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# Advanced representation of tubular joints in jacket models for offshore wind turbine simulation

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## Abstract

Jacket substructures for offshore wind turbines show strong potentials in water depths from 25 up to 70m. A review of state-of-practice and enhanced state-of-the-art modeling of offshore wind turbine jackets is conducted regarding detailed joint properties. The state-of-the-art approach takes advantage of an accurate description of the local joint behavior by use of superelements, enabling more accurate load simulations. Studies conducted in the past highlighted both strong benefits as well as shortcomings of this approach, whereas the drawbacks were mainly related to the size of superelements and the application of local wave loading. This work develops a smart sizing for detailed joint models taking into account the loading and location of the jacket joints. A concept of local wave loading is presented as well. Advice on recommendable parameters is given and enables an optimized superelement application for jacket substructures. As an example the potential for fatigue load reduction is shown using the NREL offshore 5-MW baseline wind turbine and the OC4 reference jacket. The predicted fatigue lifetime was increased by about 15%.

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*Keywords*: jackets, tubular joints, substructuring, offshore wind turbine simulation

## 1. Introduction

Offshore wind farms are increasingly realized in water depths beyond 30m, where lattice support structures are an interesting option to withstand the severe environmental actions. In particular jackets appear to be a highly competitive substructure type for offshore wind turbines (OWT) with a wide range of applicability, from approximately 25 to 70 meters water depth. Since fatigue loads are a typical design

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driver of welded jacket joints, more precise fatigue load predictions can become a powerful leverage factor for optimized designs. It is recognized practice that fatigue load predictions are derived simulation based. The accuracy of predicted loads depends on the level of detail of the structural model and the simulation approach describing the entire turbine-structure behavior. When flexibility of jacket joints is taken into account, stresses at joints decrease in comparison to simpler and simultaneously more conservative models and fatigue loads at design driving jacket joints are reduced. The ultimate goal are lighter jacket structures or improved fatigue performance. Both aspects, less material consumption as well as additional fatigue life time lead to lower cost of support structures for offshore wind turbines in deeper waters.

## 2. Review of state-of-practice and state-of-the-art of jacket models

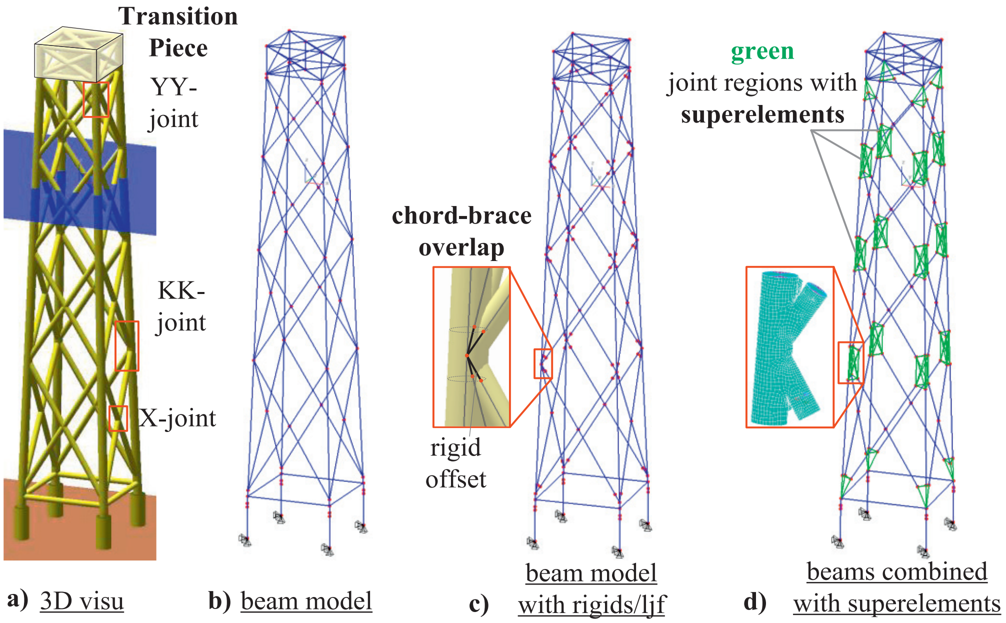


Figure 1: a) 3D Visualization of the OC4 jacket [11] and simulation models with different levels of detail from b) a simple to d) a sophisticated approach taking local joint flexibilities (ljf) into account

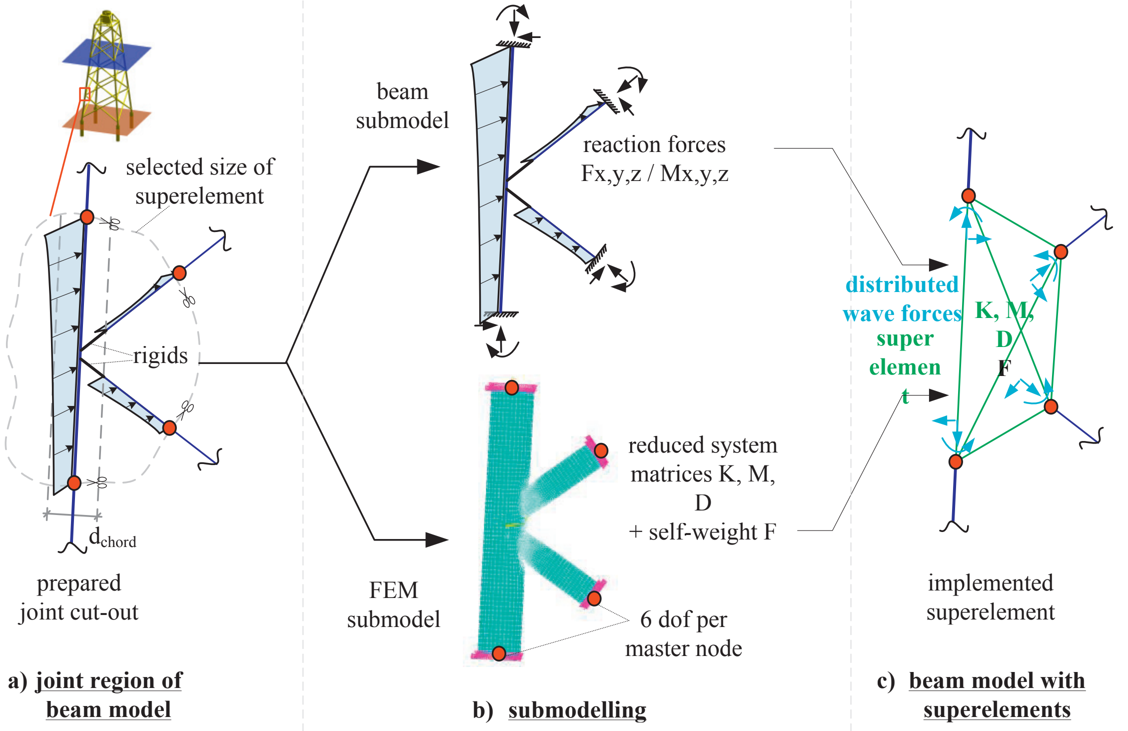
Though the overall dynamic system representing an OWT is complex, in particular for those with branched substructures as Böker showed [1], certain simplifications have to be made in order to keep the numerical model computationally affordable. This is the decisive reason why complex, branched support structures are typically modeled by beam elements (cf. Figure 1b/) and more complex model strategies, such as partially detailed FEM models, are not encountered in practice yet. Nevertheless, merely the consideration of shear deflections using Timoshenko beams instead of Bernoulli beams can affect the distributions of loads through multi-member structures significantly [2]. This has been found for a Tripod structure and might be of smaller importance for jackets (cf. section 3.3). To summarize, Bernoulli beam models are commonly applied to model jackets for OWT (Figure 1c/). Global structural properties are captured well as long as the structural geometry can be approximated by slender beam elements, but the representation of local effects may become difficult. This is state-of-practice for jacket models in OWT load simulation using fully coupled models in aero-hydro-servo-elastic tools (here Flex5 - Poseidon was used, cf. [1]).

Suggestions on model improvements for offshore platforms are, e.g., given by Billington et al. [3]. But sophisticated approaches have been rarely used for the design of oil and gas platforms, apart from a few reappraisals of aged platforms. Since simpler approaches typically lead to conservative results, this is acceptable for the oil and gas industry. Regarding the demand for OWT optimization the potential of advanced strategies should be exploited. The effect of local flexibilities at welded tubular connections was investigated by Schaumann [4] based on prior findings of Buitrago [5]. Buitrago established formulae to determine the flexibility of joints separately under axial, in-plane bending and out-of-plane bending loading. The beam sections from the joint centre to each brace intersection at the chord surface are modeled as rigid offset (Figure 1c/).The flexibilities are implemented by springs with constant stiffness attached at the ends of the rigid elements, but the loading characteristic of multi-member joints changes over time due to the dynamic loading of OWT. This complex loading would require a superposition of flexibilities due to each single member load in order to determine resulting local joint flexibilities for each simulation timestep. Alternatively, Schaumann applied a substructuring technique [6], in this paper denoted as superelement approach, taking into account these cross influencing effects using one superelement for each joint (Figure 1d/). The joint regions of the beam model are thereby refined by coupling detailed FEM models of the joints with a beam model prepared accordingly. The detailed models are implemented as statically condensed superelements according to Guyan [7] (alternative procedures like Craig-Bampton substructuring are not considered in this paper, but may become important in the future). As a result, significant advantages in fatigue loading due to decreased joint stresses as well as shortcomings due to the application of local wave loading superelement regions were concluded [6] (Figure 1d/, highlighted in green). In addition, compromises on sizing of superelements were necessary. Afterwards Vorpahl [8] continued working on the superelement approach, implemented it in an OWT design tool for the first time, including a procedure enabling a global wave load application from superelement regions on the remaining beams. Moreover, discussions on proper wave application in overlap regions of multi-member joints (detail of Figure 1c/) were conducted in the scope of the international OC3 project - phase III and general advice on wave load and buoyancy calculation was given [2], [9]. Song et al. recently published results of detailed studies conducted on wave loads of intersecting members [10]. Besides, general advice can be found in guidelines relevant for OWT.

Consequently, different levels of beam model detailing are applied in practice. Figure 1 shows an overview about the models alluded to. Simple beam models can be improved to state-of-the-art models by joint detailing the overlap regions in terms of wave loading and stiffness behavior. The work presented in this paper resolves the two drawbacks of the superelement approach for geometric conditions representative for jackets. Section 3 deals with the question of proper superelement size for jackets. Suggestions to compute the local joint loading in the superelement regions are made in section 4.

## 3. Advanced application of superelements by joint specific modeling for jackets

Before joint specific aspects are addressed, the common implementation procedure and criteria for sizing of superelements shall be considered, establishing a proper background for an advanced application on jacket models. The implementation of superelements can be divided into three stages; the preparation of joint regions and cut-out sizing, the submodelling of the joint, and eventually the implementation of superelements and associated loads into the prepared beam model. Figure 2 gives an overview of the entire procedure, and shows the prepared joint region with wave loading (Figure 2a/). Starting point is a beam model with rigid members for the overlapping brace sections at joints. Wave loading on rigid elements (rigids) is neglected, since the chord wave loads yet cover wave loads within the chord volume (Figure 2a/, $d_{chord}$). The size of the cut-out region is marked by so-called master nodes representing the interface between the beam model and the joint submodel (red dots in Figure 2). At this point, the decision on superelement size is already made, but is actually affected by structural properties of the submodels, which will be discussed in detail to develop reasonable sizing criteria.



**a) joint region of beam model**

**b) submodelling**

**c) beam model with superelements**

Figure 2: Steps of superelement implemention in beam models (dof - degrees of freedom)

### 3.1. Wave load distribution on master nodes

Vorpahl [8] suggests a quasi-static distribution of wave loading from joint regions to the global beam model when using local beam submodels (Figure 2b/, beam submodel). This approach shall be adopted and expanded in section 4 for local wave loading.

### 3.2. Mass distribution on master nodes

The stiffness condensation of the FEM submodel to master nodes following Guyan [7] is accurate, but the distribution of mass terms to master nodes is approximate and proportional to the joint stiffness at master nodes. In case of superelements of jacket joints the masses are concentrated at each end of the joint member stubs. An additional master node in the joint centre would bypass these mass concentrations at member ends, but introduce unrealistic artificial stiffness in the joint centre and distort the joint stiffness significantly (section 3.3). Differences between the approximate mass concentrations and real joint masses can be neglected if the dynamics of the full beam model with chosen superelement size are affected in a minor way. Contrary to the behavior of compact jacket legs, slender brace members of jackets are prone to local vibrations and might be affected by approximate master node masses. A simple example, generally representative for current jacket designs, shows the sensitivity of a slender tubular steel brace (Figure 3).

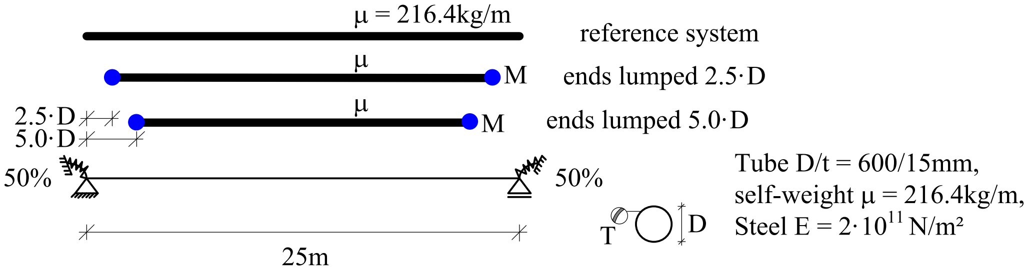


Figure 3: Sensitivity of a slender jacket brace to mass concentration effects at beam ends

The self-weight at both ends of a slender tubular brace with 25m span, 50% clamped at the supports, is concentrated to a lump mass located 2.5 or 5.0 times the diameter away from the supports. The resulting masses are doubled in a second configuration. The unlumped system represents the reference configuration. Table 1 shows the comparison of the reference and the lumped systems. A length of submodel brace stubs of 2.5D results in negligible deviations to the reference system, even if the mass is doubled, which shall represent a gross failure of distributed superelement masses. The 5.0D system with doubled lump masses yields the maximum deviation of -3.9%. This difference might be also acceptable, considering the significant spreading of local brace frequencies due to added hydrodynamic and marine growth masses [1]. These added masses can be considered simply by increasing the material density of braces and chords proportionally on each member. Comparisons of the full OC4 reference jacket model [11] with the NREL 5MW baseline OWT using different sized superelements showed similar deviations.

Table 1: Sensitivity of a slender brace to mass concentration effects with lumped self-weight n times the diameter at both beam ends

| location of masses | lumped mass | Eigenfrequency $f_0$ | Deviation |
|---|---|---|---|
| reference system | 0.0kg | 4.15Hz | - |
| 2.5D from beam ends | 324.6kg = 2.5D · self-weight | 4.14Hz | -0.2% |
| doubled lump mass | 649.2kg = 2.5D·2·self-weight | 4.13Hz | -0.5% |
| 5.0D from beam ends | 649.2kg = 5.0D · self-weight | 4.08Hz | -1.7% |
| doubled lump mass | 1298.4kg = 5.0D·2·self-weight | 3.99Hz | -3.9% |

### 3.3. Stiffness of superelements

The interface between the master nodes and the end nodes of shell elements used in the superelement acts like a rigid plate (Figure 4a/). This leads to compatible strain conditions at the master node in the beam model and the superelement model. But the ovalization at chord-brace connections is artificially obstructed (Figure 4b/) when the chord lengths are smaller than 5 times the chord diameter $d_{chord}$ [4] (normalized chord lengths to chord diameter ratio typically denoted as $\alpha$). This was concluded by Schaumann [4] for a T- or Y-joint under axial, in-plane-bending (ipb) and out-of-plane-bending loading (opb). Additionally, a ratio $\gamma$, denoting the chord diameter to chord wall thicknesses ratio, from 25 to 50 was assumed. The loading and geometry of jacket joints differs significantly from these assumptions made to derive the general criterion of $\alpha = 5$. The joint types frequently in use for OWT jacket designs are connected by YY-, KK- and X-joints (Figure 1a/). The loading of these jacket joints can be distinguished between unbalanced (YY-joints) and balanced loading (X-joints and the axial loaded KK-joints, Figure 4b/).

Efthymiou used FEM models of joints, fairly similar to superelement models, to derive the equations for stress concentration factors (SCFs) at chord-brace welds [12]. The boundary constraints at chord ends affected the resulting SCFs as well. This deviation was corrected with so-called short chord correction factors, which Efthymiou developed for T- or Y-joints and K-joints under opb. But corrections are not necessary for K-joints under balanced axial and ipb loads, even if the chord stubs length is merely two times the diameter. Both load configurations are predominating the loading of KK-joints of OWT jackets. This indicates a potential for shrinking the superelement size of KK-joints, accepting a minor overestimation of the opb stiffness. This paper supplements studies on the influence of α and γ on ljf by a K-joint under balanced axial loading (green curve, Figure 5) and a shell slenderness of γ = 10 (red curves), representing a compact cross section typical for current jacket designs (cf. OC4 jacket [11]).

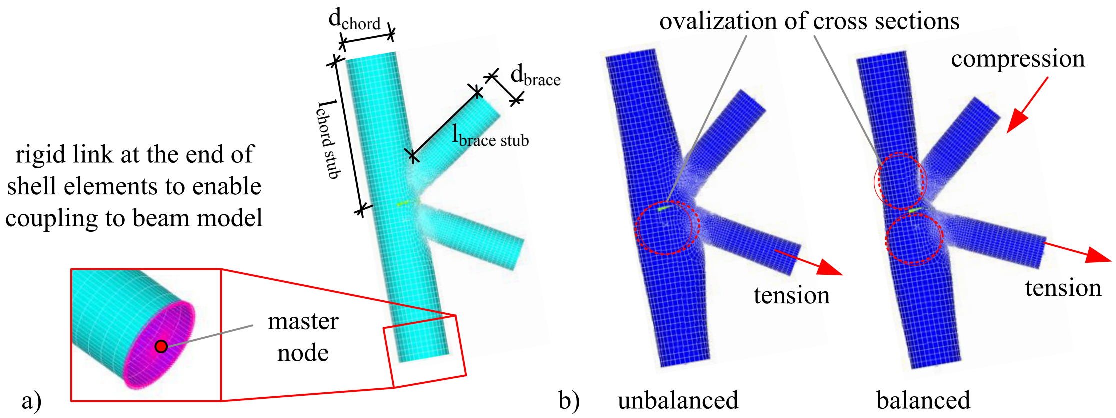


Figure 4: Rigid link interfaces at ends of superelement shell models and K-node under balanced and unbalanced loading

Results are summarized in Figure 5. The respective local joint deflections are normalized to the converged results, derived with chord lengths long enough to avoid artificial joint stiffening. Assuming a chord wall slenderness around γ = 10 and α = 2, the mean failure (induced by artificial stiffening due to boundary constraints) decreases to a level comparable to a shell slenderness between 25 to 50 at α = 5, where on average more than 95% of the joint flexibility is captured by the superelement.

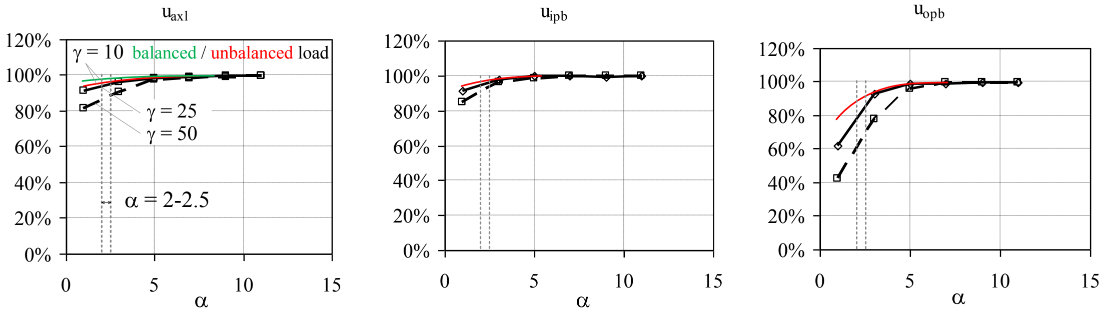


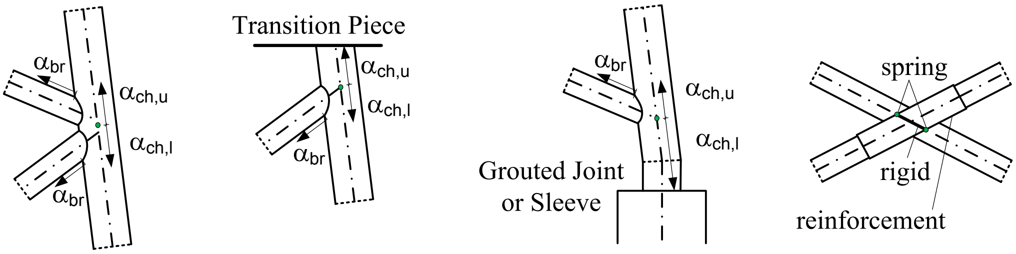
Figure 5: Normalized axial, ipb and opb deflection a tubular T- or K joint, supplemented study based on [14], depending on α (chord stub length to chord diameter ratio) and γ (chord diameter to chord wall thickness ratio)

The main failure occurs under opb load, since the opb stiffness is overestimated. In OWT jackets opb mainly occurs due to local wave loads on jacket faces and out-of-plane vibrations of bracings, while wind loads are mainly causing axial and ipb loads and govern the fatigue loading of jackets for OWT [13]. Taking into account compact jacket legs with factors γ from 10 to 15 and a predominantly balanced axial loading, a significant reduction of α = 5 regarding superelements for use in jacket structures is feasible. In particular the superelement size for balanced loaded KK-joints can be reduced. In addition, the numerical analysis showed a negligible influence of the brace stub length on the superelement stiffness, when the modeled length is about 2.5 times the brace diameter (graphs are not included). Moreover, the stiffness behavior of superelements captures shear deflections as well, since shell models naturally consider shear distorsions. Major parts of possible shear deflections are thus taken into account, even if Bernoulli beam elements are in use, since the joints are exposed to the highest shear forces.

### 3.4. Joint specific recommendations

Based on the structural behavior of superelements described in previous subsections, joint specific recommendations for KK-, YY- and X-joints have been derived (Figure 6). The special case of a YY/T-joint, solely in use in the OC4 OWT jacket model, but currently not in practice, is not addressed in detail. Anyhow, modeling should be inspired by the mean values given for YY- and KK-joints in Table 2.

KK-joints of OWT jackets are typically located between the bottom of the upper jacket bay and the bay top of the mudline bay. The upper and lower joints are usually YY-joints. KK-joints are predominantly axial loaded when the differences in brace-chord angles of each attached brace are small. Since the slope of jacket legs is commonly steep and brace angles are selected as constant, the differences of chord brace-angels can be considered as small. Assuming these conditions and compact jacket legs with factors $\gamma$ from 10 to 15, a dimensionless chord ratio for the upper and lower chord length of $\alpha_{ch,u} = \alpha_{ch,l} = 2$ is reasonable. This should be increased to 3 in case of a slender chord wall thickness $\gamma = 25$. Brace stub lengths shall be determined with $\alpha_{br} = 2.5$ and respective brace diameter, measured from the crown heel (Figure 6a/, $\alpha_{br}$).



a) KK-joint b) YY-joint top c) YY-joint bottom d) X-joint

Figure 6: Overview of investigated joint types and related dimensionless geometric parameters

YY-joints are generally, unlike KK-joints, unbalanced loaded, which requires a larger length of chord stubs. The upper and lower YY-joint (Figure 6b/ and c/) represent special cases due to the connection between the upper chord part to the transition piece or the lower chord part to the foundation pile. For this chord stub the rigid link at the master node is a realistic approximation, because ovalization of the upper chord is obstructed due to the welded or grouted connection to the transition piece. The chord stubs shall be modeled with a minimum length of the distance to the transition piece or the sleeve and $\alpha_{ch} = 3$ to 3.5. In contrast, the other chord stub, pointing to the adjacent KK-joint, should be modeled with a dimensionless length of $\alpha_{ch} = 3$ to 3.5. Braces shall be modeled similar to KK-joints.

Table 2: Overview of recommended parameters for modelling the joints shown in Figure 6 (distTP – distance to the lower edge of transition piece, distPile – distance to the upper edge of pile)

| dimensionless stub length | KK-joint | | YY-joint (top/bottom) | | XX-joint |
|---|---|---|---|---|---|
| | $\gamma = 10$ | $\gamma = 25$ | $\gamma = 10$ | $\gamma = 25$ | |
| $\alpha_{ch,u}$ | 2 | 3 | distTP / 3.0 | distTP / 3.5 | superelement not necessarily beneficial |
| $\alpha_{ch,l}$ | 2 | 3 | 3.0 / distPile | 3.5 / distPile | |
| $\alpha_{br}$ | 2.5 | 2.5 | 2.5 | 2.5 | |

X-joints do not necessarily require a superelement implementation due to the fact of negligible local cross influences between members of X-braces. This is owed to the constructional detail with one brace passing through the joint, usually with additional reinforcement (Figure 6d/), and the other brace welded on the surface of the passing brace. If possible ljf shall be considered, spring elements can be implemented for the govering configuration of loading [5], which is mainly balanced axial loading and balanced opb. This implementation accommodates a simple wave load application in X-joint regions as well.

## 4. Simplified hot-spot stress extrapolation approach

The cut-out of joint regions leads to a beam model, which does not provide the hot-spot relevant member forces at chord-brace welds (Figure 7a/). Hence, an extrapolation is suggested to enable the calculation of those fatigue relevant forces. The widely used concept of structural stresses should be maintained. A solution can be established based on the following assumptions:

- cut-out regions in the beam model are comparably small
- dynamic amplification of loads in the area of super elements can thus be neglected
- the course of wave-loading and shape of the full model is also known in cut-out regions
- the wave-load contribution of distributed master node loads to member end shear load is known

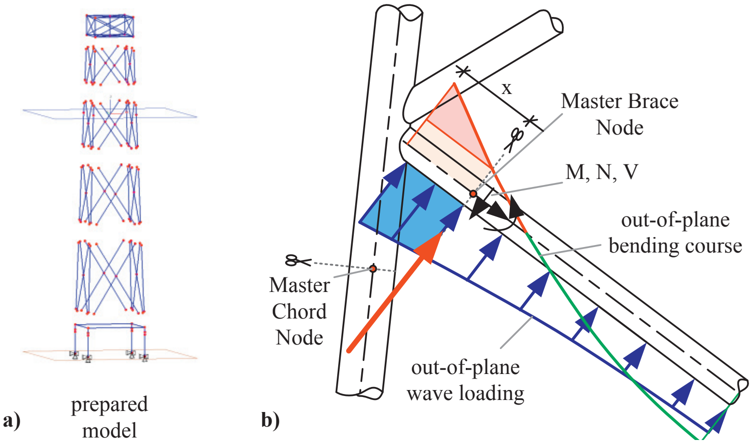


Figure 7: Extrapolation of member forces schematically shown for the chord-brace intersection in cut-out regions

The raised requirements imply smartly sized superelements (section 3). Furthermore, the computation and storage of additional parameters in the cut-out region during the simulation is necessary to provide the input for the following simulation based extrapolation concept. By analogy with the quasi-static wave load distribution to master nodes, the optimized superelement size allows for a quasi-static extrapolation of hot-spot stress relevant member forces, because dynamic amplifications are already included in member forces obtained at master nodes. By knowledge of the distance x between the chord-brace intersection and master node and the wave load at x/2 and x, the member forces can be extrapolated sufficiently into the superelement region, either by use of numerical integration of the wave load or semi-analytically (e.g. assuming a cubic course of wave loads between master node and the chord-brace intersection). It should thereby be taken into account that the shear force at the master nodes has to be reduced by the master node wave force (Figure 7, red force). Otherwise the local wave force contribution will be considered twice. A similar procedure enables the extrapolation of chord forces to the centre of the joint.

## 5. Impact on dynamics and fatigue performance of the OC4 jacket

Finally, the superelement approach is applied in the described enhanced manner to the OC4 jacket with the NREL 5MW reference wind turbine, showing the improvements in fatigue performance of essential jacket joints. The simple support model of OC4, clamping piles at mudline level, is adopted. The enhanced beam model shown in Figure 1c) is used as reference structure. The mudbraces have been kept as beam elements in the superelement jacket, maintaining the lowest superelement as a YY-joint. This type is typically in use for these joint locations in practice, instead of the YY/T-joint used for the OC4 jacket. A comparison of the superelement model for both joint types showed that this idealization leads to conservative fatigue results (not shown). Thereby, the results shown in this study can be transferred to the type of jacket designs commonly used in current offshore wind projects.

A modal analysis was performed and a reduced set of fatigue load cases according to the IEC 61400-3:2009 standard was simulated (design load case 1.2). The fatigue damage was calculated based on design S-N curves given in Germanischer Lloyds' Guideline for the Certification of Offshore Wind Turbines, Edition 2005. The overall dynamic behavior is slightly changed. The first two global dynamic bending modes are virtually unaffected, but higher global mode shapes with contribution of local brace modes as well as first local brace modes are changed in a magnitude of 3% for higher global and 7% for predominantly local modes. A decisive change occurs in terms of distribution of axial forces and bending moments in structural members, most important to the in-plane and out-of-plane bending stiffnesses of chord-brace connections. A superelement takes into account the relatively high axial stiffnesses of KK-joints in case of balanced loading or of YY-joints with obstructed ovalisation (see Figure 6b/ and c/). This leads to reduced amplitudes of stress cycles, primarily induced by reduced bending moments due to decreasing framework bending. In contrast, a slight increase of axial forces in the jacket legs can be observed. This is caused by an increase of bipod-like bearing behavior of both jacket legs in each jacket face.

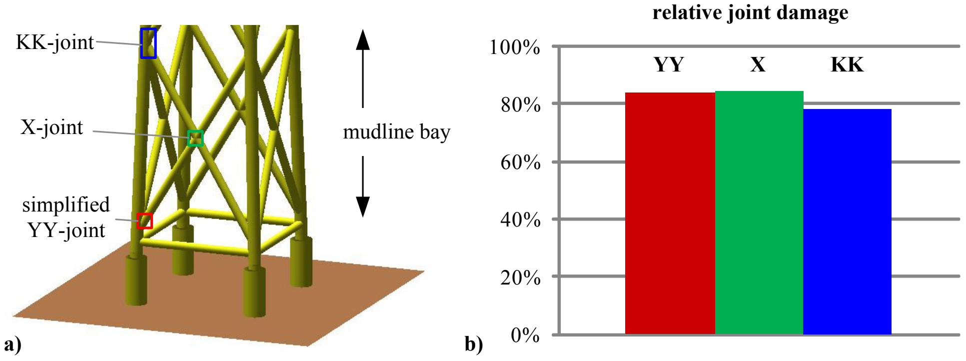


Figure 8: Maximum ratio of predicted joint damage between superelement model and beam model

Figure 8a) shows the position of the considered joint locations which are subject of the fatigue damage comparison presented in Figure 8b). The advanced representation of joints by use of superelements leads to an overall fatigue load reduction of 16% at the lower YY-joint, of 15% at the lower X-joint and of 22% at the upper KK-joint of the mudline bay, which indicates a significant increase of fatigue performance. Comparing these reductions to results of prior studies concerning the research platform FINO with slightly more slender $\gamma$ ratios, variable jacket leg slope, smaller brace angles and governing wave loading [6], a smaller influence on fatigue loads is observed for this OWT jacket. Nevertheless, in this example the application of the superelement approach enables an overall fatigue life increase by approximately 15%.

## 6. Summary and Outlook

An optimized implementation of superelements in jackets for OWT simulation was presented. Recommendations were given which resolve known shortcomings of this approach. As a result, tubular joints can be implemented as super elements in integrated OWT simulations models in an optimized manner, and one can take full advantage of this approach. The positive impact on fatigue loads is exemplarily presented, and life time extensions by 16% were feasible in this study. Studies should be conducted using different types of jacket models, including detailed soil properties, in order to verify the positive impact of this enhanced superelement approach. Additionally, one could validate this approach by real world measurement data to confirm these simulation results, e.g. using data from alpha ventus. It could be also desirable to develop a simplified engineering approach for enhanced beam models which allows engineers in practice to cover the major part of the presented reduction of predicted fatigue loads.

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