NONLINEAR RESPONSES OF K-BRACED STRUCTURES WITH REINFORCEMENT OF CRITICAL JOINTS THROUGH INTERNAL GROUTING

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This paper compares the overall performance of K-braced offshore structures with critical K-joints that require reinforcement to ensure adequate ultimate and associated residual strength. The nonlinear behaviour of the frame is first analyzed for critical joints with reduced dimensions, due to corrosion, of chord and braces. The associated joint characteristics for the grouted joints are then represented appropriately for nonlinear frame analysis. The pushover analysis utilizes the USFOS (Ultimate Strength for Framed Offshore Structures) software, which provides the MSL joint formulation for as-welded tubular joints with appropriate geometric parameters. As reported in the author's Ph.D. thesis, a joint formulation for fully grouted K-joints is proposed and represented in the USFOS software. This study investigates three framed structures on the strengthening effect of grouting critical joints: (1) 2D BOMEL K-frame, (2) 2D K-frame designed in NUS, and (3) 3D K-braced jacket platform. The results show that the phenomenological representation of joint characteristics provides a practical approach to incorporate nonlinear joint behaviour in framed analysis. It is also found that grouting under-strength as-welded critical joints can be very effective for strengthening of selected offshore structures.

Keywords: K-joint, grouted joint, joint representation, pushover analysis, ultimate strength, residual strength.

1 Introduction

The potential of a large demand for strengthening tubular structures in offshore engineering has been noticed, as some ageing platforms have remained in operation longer than their original estimations due to the forces of the global oil and gas market. The tubular connections or tubular joints, at which the member ends meet the associated chords, may be the weakest part of the jacket structure and various methods to strengthen or repair these joints have been investigated. Injecting cement grout into the chord has been recognized as one of the most efficient and cost-effective methods for offshore applications (Tebbett *et al.*, 1979; Lalani *et al.*, 1985). The strengthened jacket platform needs to be reassessed to evaluate the overall response of the tubular structure after grouting. The reassessment requires advanced nonlinear frame analyses which should include an accurate representation of the local joint responses under overloading conditions.

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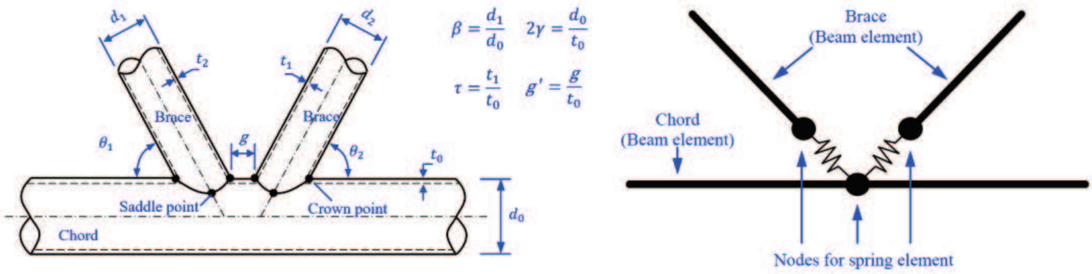
An accurate evaluation of the nonlinear frame response requires correct representations of the local member and joint behavior. The research of past decades has formed a strong basis to capture accurately the nonlinear member behavior (Hellan, 1997; Skallerud & Amdahl, 2002). As regard the joint behavior, the rigid joint hypothesis may cause severe deviation in the prediction of the frame failure mechanism due to the underestimation of the deformation and over-estimation of the ultimate capacity for the critical joint. Therefore, the rigid joint assumption in the conventional frame analysis becomes no longer applicable in the evaluation of the nonlinear frame response. In order to capture the nonlinear joint characteristics in pushover analysis, previous researchers have proposed different approaches to represent the nonlinear joint behavior in the frame response. One of the main approaches is to use a sub-structure with detailed FE mesh to model the critical joint (Bouwkamp *et al.*, 1980; Romeijn *et al.*, 1991; Pan *et al.*, 2002; Chakrabarti *et al.*, 2005; Pan *et al.*, 2006; Mirtaheri *et al.*, 2009). But this approach is infeasible for a practical offshore platform consisting of multiple joints, which requires considerable modelling efforts and computational resources. Alternatively, the joint behavior can be phenomenologically represented through nonlinear joint spring elements. Various types of joint formulations have been proposed to characterize the spring elements, and the most common ones include the MSL formulation (Dier & Hellan, 2002), Choo's formulation (Choo *et al.*, 2005), and Qian's formulation (Qian *et al.*, 2013a, 2013b). However, these joint formulations are only applicable to as-welded tubular joints, and cannot be applied to fully grouted joints.

Zhang (2019) has proposed an accurate joint formulation for fully grouted X- and K- joints to represent the elastic-plastic joint behavior. Based on the characteristics of typical load-deformation curves, the formulation is developed as a function of the geometric parameters of α and β. To predict the ultimate strength of grouted joints due to ductile fracture, Zhang (2019) establishes the relationship between the equivalent strain to fracture and stress triaxiality based on the fracture locus approach (Bao, 2003; Bao & Wierzbicki, 2004; Bao, 2005) for the material of tubular joints. The regression analyses propose two equations to predict the ultimate strength for fully grouted X- and K- joints respectively. The accuracy of the proposed equations is proved through comparison with available database on the test results of grouted joints. This paper first introduces the MSL joint formulation for as-welded tubular joints and the proposed joint formulation for fully grouted tubular joints. Then by implementing these two joint formulations into the nonlinear frame pushover analysis software USFOS, this study investigates the strengthening effect of grouting critical joints on three framed structures: (1) 2D BOMEL K-frame, (2) 2D K-frame designed in NUS, and (3) 3D K-braced jacket platform.

2 Joint formulation

As discussed above, the joint behavior can be phenomenologically represented through nonlinear joint spring elements. Figure 1(a) displays the configuration of a typical tubular K-joint with the denotation of the geometric parameters, including the brace to chord diameter ratio β, the chord diameter to chord thickness ratio 2γ, the brace to chord thickness ratio τ, and the gap ratio g'. Figure 1(b) shows the phenomenological representation of local joint behavior through nonlinear spring elements. In this study, the MSL joint formulation is used to represent as-welded tubular joints in pushover analysis; while the proposed joint formulation in Zhang (2019) is used to represent fully grouted tubular joints. The details of these two formulations are introduced in this section.



(a) Configuration of typical K-joint (b) Nonlinear joint spring element

Figure 1: Phenomenological representation of nonlinear behavior of tubular joints

2.1 *MSL joint formulation for as-welded joints*

The Joint Industry Project led by a UK company has developed the MSL joint formulation to simulate the nonlinear behavior of tubular joints under combined axial, in-plane and out-of-plane moment loadings, across the full range of the load-deformation response (Dier & Lalani, 1995; Dier & Hellan, 2002). The uncoupled $P-\delta$ and $M-\theta$ responses are first represented by a single continuous function as shown in Eq. (1) and Eq. (2). The coefficients of A_1, A_2, B_1 and B_2 related to the joint geometric parameters and loading conditions are determined from a database of tubular joint tests. The coupling for combined brace loading conditions is then addressed by adapting the plasticity theory algorithms. The mathematics of the plasticity algorithm comprise a yield function, flow rules, hardening rules, etc., which are in principle similar to those of following the yielding of metals as coded in any general purpose finite element program. Although the data used to calibrate the coefficients of the formulation is only obtained from very few test results, which may limit its application to other types of joints or the joints with other geometries, currently the MSL joint formulation is widely used to represent critical as-welded tubular joints in the pushover analysis of frame structures (USFOS, 2009).

$$P = P_u \left\{ 1 - A_1 \left[1 - \left(1 + 1/\sqrt{A_1} \right) \exp\left(-A_2 \delta / d_0 f_{y0} \right) \right]^2 \right\} \tag{1}$$

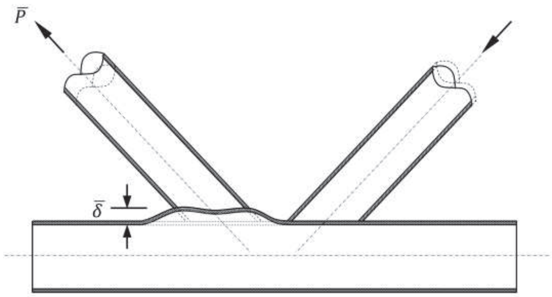
$$M = M_u \left\{ 1 - B_1 \left[1 - \left(1 + 1/\sqrt{B_1} \right) \exp\left(-B_2 \theta / f_{y0} \right) \right]^2 \right\} \tag{2}$$

2.2 *Proposed joint formulation for fully-grouted joints*

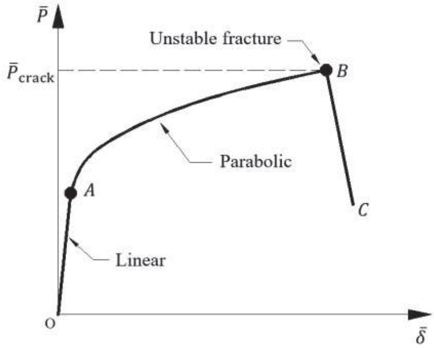
Zhang (2019) has developed accurate representations for fully grouted X- and K- joints under brace axial tensile loading, including the linear elastic and nonlinear plastic load-deformation formulations, as well as the prediction of ultimate strength. Fig. 2(a) exhibits the deformation pattern for fully grouted K-joints under balanced brace axial loading. Due to the constraints of the infilled grout, the chord deformation on the tensile brace side is highly localized in the immediate vicinity of the tensile brace-to-chord intersection, which is the so-called punching shear mode. Other than this small region, there is almost no deformation at all. Also due to the prevention of the infilled grouted, the connection between the chord and the compressive brace can be considered as rigid. Numerical simulations have revealed that the typical relationship between the tensile brace force and the chord deformation for fully grouted K-joints is monotonically increasing until the ultimate capacity is reached. To accurately estimate the joint response and make the representation as simple as possible, the typical nondimensional load-deformation curve is divided into three stages as shown in Fig. 2(b): (1) Linear stage (O-A); (2) Nonlinear stage (A-B); (3) Failure stage (B-C). Based on the shape of the curve, the nonlinear stage normally can be fitted by a parabolic function or a logarithmic function. Compared to the logarithmic function, the parabolic function is much easier to solve and thus is chosen to represent the nonlinear stage. To predict the ultimate strength due to ductile fracture, Zhang (2019) has established the relationship between the equivalent strain to fracture and stress triaxiality for the material of tubular joints and implemented this failure criterion into fracture simulation. The regression analyses propose one simple equation to predict the value of $\overline{P}_{\text{crack}}$. Finally, the load-deformation formulation and the equation to predict the crack force for fully grouted K-joints are summarized as below.

$$\begin{cases} \text{Linear} & \overline{P} = 2400h(\beta,\gamma)\cdot\overline{\delta} & \overline{\delta} \le 0.00125 \\ \text{Nonlinear} & \overline{P} = h(\beta,\gamma)\cdot\left(2.5+14.7\beta^{0.2}\gamma^{0.22}\sqrt{\overline{\delta}-0.001}\right) & \overline{\delta} > 0.00125 \\ \text{Failure} & \overline{P}_{\text{crack}} = \left(2.07\beta^{2.0}+3.83\right)\beta\gamma & \end{cases} \tag{3}$$

where $h(\beta,\gamma) = (1.14-0.021\gamma+0.019\beta\gamma)\beta\gamma$, $\overline{\delta}=\delta/d_0$, $\overline{P}=\dfrac{P\sin\theta}{f_{y0}t_0^2}$, $\overline{P}_{\text{crack}}=\dfrac{P_{\text{crack}}\sin\theta}{f_{y0}t_0^2}$.



(a) Deformation pattern



(b) Proposed load-deformation curve

Figure 2: Proposed joint representation for fully grouted K-joints

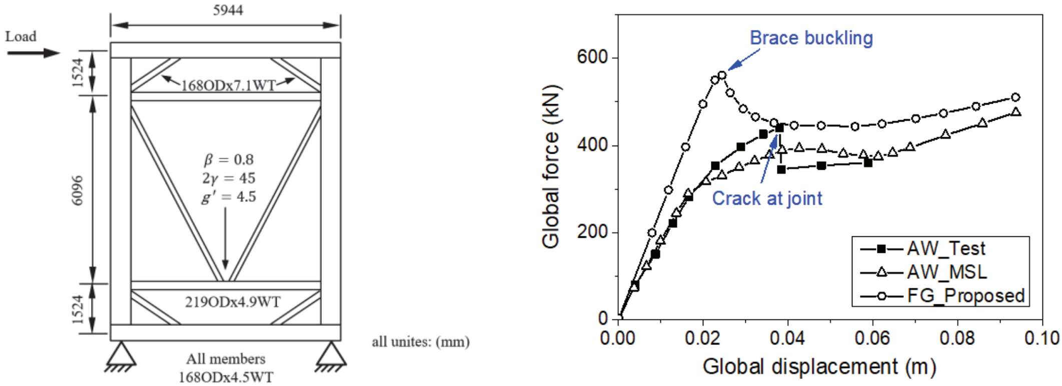
3 Frame analysis

This section implements the MSL joint formulation for as-welded joints and the proposed joint formulation for fully grouted joints into the frame analyses of a 2D BOMEL K-frame, a 2D K-frame designed in NUS and a 3D K-braced jacket platform to discuss the effect of grouting critical joints to the overall frame response.

3.1 *2D BOMEL K-frame*

Figure 3(a) sketches the detail dimensions for the 2D BOMEL K-braced frame, namely Frame VIII. During the loading procedure, the frame remains pin connected at the base to a triangulated test rig. The test arrangement applies a monotonically increasing horizontal load at the top of the frame until the critical joints or members deform significantly and the residual strength of the overall frame is obtained. The experiment observes the yielding of the weak K-joint with plastic deformations in the chord material near the compression side, followed by further plastic deformations concentrated at the tension side. The subsequent loading initiates a crack near the weld toe of the tensile brace, at the crown point in the chord gap region. The crack propagates rapidly around the weld toe generating an abrupt and significant reduction in the joint capacity, which leads to a global unloading of the K-frame, as shown in Fig. 3(b). The MSL joint formulation, which assumes a joint ductility limit proportional to the chord diameter, predicts the weakening of the joint followed by a more ductile frame response than that observed in the test. However, the frame capacity estimated by the MSL joint assumption is close enough to the test result from the engineering point of view.

The chord of the K-joint is then grouted to strengthen Frame VIII. Instead of the joint failure observed on the frame before grouting, the compressive brace is buckled which governs the behavior of the frame after grouting. The infilled grout has increased not only the stiffness but also the ultimate strength of the K-joint frame. Figure 3(b) compares the global force-displacement curves for the frame before and after grouting. The capacity of the frame has increased about 25% due to the infilled grout.

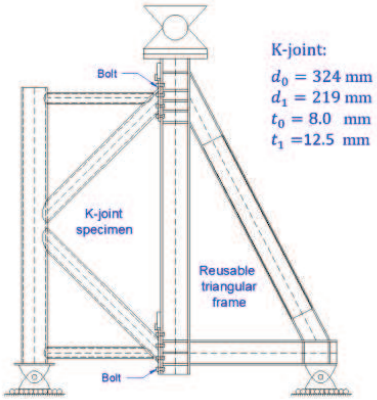


(a) Configuration (b) Global response curve

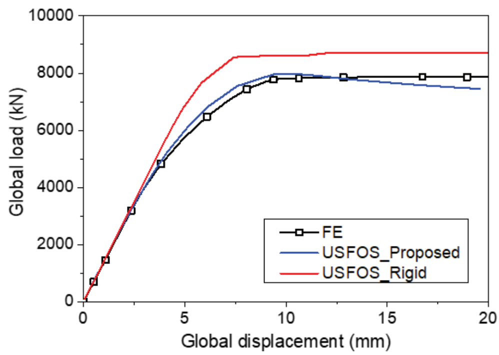
Figure 3: 2D BOMEL K-frame

3.2 *2D K-frame designed in NUS*

Figure 4(a) shows the configuration of the 2D K-frame designed in NUS (National University of Singapore). The K-joint specimen is connected to a rigid triangular frame by bolted connection. The bottom two ends of the frame are seated on two pairs of rocker and roller, while the top of the frame is connected with the actuator. The dimensions of the K-joint are: $d_0 = 324\text{mm}$, $d_1 = 219\text{mm}$, $t_0 = 8\text{mm}$, $t_1 = 12.5\text{mm}$. The design details of the 2D K-frame can be found in Zhang (2019). With these values, the load-deformation curve for the fully grouted K-joint under brace axial tension is derived. Since the experiment has not been conducted yet, the advanced FE result of the K-joint frame is provided for verification. The FE analysis selects the "Tie" constraint to simplify the bolted connection between the specimen and the triangular frame, and uses the "hard contact" to define the interaction between the grout outer surface and the chord inner surface. Figure 4(b) compares the FE result with the USFOS results obtained with different joint formulations. Since the MSL joint formulation is not applicable to represent the behavior of fully grouted joints, the rigid joint formulation is assumed. However, the rigid joint formulation overestimates the stiffness and ultimate strength of the K-joint frame. The yielding of the compressive brace and tensile brace dominates the frame behavior. In contrast, the curve by the proposed formulation agrees well with the FE result. And it is the joint behavior between the tensile brace and the chord governs load-deformation curve.



(a) Configuration



(b) Global response curve

Figure 4: 2D K-frame designed in NUS

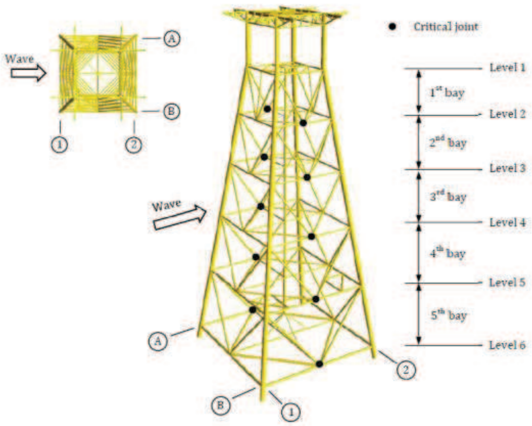
3.3 *3D K-braced jacket platform*

Some old jacket structures employ K-brace as a major framing pattern sustaining the large deck gravity loading and wave forces (Zettlemoyer, 2010). Figure 5(a) shows an overall view of a realistic platform located in the Gulf of Mexico failing to sustain the significant wave force generated during the hurricane Rita. The post-hurricane investigation observes a completely toppled platform lying on the seafloor with no structure visible above the sea surface. The pile supported platform employs five bays of K-braced configuration, with weak gapped K-joints at each bay. The model consists of four levels of deck structure, with the lowest deck bottom located at 15.3m above the mean sea level. The yield strength is kept 235MPa for all member materials. Table 1 lists the loading conditions for the 3D jacket. The environmental information follows the wave data predicted during the hurricane Rita, where the wave height is 12.2m and the wave period is 14.25s. The bottom nodes of the four legs remain pin-supported as a further investigation finds very little effect from the foundation. All the gapped K-joints along the wave direction as indicated in Fig. 5(a) are treated as critical joints, and represented by the MSL joint formulation. The global force-displacement curve for the K-braced jacket before grouting is shown in Fig. 5(c). The MSL joint formulation predicts a ductile frame response with a sequence of K-joint yielding.

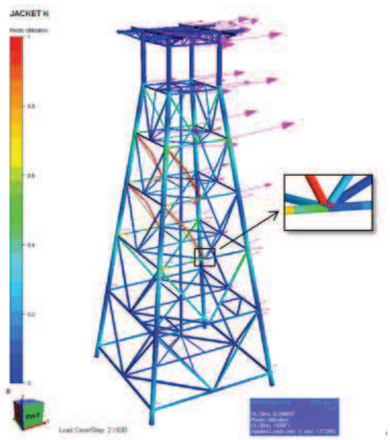
All the critical K-joints are then grouted to improve the capacity of the frame. The proposed formulations for fully grouted K-joints predict the following failure sequence: (1) the critical K-joints on level 2 fail and the compressive K-braces on the 3rd bay buckle; (2) the compressive K-braces on the 2nd bay buckle; (3) the critical K-joints on level 4 fail. Both member failure and joint failure are observed on the grouted jacket. Figure 5(b) plots the contour of plastic utilization for the grouted jacket at the final stage. Figure 5(c) shows the global force-displacement curves for the 3D K-jacket before and after grouting. Compared to the jacket before grouting, the member failure or joint failure for the grouted jacket always generates a significant loss of frame capacity. It is thus reasonable to conclude the jacket after grouting is more brittle than the jacket before grouting. However, the ultimate strength of the jacket corresponding to the first component failure has increased about 115% due to the infilled grout.

Table 1. Loading conditions for the 3D K-jacket

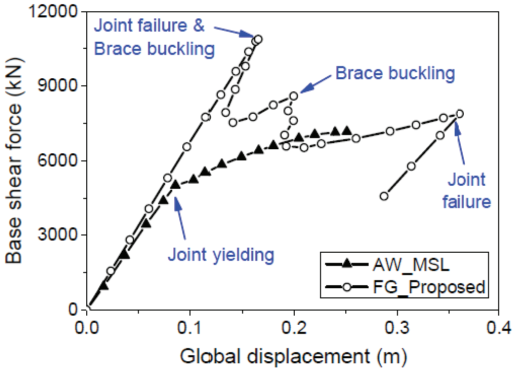
Deck weight	Wave		
	Wave height	Wave period	Water depth
1070 ton	12.2 m	14.25 s	66 m



(a) Configuration



(b) Contour of plastic utilization



(c) Global response curve

Figure 5: 3D jacket platform

4 Summary and inclusions

This paper implements the MSL joint formulation and the proposed fully grouted joint formulation into the frame analyses to represent the local joint behavior of as-welded tubular joints and fully grouted tubular joints respectively. In total three frames are analyzed to discuss the effect of grouting critical joints to the overall frame response: a 2D BOMEL K-frame, a 2D K-frame designed in NUS and a 3D K-braced jacket platform. The results reveal that grouting the critical joint is a very effective way to strengthen the offshore structures. Although the infilled grout makes the joint more brittle, it increases the capacity of the whole frame to a considerable degree. The joint formulations, including the nonlinear load-deformation behavior and the ultimate strength estimation, provide an efficient approach to predict the ultimate strength and failure sequence for the frame structure with fully grouted joints. The extension to realistic jacket platforms proves the applicability of the proposed joint formulations in practical engineering.

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