.

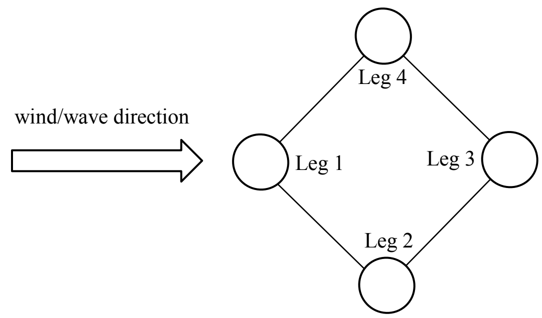


Fig. 14 Uni-directional loads acting on the conservatively positioned OWT jacket structure

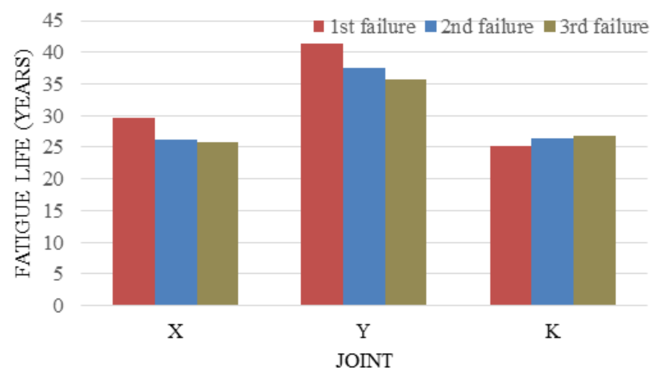


Fig. 15 Fatigue life in selected X-, Y- and K-joint when the first, the second and the third failure in the jacket occur

Figure 15 illustrates the estimated fatigue lives in selected joints with the occurrence of the first, the second and the third failure in the jacket. It is obvious that increase of DELs due to modified loading paths (see section Damage Equivalent Loads) induces a reduction of the fatigue life of X- and Y-joint. When the first failure in the jacket occurs the estimated fatigue lives are reduced by around four and six years for X- and Y-joint respectively compared to the moment when the third joint in the jacket fails. Also, these changes are more pronounced after the first than after the second failure. On the other hand, slightly reduced DELs in K-joint induce one year extension of the fatigue life.
The effect of wind/wave directionality on the fatigue life of the jacket structure is investigated in this study as well. A multi-directional load application considers six representative sectors with co-directional wind/wave loads (see section Co-directional versus Multidirectional approach). A respective probability of occurrence of load cases for each

of six directions is accounted for. Sequential OWT simulations and fatigue analyses show the same order of fatigue failures in the jacket if the multi-directionality is taken into account.

Fatigue lives of selected K-, Y-, and X-joints, estimated when the third failure in the jacket occurs, are compared for two cases: uni-directional load application with the conservative jacket position and multi-directional load application. Differences in estimated fatigue lives for these approaches are illustrated in Fig. 16.

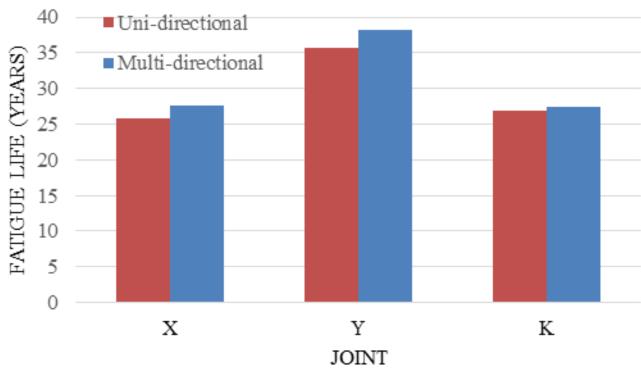


Fig. 16 Fatigue life in selected X-, Y-, and K-joint when the first, the second and the third failure in the jacket occur

The consideration of multi-directionality leads to slightly longer fatigue lives. In the case of the X- and the Y-joint, the fatigue life is approximately two years longer, while for the K-joint this difference is around 0.5 years. Generally, the fatigue life of jacket structure can be estimated sufficiently accurate using the uni-directional approach (load application on the conservatively positioned jacket).

Fatigue life extension

For the investigated jacket, the K3-joints are the most critical in terms of fatigue. The highest fatigue damage accumulations around the circumference of the joint are observed at the brace side (see section Structural Redundancy). These positions are identified as potential spots for the crack initiation.

In the state of practice, fatigue life of the jacket structure is determined by the first fatigue failure. Accounting for the redundant capacity of the jacket structure can extend the fatigue life without significant losses of its structural properties (see section Eigenfrequencies).

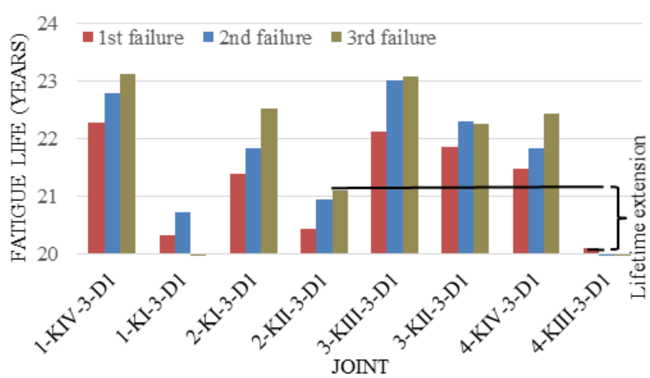


Fig. 17 Fatigue life in selected X-, Y- and K-joint when the first, the second and the third failure in the jacket occur

The benefit of structural redundancy in the fatigue life of the jacket structure is shown in Fig. 17. Following the approach which is generally used in the design process, the fatigue life of the investigated jacket is 20.10 years (equal to the first failure in the jacket, joint 4-KIII-3-D1). It is obvious that the fatigue life can be extended if further cumulative fatigue damages and fatigue failures are allowed in the structure. When the second failure occurs (joint 1-KI-3-D1), fatigue life of the structure is 20.74 years. The estimated fatigue life when the third failure occurs (joint 2-KII-3-D1) is extended for one year (fatigue life 21.10 years).

The sequential OWT simulations and the fatigue analyses are important aspects in the implementation of the structural redundancy concept. It is obvious in the Fig. 17 that load redistributions positively affect fatigue life in eight K3-joints which are the most critical ones in terms of fatigue. In almost all of them, the fatigue life is extended for one year. Without consideration of modified loading paths in the structure, the fatigue life would be 20.45 years when the third joint fails (only the first failure is considered in this case).

Estimated fatigue lives and cumulative fatigue damages (for all K3-joints), when the first, the second, and the third failure sequentially occur, are given in Table 2. The failures (and failed joints as well) are marked in red.

Table 2. Estimated fatigue lives for K3-joints when the first, the second, and the third fatigue failure in the jacket occur

Joint	Fatigue life (years)/Cumulative fatigue damage D		
	1st failure	2nd failure	3rd failure
1-KIV-3-D1	22.28 / D=0.90	22.80 / D=0.91	23.12 / D=0.92
1-KI-3-D1	20.33 / D=0.98	20.74 / D=1.00	-
1-KIV-3-D2	27.23 / D=0.74	25.93 / D=0.80	25.23 / D=0.84
1-KI-3-D2	25.56 / D=0.79	24.98 / D=0.83	23.30 / D=0.91
2-KI-3-D1	21.39 / D=0.94	21.85 / D=0.95	22.52 / D=0.95
2-KII-3-D1	20.45 / D=0.97	20.95 / D=0.98	21.10 / D=1.00
2-KI-3-D2	27.30 / D=0.74	24.69 / D=0.84	23.62 / D=0.89
2-KII-3-D2	28.53 / D=0.70	27.65 / D=0.75	25.86 / D=0.82
3-KIII-3-D1	22.12 / D=0.90	23.01 / D=0.90	23.09 / D=0.91
3-KII-3-D1	21.87 / D=0.92	22.31 / D=0.93	22.27 / D=0.96
3-KIII-3-D2	26.06 / D=0.77	26.94 / D=0.77	27.04 / D=0.78
3-KII-3-D2	28.18 / D=0.71	26.25 / D=0.79	24.76 / D=0.85
4-KIV-3-D1	21.49 / D=0.94	21.83 / D=0.95	22.44 / D=0.95
4-KIII-3-D1	20.10 / D=1.00	-	-
4-KIV-3-D2	27.60 / D=0.73	27.29 / D=0.76	26.08 / D=0.81
4-KIII-3-D2	26.88 / D=0.75	27.65 / D=0.75	28.06 / D=0.77

The introduction of the structural redundancy demonstrates the possibility for the extension of the fatigue life in a jacket structure. Further verifications are related to the ultimate limit state (ULS) and the control of the structural capacity to withstand extreme loads when the failures occur.

CONCLUSIONS AND OUTLOOK

In this study, the influence of structural redundancy on the fatigue life of a real-life OWT jacket structure is investigated. Moreover, uni-directional and multi-directional wind/wave actions are taken into account. The investigations show that the effects of misalignment between wind and wave directions can be neglected in the fatigue analysis of a jacket structure. The multi-directional analysis of a four-legged jacket can be well represented considering six co-directional wind/wave sectors. Modal analyses show that failure in braces lead to a slight reduction of eigenfrequencies in higher eigenmodes. On the other hand, the failure in a jacket leg reduces eigenfrequencies of the first global bending eigenmodes. Failures in joints lead to a redistribution of loads. The significant increase of in-plane and out-of-plane bending moments is the most conspicuous result for the X-joints. Fatigue analyses show that the highest cumulative damage due to fatigue occurs at the brace side of the K3-joints (at the crown). The multi-directional analysis approach induces slightly higher estimated fatigue life of the jacket compared to the uni-directional analysis approach. The implementation of the structural redundancy in fatigue analysis of an OWT jacket structure leads to an extension of the designed lifetime.

The work presented in this paper will be continued in several ways. Ultimate limit state analysis will be performed in order to determine residual capacity and to check the ability of the jacket structure to withstand extreme loads when the fatigue failure occurs. Residual strength capacity of the damaged and the intact jacket structure can be used to quantify its level of redundancy. This can be a basis to assess the inspection plan to be used. Additionally, the other DLCs will be checked in a case that the load bearing capacity of the jacket structure is reduced. The main goal is to implement the fracture mechanics based fatigue analysis. By doing this, the crack propagation phase and the effects of load sequences on the performance can be accounted for.

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