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On Fatigue Damage Assessment for Offshore Support Structures with Tubular Joints

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Abstract

The hot spot stress approach is commonly used for fatigue lifetime estimation of tubular joints. The standard approach consists of the linear superposition of stress components from axial, in-plane, and out of plane action, leading to 8 hot spot stresses equally divided along the circumference of each tubular joint. The fatigue lifetime for a joint is calculated by accumulating the fatigue damage over several load cases. The fatigue damage used per load case is commonly the maximum fatigue damage out of the 8 hot spots. In this study, another approach has been evaluated. Fatigue lifetime is estimated by accumulation of fatigue damage over load cases for each hot spot individually, instead of taking the maximum out of the 8 hot spots. The proposed approach is compared with the commonly used approach using a generic lattice type support structure for offshore wind turbines. In addition, the number of hot spots along the circumference of the joint is increased to 32 points in order to study the influence on the fatigue lifetime estimation. Results show a difference in the fatigue lifetime estimation for individual joints up to 26% when using the proposed approach for estimating the fatigue lifetime. Furthermore, it is shown that the consideration of 32 points along the circumference of tubular joints lead to more precise fatigue damage. Differences up to 11% were detected.

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Keywords: Offshore wind energy; jacket support structure; hot spot stress; fatigue analysis; fatigue lifetime estimation

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1. Introduction

Lattice type support structures, such as jackets, are a preferred solution for offshore wind turbines (OWTs) in a water depth up to 50m. Designing this type of support structures is a non-trivial task, since they are highly dynamic and tightly coupled to the wind turbine [1]. Thus, the structure is exposed to a large number of quasi-periodic excitations caused by the rotor. In addition, the support structure experiences excitation from oscillating waves resulting in additional quasi-periodic motions. These excitations are usually less dominant compared to the effects by the wind turbine due to the typically small diameters of the support structure, but have to be considered in the structural analysis of an OWT. Experiencing this type of loading during the lifetime, a lattice type support structure is usually prone to fatigue damage. Critical locations for fatigue damage are the joints, where two or more elements of the structure are welded together. The design lifetime of a lattice type support structure is, therefore, determined by the fatigue lifetime of joints of the structure.

Fatigue life for welded joints is typically analyzed using the hot spot stress (HSS) approach. In this approach the fatigue lifetime is estimated comparing the intensity of the stresses at critical points with the endurance limit given by S-N curves. The critical points are spots along the circumferences of the tubular joint with high stress concentration, where a fatigue crack is expected to occur. These spots are referred to as hot spots and HSSs can be measured with strain gauges or determined with finite element analysis or empirical formulas when used for design evaluation [2]. For design purposes, the finite element analysis is the more accurate method to determine HSS, thereby estimating the fatigue lifetime. However, performing a detailed finite element analysis for each joint of the support structure and applying it in the design process where several iterations and a numerous amount of simulations are needed is computationally expensive and time consuming. Hence, guidelines for the fatigue design of offshore steel structures recommend deriving HSSs with empirical formulas using nominal stresses and stress concentration factors (SCFs) [3]. According to guidelines, the HSSs should be evaluated at 8 spots equally located around the circumference of the joint, including the crown and saddle points. It is common practice to calculate fatigue damage for different load situations (load cases) at each of these 8 hot spots and to take the highest fatigue damage value out of the 8 hot spots in order to determine the fatigue damage per load case. The fatigue lifetime of a joint is estimated by accumulating these maximal fatigue damage values per load case based on its probability of occurrence. This implies that different hot spots can contribute to the fatigue lifetime of a joint.

This study investigates a different approach. Here, the fatigue lifetime is estimated for each hot spot individually instead of taking the highest fatigue damage value per load case. The lowest fatigue lifetime out of these hot spots determines the fatigue life for each joint. In addition, HSS and fatigue damage is calculated for intermediate points between the 8 hot spots recommended by guidelines, since these might be higher. The main objectives of this study is to assess the differences between (1) the proposed approaches regarding fatigue lifetime estimation for tubular joints and (2) the extended use of hot spots around the circumference of the joints compared to the standard approach recommended by guidelines.

2. Estimating fatigue lifetime for lattice type support structures

2.1. Fatigue analysis

The fatigue lifetime of a lattice type support structure may be predicted based on the fatigue damage analysis for structural details such as joints. Fatigue damage per joint is calculated using HSSs as briefly described in the previous section. In a structure, the term hot spot refers to critical points where the stresses are typically higher than in other parts. For welded tubular joints, these points are positioned along the circumference of the joint, and fatigue calculations should be performed on each side of the weld (see Fig. 1). Fig. 2 shows the positions of the 8 hot spots for fatigue analysis recommended by guidelines [3] including the position of crown and saddle.

HSSs are reference stresses calculated at hot spots using empirically based equations. Inputs for these equations are nominal stresses and SCFs [3-4].

$$\sigma_{HSS} = SCF \cdot \sigma_{nominal} \tag{1}$$

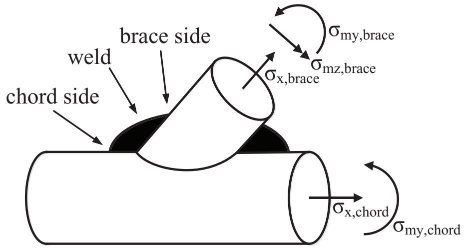

Fig. 1. Stresses and weld at tubular joint

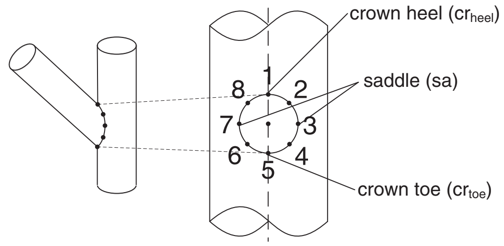

Fig. 2. Positions of hot spots in tubular joints

Nominal stresses are typically obtained from time domain analyses of the structure, while SCFs are dimensionless parameters which can be derived from parametric equations. These equations can be found in guidelines and depend on joint type, geometrical properties, and the loading conditions [3, 5].

The equations for HSSs at distinct points around the circumference of the joint are given by guidelines and are composed of a superposition of nominal stresses from axial load, in-plane, and out-of-plane bending. The HSSs around the circumference of the joint are derived by a linear interpolation of the stresses from axial loading at crown and saddle and a sinusoidal variation of the bending stresses resulting from in-plane and out-of-plane bending (see equations 3.3.1 in [3]). These equations were used in combination with nominal stresses from brace-side ($\sigma_{x,brace}$, $\sigma_{my,brace}$, and $\sigma_{mz,brace}$ in Fig. 1) and their corresponding SCFs in order to calculate HSSs on the brace side of the weld. The equations for HSSs on the chord side additionally account for the effect of local loading on the chord (σ_{chord}), which is calculated as the algebraic sum of the axial and bending stress of the chord [6-7].

$$\sigma_{chord} = \sigma_{x,chord} + \sigma_{my,chord} \tag{2}$$

where $\sigma_{x,chord}$ is the stress due to axial loading and $\sigma_{my,chord}$ is the stress due to in-plane bending at the chord (see Fig. 1). It has been shown that the chord loading mainly affects the crown position [7]. The equations for HSS are, therefore, superimposed with a sinusoidal variation of the chord nominal stress as shown in Equation 3.

$$\begin{aligned}
\sigma_1 &= SCF_{CC}\sigma_{chord} + SCF_{AC}\sigma_{x,brace} + SCF_{MIP}\sigma_{my,brace} \\
\sigma_2 &= \tfrac{1}{2}\sqrt{2}SCF_{CC}\sigma_{chord} + \tfrac{1}{2}\left(SCF_{AC} + SCF_{AS}\right)\sigma_{x,brace} + \tfrac{1}{2}\sqrt{2}SCF_{MIP}\sigma_{my,brace} - \tfrac{1}{2}\sqrt{2}SCF_{MOP}\sigma_{mz,brace} \\
\sigma_3 &= SCF_{AS}\sigma_{x,brace} - SCF_{MOP}\sigma_{mz,brace} \\
\sigma_4 &= -\tfrac{1}{2}\sqrt{2}SCF_{CC}\sigma_{chord} + \tfrac{1}{2}\left(SCF_{AC} + SCF_{AS}\right)\sigma_{x,brace} - \tfrac{1}{2}\sqrt{2}SCF_{MIP}\sigma_{my,brace} - \tfrac{1}{2}\sqrt{2}SCF_{MOP}\sigma_{mz,brace} \\
\sigma_5 &= -SCF_{CC}\sigma_{chord} + SCF_{AC}\sigma_{x,brace} - SCF_{MIP}\sigma_{my,brace} \\
\sigma_6 &= -\tfrac{1}{2}\sqrt{2}SCF_{CC}\sigma_{chord} + \tfrac{1}{2}\left(SCF_{AC} + SCF_{AS}\right)\sigma_{x,brace} - \tfrac{1}{2}\sqrt{2}SCF_{MIP}\sigma_{my,brace} + \tfrac{1}{2}\sqrt{2}SCF_{MOP}\sigma_{mz,brace} \\
\sigma_7 &= SCF_{AS}\sigma_{x,brace} + SCF_{MOP}\sigma_{mz,brace} \\
\sigma_8 &= \tfrac{1}{2}\sqrt{2}SCF_{CC}\sigma_{chord} + \tfrac{1}{2}\left(SCF_{AC} + SCF_{AS}\right)\sigma_{x,brace} + \tfrac{1}{2}\sqrt{2}SCF_{MIP}\sigma_{my,brace} + \tfrac{1}{2}\sqrt{2}SCF_{MOP}\sigma_{mz,brace}
\end{aligned} \tag{3}$$

SCFs for the nominal stresses from the brace (i.e. SCFs for axial load, SCF_{AC}, in-plane, SCF_{MIP} and out-of-plane bending, SCF_{MOP}) are given by guidelines and are taken from Efthymiou [3, 6, 8]. The SCF for the additional chord nominal stress at crown position (SCF_{CC}) is determined by considering the joint as a cruciform joint, with the brace being attachments welded to the surface of the chord. This classification and the thickness of the brace define a certain detail category for the welded joint (see Appendix A in [3]). The SCF corresponding to this detail category is listed in the guideline as well (see Table 2-1 in [3]). All braces of the tubular joints that are considered in this study have a thickness smaller than 25 mm. Thus, they belong to category E with a SCF_{CC} of 1.13.

For HSSs from brace as well as chord side the rainflow counting algorithm is applied to extract the number of cycles per stress ranges [3, 9]. These stress ranges are used in combination with corresponding S-N curves in order to determine the allowed number of cycles before failure and to calculate the fatigue resistance [3-4]. The Palmgren-

Miner rule is invoked to derive the fatigue damage, thereby assuming a linear fatigue damage accumulation [3]. The accumulated fatigue damage is calculated by

$$D = \sum_{j=1}^{k} \frac{n_j}{N_j} \tag{4}$$

where D is the accumulated fatigue damage, n_j the number of stress cycles in stress range j, N_j the number of cycles to failure at stress range j, and k the number of stress ranges. Two different approaches are used in order to obtain the accumulated fatigue damage per joint:

- The **standard approach**, which is recommended by guidelines and evaluates HSSs at 8 spots around the circumference of the joint [3] (see Fig. 2).
- An **extended approach**, where HSSs are evaluated at in total 32 spots around the circumference of the joint. HSSs at these spots are derived in exactly the same manner as it was done for the standard approach with 8 spots. HSSs between crown and saddle position are a linear interpolation of the stress due to axial loading at crown and saddle and a sinusoidal variation of bending stress resulting from in-plane and out-of-plane bending, and chord nominal stress (for HSSs at chord side).

2.2. Fatigue lifetime estimation

The fatigue analysis has to be performed for different load and design situations referred to as load cases. Load cases can differ in system state of the turbine (e.g. operational or idling) as well as environmental conditions (e.g. wind speeds or wave characteristics) and are always with respect to the specific site under consideration. Finally, fatigue lifetime of offshore structures is estimated by accumulating the fatigue damage per joint and load case with the probability of occurrence of this load case over the lifetime of the structure. Two methods will be investigated within this study (see also Fig. 3):

- The commonly used method referred to as **common method (CM)**, where for each load case the highest fatigue damage out of the hot spots around the circumference of the joint is used to determine the fatigue damage per joint and load case. Accumulating these damage values over the lifetime of the structure leads to an estimation of the fatigue lifetime for each joint. The position of the highest fatigue damage may differ from one load case to another. This means that the estimated fatigue lifetime may be based on fatigue damage of HSSs from different positions for each load case.
- An **alternative method (AM)**, where the fatigue lifetime is predicted for each hot spot individually by accumulating fatigue damage per load case and hot spot over the lifetime of the structure. Finally, the lowest lifetime out of the hots spots around the circumference of the joint determines the fatigue lifetime of the joint.

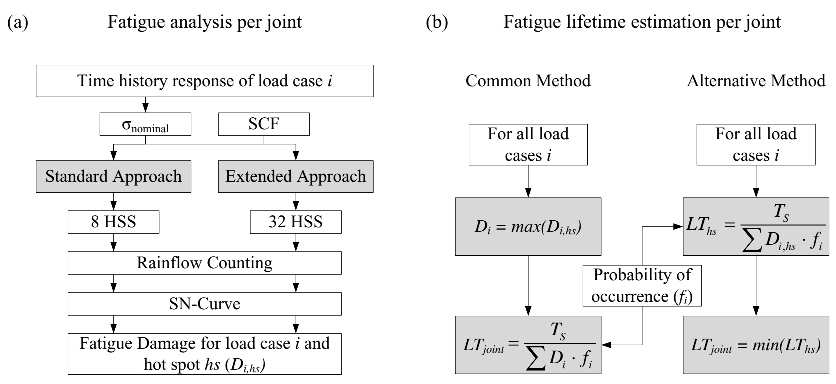

Fig. 3. (a) Standard and extended approach to predict fatigue damage (D) in tubular joints, (b) common and alternative method to estimate fatigue lifetime (LT) as defined in this paper. Index i describes a load case with a simulated length of T_S.

3. Method

An empirical study was carried out in order to investigate differences between the two different approaches and the two methods presented in the previous section. A generic model of an OWT supported by a lattice type sub-structure as described in Section 3.1 is used for this purpose and load analyses were performed for fatigue load cases as recommended by guidelines (see Section 3.2). Differences were assessed by means of ratios presented in Section 3.3.

3.1. The offshore wind turbine model

The study was performed with a generic OWT composed of the UpWind reference jacket used within Phase I of the Offshore Code Comparison Collaboration Continuation (OC4) project [10] and the NREL 5-MW reference wind turbine atop [11]. The UpWind reference jacket is a four-legged jacket support structure with four X-braces per side and a length of 70.15 m. It is located in a water depth of 50 m and clamped rigid at mudline. A detailed description is available in Vorpahl et al [12]. The jacket structure includes three different types of tubular joints (see Fig. 4):

- **Y-joints** are used for the connections between X-braces and legs of the structure. They are located at the bottom of the structure (close to mudline) and the top of the structure. In total 16 Y-joints are used within the jacket structure subject to this study.
- **K-joints** connect X-braces and legs as well. However, they differ from Y-joints, since they connect two X-braces, one below and one above the location of the joint. The structure includes 24 K-joints which are all located at the middle of the leg, surrounded by Y-joints at the bottom and top of the structure.
- **X-joints** are joints located in the middle of X-braces. Due to four X-braces per side, the structure consists of in total 16 X-joints.

Fig. 4 Model of the OWT.

3.2. Load analysis

The numerical model of the OWT was implemented in the state-of-the-art wind turbine simulation software FEDEM Windpower (Version R7.1.4, Fedem Technology AS, Trondheim). FEDEM Windpower is a flexible multibody simulation tool allowing the simulation of an OWT under combined hydrodynamic and aerodynamic loading in the time domain. It has been verified in the OC4 project [10]. Environmental conditions, such as marine growth and water depth, were taken from the UpWind Design Basis [13].

Load simulations were performed for operational and idling load cases following current design standards [4, 14]. These are the most relevant load cases for fatigue analysis and cover the design load cases 1.2 and 6.4. Properties for the wind model and sea states as well as the probability of occurrence per load case were adopted from the UpWind Design Basis [13].

In total 15 load cases with duration of 3600 seconds each were performed. Time series for axial forces, in-plane, and out-of-plane bending moments at joints were extracted from the simulations and nominal stresses were calculated using the dimensions of the structures. A design fatigue lifetime of 20 years is assumed for all calculations [4].

3.3. Evaluation

Two different ratios were used to assess differences between the two different approaches and the two methods. For the comparison between the common approach and extended approach for fatigue analysis, the position of the spot with the highest fatigue damage per joint and load case was recorded. This leads to 240 fatigue damage values for Y-joints and X-joints (15 load cases and 16 joints per type), and 360 fatigue damage values for the 24 K-joints, respectively. For each position around the circumference of the joint an incidence ratio was calculated. This ratio determines the relation between the occurrence of the highest value for fatigue damage at a certain position and the total number of fatigue damage values. It is calculated for a position HS by

$$Incidence\ Rate_{HS} = \frac{occurrence\ of\ highest\ fatigue\ damage\ at\ HS}{total\ number\ of\ fatigue\ damage\ values} \tag{5}$$

The incidence ratio can be seen as a probability that the highest fatigue damage will occur at the position in question. Differences in the estimation methods (command and alternative method) for fatigue lifetime of a joint are assessed by calculating the ratio between the methods with LT_{CM} being the lifetime estimated with the common method and LT_{AM} being the lifetime estimated with the alternative method..

4. Results and discussion

This section presents a comparison between the standard approach and the extended approach for fatigue analysis (see Section 4.1) as well as a comparison between the common method and alternative method to estimate fatigue lifetime (see Section 4.2). Differences only occur due to the applied approach or method itself, since all calculations are carried out using the same time series as an input. These time series for axial forces and bending moments are obtained from the load simulation as described in the previous section.

4.1. Extended approach for fatigue analysis

The incidence ratio plotted against the hot spot positions is shown for the three different joint types in Fig. 5. The figure shows the results for the extended approach using 32 hot spots and combines both sides of the weld (brace and chord side). Apart from three load cases where the highest damage for an X-joint was detected at the brace side, all of the values plotted in Fig. 5 are related to the chord side of the weld. Each dot within the figure represents the position of a hot spot around the circumference of the joint. Crown (cr) and saddle (sa), which are the hot spots also used for the standard approach with 8 positions and the four intermediate positions, are marked on the horizontal axis. It can be seen that the highest fatigue damage does not always occur at these hot spots. In fact, for Y-joints some of the highest fatigue damage values are detected for positions close to, but never exactly at the crown toe. A similar trend can be observed for hot spots next to the same position (crown toe) in K-joints. The position with the occurrence of the highest fatigue damage per load case is somewhat equally divided for crown and saddle points for K-joints, while the highest fatigue damage values for the Y-joints occurred mainly at the crown heel (incidence ratio = 0.34). More significant is the position with the highest fatigue damage for X-joints. Here, the highest fatigue damage occurs almost solely at the saddle points (incidence ratio = 0.79). The equations for HSSs at the saddle points are dominated by the out-of-plane bending moment (see Equation 3). In fact, earlier studies detected the bending moment at X-joints as a design driver for X-braces of jacket support structures and identified local vibrations as a reason for it [1, 15-17].

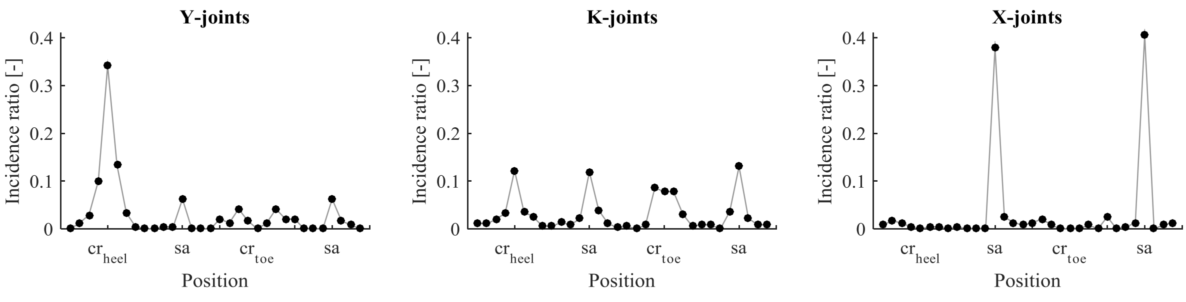

Fig. 5. Incidence ratio of highest fatigue damage per joint type plotted against the position around the circumference of the joint. Position of the crown heel (cr_{heel}), saddles (sa), and crown toe (cr_{toe}) are marked on the horizontal axis.

Table 1 lists the number of joints with higher fatigue damage using the extended approach in comparison to the standard approach with 8 hot spots. In addition, the maximal increase in fatigue damage is shown.

The table confirms the observation from Fig. 5. Differences for X-joints, where the highest fatigue damage mainly occurs for hot spots that are also part of the standard approach with 8 hot spots, are less significant compared to Y-joints and K-joints, where the highest fatigue damage values are more divided around the circumference of the joint. However, more important than the position of the highest fatigue damage is the impact on the fatigue lifetime estimation, which is shown and discussed in the following section.

Table 1. Comparison between standard and extended approach for fatigue analysis.

Joint type	Joints with higher fatigue damage	Maximal increase in fatigue damage
Y-joint	38%	5%
K-joint	83%	11%
X-joint	6%	1%

4.2. *Differences in fatigue lifetime estimation*

The standard approach with 8 HSS was used for the fatigue lifetime estimation. The ratio between the common method and alternative method is plotted in Fig. 6 against the joint location within the jacket structure for all three different types of tubular joints.

Differences for Y-joints are marginal (<1%), while differences in the predicted lifetime for X-joint up to 2.5% occurred for joints close to the mudline. The largest differences between the two methods investigated in this study occur for K-joints and mainly around the mean sea level (MSL). Differences in the estimated fatigue lifetime up to 26% are detected (see Fig. 6).

Predicting fatigue lifetime by means of the common method and the alternative method lead to the same result when the highest fatigue damage per load case always occurs at the same spot. In this case it makes no difference whether the fatigue lifetime is calculated for each spot individually before taking the minimum or the highest fatigue damage per load case is considered in order to estimate the fatigue lifetime. Results presented in the previous section showed that the spot with the highest fatigue damage may differ within the joint (see Fig. 5). This already indicates that differences between the common method and the alternative method will appear as well.

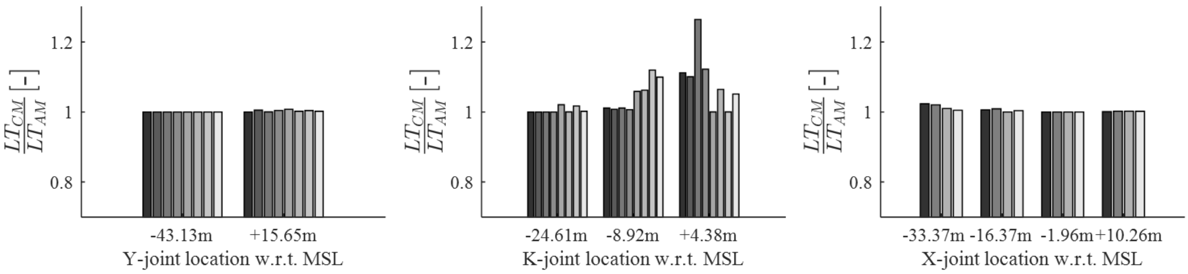

Fig. 6. Ratio for estimated fatigue lifetime (LT) between common method (CM) and alternative method (AM) for different types of joints. The joints are grouped per height with respect to (w.r.t.) mean sea level (MSL).

5. Conclusion and future work

The empirical study presented in this paper compares two ways to analyse the fatigue damage for tubular joints using the HSS approach. Furthermore, an alternative method in estimating the fatigue lifetime of tubular joints, has been evaluated. It is shown that using an extended number of hot spots around the circumference of a joints leads to a more precise fatigue analysis, since the highest fatigue damage may occur for intermediate positions between the 8 hot spots of the standard approach. Moreover, predicting the fatigue lifetime of a tubular joint based on the individual fatigue lifetime of hot spots leads to a difference in estimated fatigue lifetime up to 26% for K-joints located around the MSL. This result suggests that using the alternative method proposed in this paper can lead to less conservative designed structures, which will ideally result in a cost reduction for the design. However, this conclusion has to be drawn carefully, since (1) the study is of an empirical kind and does only consider one particular support structure design and (2) an improved design of particular joints does not necessarily have to result in a lifetime extension of the support structure (e.g. when the joint in question is not a design driving element). Moreover, only a limited set of design load cases was performed and used for the fatigue analysis.

Future studies should, therefore, look at a larger set of load cases and further increase the number of hot spots around the circumference of the joint. Ideally, the incidence ratio will converge for a larger number of hot spots. Furthermore, the design driving elements should be detected within the structure in order to make a more accurate assumption regarding the cost saving potential of the alternative method to estimate fatigue lifetime.

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