Performance-based Design and the Load-deformation of Welded Tubular Connections in Offshore Jacket Structures

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ABSTRACT
Tubular connections in offshore jacket structures are currently designed using strength-based criteria, intended to ensure that the connection behaves elastically during environmental conditions at design recurrence periods. In contrast, performance-based design requires consideration of environmental conditions at recurrence periods well beyond those of current practice, when structural damage is expected and connections are likely to behave inelastically. Performance-based design considers both the occurrence and consequence of structural damage caused by extreme conditions and could improve the performance of offshore structures. This paper assesses the post-elastic behavior and ductility of common connection details for offshore jacket structures based on a survey of experiments and empirical joint models and on nonlinear finite element analyses. The assessment includes common connection details under tension, compression, and bending. The prediction of the inelastic load-deformation response, based on MSL and API, two empirical joint models in the structural analysis program, USFOS, is compared to experiments. As an illustrative example to demonstrate the performance assessment capabilities of this approach, a pushover analysis is carried out for an offshore jacket structure supporting a wind turbine and subjected to extreme wind and wave loading.

1 INTRODUCTION
The Atlantic coast of the U.S. is a natural location for offshore wind energy development because of the abundant wind resource and proximity to major population centers. The most common support structure of fixed-bottom offshore wind
turbines is a monopile, support structure which can be economically installed in water depths up to 30m. In order to also install OWTs in deeper water where winds can be stronger and steadier, a stronger substructure like a jacket is needed instead of a monopile (Bhattacharya et al. 2013). A jacket structure is a steel space frame composed of steel circular hollow sections. Offshore structures located near the U.S. Atlantic coast are exposed to risk of damage from hurricane-induced storm surge, wind and waves (Wang et al., 2005; Sparks 2003). According to the post-hurricane assessment reports of offshore jacket platforms (Energo Engineering Inc. 2005, 2007, 2010), many tubular connection failures have been observed (e.g. cracks at welds, cracks in the chord or brace, punch-through or pull out of brace, buckled members, etc.). In offshore engineering, tubular joints are typically classified as T-, Y-, K- or X-joints according to the geometric orientation of the chords and braces. In most cases, such joints are prepared with complete joint penetration welds connecting the contoured ends of the brace member to the continuous chord member without stiffeners or grout.

The design of the tubular joint connections in offshore jacket structures relies on strength-based criteria. Several empirical and semi-empirical equations have been published to predict ultimate strength for different types of tubular joints considering a wide range of failure modes. For example, Yura et al. (Yura et al., 1980) proposed capacity equations for four types of tubular joint geometries based on a series of 137 tests. Kurobane et al. (Kurobane et al., 1984; Kurobane 1998) and Paul et al. (Paul et al., 1994) studied unstiffened TT and KK joint geometries under symmetric and anti-symmetric brace axial forces and proposed strength equations based on these tests. These experimental studies have provided important insight into the design of jacket connections, however, there are still some challenges in applying these equations to design, such as mismatch between the geometry of the test specimens and the designed connection and the effects of moment-axial force interaction in the member forces that are typically not covered in these studies. Moreover, the above approaches do not provide information on the load-deformation behavior of the connection, an important limitation especially in the context of performance-based design which requires an understanding of the post-elastic behavior of the connections.

Motivated by these limitations, the MSL joint industry project has developed the MSL joint formulation (Dier and Hellan, 2002) which provides fully nonlinear formulae for the load-deformation response of K-, X-, T- and Y-tubular joints subjected to axial force, in-plane bending and out-of-plane bending, including interaction between the chord and brace loads. In addition, design guidance for tubular joints in API RP2A (Pecknold et al., 2007) also provides alternative ultimate strength and load-deformation formulations for the design of simple tubular connections based on both the MSL databases and on extended data from finite elements, to increase the range of applicable joint types. Both formulations for joint deformation and strength are implemented in the commercial analysis program USFOS (Holmaas et al., 2006).

To encourage performance-based design of offshore structures, this paper focuses on the post-elastic behavior and ductility of welded tubular connections for jacket structures, and predictions from the API and MSL formulations are compared with experimental data from other researchers. After this comparison, the performance of a hypothetical offshore jacket supporting a wind turbine is evaluated using a static pushover procedure on an analysis model including joint behavior modeled based on the API formulation.
2 MODELING OF WELDED TUBULAR CONNECTIONS

2.1 Joint Modeling in USFOS

In many cases, it is conventional to model connections in jacket structures as rigid (Figure 1a). An alternative joint model, which provides the potential for assessing joint damage (Figure 1b), includes extra elements to represent the behavior of the brace-chord connection. For this alternative model, the ductility of the joint is modeled by selecting parameters for the extra elements according to the selected joint capacity formulation. The nonlinear analyses performed in this study are conducted with the structural analysis program USFOS (Holmaas et al., 2006). In this program, nonlinear joint behavior is modeled with nonlinear spring elements between the brace member and the chord member, as shown in the right of Figure 1b. MSL and API capacity formulae have been implemented in USFOS and either can be selected to model the behavior of the joints. MSL involves three different load-deformation curves, one based on the first crack, one on the mean and one on the characteristic capacity. For consistency of the ultimate capacity results for the MSL and API formulations, the ultimate capacity considered in this study is the load when the first crack appears. More detail of MSL and API formulations can be found in the following references (API, 2005; MSL Engineering Limited, 1999).

2.2 Validation of Applicability of Practical Joint Capacity Formulas

The purpose of this section is to compare the MSL and API joint models with experimental data, in terms of both strength and load-deformation. The first comparison consider four X-joint specimens tested by Noordhoek et al. (Noordhoek et al., 1996). The four specimens include two compression specimens, X355c which is made from grade 355 steel and X500c which is made from grade 500 steel, and two tension specimens, X355t which is made from grade 355 steel and X500t which is made from grade 500 steel. The nominal dimensions of the braces and chords are (370x10 mm) and (450x10 mm). Details of the experimental setup can be found in the report published by Noordhoek et al. (Noordhoek et al., 1996). Table 1 compares the ultimate strength from the tests with the ultimate strength calculated by the MSL and API formulations in USFOS. The ultimate strength results from MSL and API formulations match the experimental data closely.
Table 1 Comparison of ultimate strengths for X-joint specimens (unit: kN).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Load pattern</th>
<th>Test</th>
<th>MSL</th>
<th>API</th>
</tr>
</thead>
<tbody>
<tr>
<td>X355c</td>
<td>Compression</td>
<td>661</td>
<td>688</td>
<td>695</td>
</tr>
<tr>
<td>X500c</td>
<td>Compression</td>
<td>814</td>
<td>855</td>
<td>863</td>
</tr>
<tr>
<td>X355t</td>
<td>Tension</td>
<td>727</td>
<td>701</td>
<td>735</td>
</tr>
<tr>
<td>X500t</td>
<td>Tension</td>
<td>802</td>
<td>796</td>
<td>890</td>
</tr>
</tbody>
</table>

Figure 2 compares the load-deformation curves from the MSL and API model with the test data. As shown in Figure 2, the MSL and API formulations predict the deformation accurately for the X355t specimen in tension, while they did not predict the deformation as accurately for the X355c in compression. This is because the failure mode in the test for Specimen X355c involves an indentation of about 50% of the chord diameter, a deformation effect not included by either the MSL or API formulation.

The second comparison between experiments and models is based on tests by Yura et al. (Yura et al., 1978). These tests included T- Y- and K-joint specimens, and five of these are selected here and listed in Table 2. They include one T-joint subjected to out-of-plane bending, one Y-joint subjected to out-of-plane bending, and three K-joints (one subjected to axial force, one subjected to in-plane bending and one subjected to out-of-plane bending). The Y-joint has 30° brace, and the K-joints have a 30° brace and a 90° brace.

Table 2 Specimen identification from the report (Yura et al., 1978).

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Loading</th>
<th>Type of Specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>G_1</td>
<td>Out-of-plane bending</td>
<td>T</td>
</tr>
<tr>
<td>E_1</td>
<td>Out-of-plane bending</td>
<td>Y</td>
</tr>
<tr>
<td>C1_2</td>
<td>Axial (90° brace - compression; 30° brace - tension)</td>
<td>K</td>
</tr>
<tr>
<td>A2_X</td>
<td>In-plane bending</td>
<td>K</td>
</tr>
<tr>
<td>C2_1</td>
<td>Out-of-plane bending</td>
<td>K</td>
</tr>
</tbody>
</table>
Figure 3 compares the ultimate strength and load-deformation behavior for the MSL and API formulations compared to test data for T-joint specimen G_1 and Y-joint specimen E_1. Both of these specimens are loaded by out-of-plane bending. In both tests, brace yielding occurred first at the hot spot on the compression side of the brace. After yielding, a crack occurred in the chord at the tension side hot spot. For both tests, the ultimate capacity and deformation prediction of MSL is better than that of API, but both MSL and API predict strength and ductility that is significantly less than the tests.

Figure 4 compares the ultimate strength and load-deformation behavior obtained from MSL and API formulations compared to test data for K-joint specimen C1_2 with 30-degree brace under tension and with 90-degree brace under compression. In both cases, the ultimate strengths of the formulations are similar to the tests. For the tension brace, the results of MSL and API agree with the testing curve. However, for the compression brace, the agreement in terms of load-deformation was worse, similar to the comparison shown in Figure 2 for specimen X355c.
Figures 5 and 6 compare the load-deformation curves obtained from the MSL and API formulations and the testing data for the K-joint specimens under in-plane bending and out-of-plane bending for Specimens A2_X and C2_1 and for both the 30 and 90-degree braces. For both specimens, the results of the MSL and API formulations agree reasonably with the test data for the 30-degree brace, especially so for in-plane bending, while for the 90-degree brace, the formulations have significant differences in stiffness and ductility, for the case of specimen A2_X ultimate strength.

3 EXAMPLE STUDY

Next, this paper illustrates the use of a pushover analysis to assess the structural performance of the NREL 5-MW wind turbine supported by a jacket structure installed in 50 m water depth and subject to extreme environmental loadings. The structure is modeled in USFOS with joint behavior modeled using the API formulation. The jacket design is taken from the UpWind project (Vorpahl et al., 2011). As shown in Figure 7, the rotor-nacelle-assembly (RNA) has a total mass of 350,000 kg and the jacket consists of four legs with four levels of X-braces and cross braces. A concrete deck with a mass of 666,000 kg and plan dimensions of 4.0×9.6×9.6 m is positioned on top
of the jacket and serves as a support platform for the tower of the turbine. See Wei et al. (Wei et al., 2014) for further details on this structure. In this pushover analysis, several simplifying assumptions regarding the structural configuration and loading conditions are made to allow primary attention to be paid to the post-elastic behavior of the jacket. First, the wind and wave loads are assumed to be co-directional and approaching the jacket broadside, second, regular wave kinematics are adopted, and, third, the jacket legs are fully fixed at the mud line without soil-pile interaction.

Figure 7 Schematics of the jacket supported OWT: (a) dimensions of reference jacket support structure; (b) 3D view of jacket components.

In order to evaluate the nonlinear performance of the example structure under extreme conditions, a stress-resultant plasticity formulation with plastic hinges combined with the API joint formulation are specified in the model to simulate the nonlinear behavior of both the members and joints. The model is then analyzed with a static nonlinear pushover analysis to estimate damage and assess the performance of the jacket. Wind loads on the turbine and tower and wave loads on the jacket and transition piece are calculated and combined to create the lateral loading in the pushover analysis. The considered extreme environmental conditions are an extreme wave height of 30 m and an extreme wind speed (1min; 10m) of 50 m/s. The analysis was controlled by jacket top displacement until the structure reaches its ultimate state.

Figure 8 shows the pushover curve of the example structure loaded by an extreme wind and wave load pattern. Figure 9 illustrates the locations of damage that occurred due to the extreme environmental loads. The figure shows that the most severe plastic damage occurred in the bottom section of the jacket legs. Additional damage predicted by the models include brace yielding and full plastic hinging of braces in the third and fourth X frame level of the jacket (counted from top to bottom) and buckling of two braces in the second X frame level. None of the joints were predicted to reach their ultimate strength, however yielding was predicted at the joints.
CONCLUSION
The current study focuses on the post-elastic behavior and ductility of commonly used connections for offshore jacket structures. The study compares strength and load-deformation behavior predicted from the MSL and API joint formulations, implemented using the finite element analysis program USFOS, with selected experimental results from studies by Noordhoek et al. (Noordhoek et al., 1996) and Yura et al. (Yura et al., 1978) on X-, T-, Y- and K-joints. An example static pushover analysis with plastic hinges and joint capacity formulation based on API was implemented in USFOS for a
jacket structure supporting an offshore wind turbine and subjected to wind and wave loading. The study summarized above supports two conclusions:

(1) The MSL and API joint formulation provides a reasonable approach to estimate the ultimate strength of X-, T-, Y- and K- joint connections, however the predictions for the load-deformation of such connections is less accurate, especially for connections subjected to compression.

(2) The MSL and API joint formulations combined with plastic hinge models can be used to estimate the performance of a jacket structure subjected to extreme loads, considering damage due to member yielding, member plastic hinging, member buckling and joint damage.

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REFERENCES


Energo Engineering Inc. (2005), Assessment of Fixed Offshore Platform Performance in Hurricanes Andrew, Lili and Ivan.


Energo Engineering Inc. (2010), Assessment of Damage and Failure Mechanisms for Offshore Structures and Pipelines In Hurricanes Gustav And Ike.


MSL Engineering Limited. (1999), JIP - Assessment Criteria, Reliability and Reserve Strength of Tubular Joints (Phase II).


