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Determination of operating load limits for rotary shouldered connections with three-dimensional finite element analysis

Feng Chen [a,b], Qinfeng Di [a,*], Ning Li [c], Chunsheng Wang [c], Wenchang Wang [a,b,*], Mingjie Wang [a]

[a] Shanghai Institute of Applied Mathematics and Mechanics, Shanghai University, Shanghai 200072, China
[b] Shanghai Key Laboratory of Mechanics in Energy Engineering, Shanghai 200072, China
[c] Tarim Oilfield Company, Korla 841000, China

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ABSTRACT

With the development of ultra-deep and extended reach drilling technology, rotary shouldered connections (RSCs) must withstand more and more complex mechanical and chemical loads. Unfortunately, RSCs often fail when the combination of torsion and tension loads beyond a certain value. It is thus necessary to know the reasonable operating load limits of RSCs to decrease the failure risk of RSCs. Although API RP 7G provides the ultimate working torque for API RSCs, the relationship between the ultimate working torque and axial tension is simplified to be linear, which is only true when the axial tension is not too large. Moreover, the ultimate working torque for the widely used double shoulder connections (DSCs) has not been described in API RP 7G. In the present study, a nonlinear elasto-plastic finite element analysis is employed to reveal the nonlinear characteristic of RSCs under complex mechanic conditions. The ultimate working torque of RSCs combined with the impact of make-up torque and axial tension is calculated. Two limit operating load profiles, which describe the permissible working torque under various axial loads for API RSC and DSC, were provided by numerical calculations. Two useful diagrams were provided, in which three operation load zones were distinguished: the red zone stands for dangerous, the yellow one means admitted and the green one is recommended area. The deviation between the present results and those given by API RP 7G increases as the axial tension increases; e.g., it may reach 17.5 percent at an axial tension of 2182 kN. Moreover, a nonlinear relation is obtained when the axial tension exceeds a critical value (2182 kN for API RSC and 3255 kN for DSC). The results have been validated by an application case in Tarim oilfield of China. With the help of operating load limits described in this paper, effective decisions can be made in more complex drilling situations.

1. Introduction

Drill string plays an important role in oil and gas drilling process, which is used to transmit power and convey drilling fluids. Nowadays, as available oil and gas resources are located at deeper depths and harsher environments, rotary shouldered connections (RSCs) in the drill string thus must withstand extremely high levels of combined loadings. Thread connection commonly fail under excessive torsion and tension, resulting in heavy economic losses. Therefore it is necessary to provide the reasonable operating limits to decrease the failure risk of RSCs.

In order to adapt to the harsh environment, extensive investigations have been carried out to promote the performance of RSCs greatly. Over the last 40 years, RSCs have experienced a continuous evolution. Currently, there are mainly three types of high-performance RSCs. The first type is interchangeable with the corresponding API RSCs, such as GPDS (Grant Prideco), VAM CDS, VAM EIS (Flores et al., 2011). The second one has some manufacturers' designs departed from the conventional API RSC parameters, such as HT, XT (Jellison et al., 2000), WT (Reynolds and Greenip, 2002), FOX (Yamamoto et al., 1990), KSBEAR (Takano et al., 2002). The third one further provides increased mechanical performance and benefits on rig floor operations, such as Turbo-Torque (Brock et al., 2008), VAM Express (Biddle et al., 2013). It is worth noting that most of these high-performance RSCs are double shoulder connections (DSCs).

The investigation of the RSCs mainly involved with connection strength and sealing performance, which are determined directly by the stress state. There are three categories of methods for the study of

* Corresponding authors.
E-mail address: qinfengd@sina.com (Q. Di).

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threaded connections. They respectively are experimental technique, analytical method and numerical method. Full-scale experimental techniques can be carried out to evaluate the performance of RSCs, but it is costly and time consuming. Moreover, complex loadings, such as torque, bending, etc., are hard to be applied. Analytical methods have the advantage of parameterization of the model and understanding the mechanism. Many researchers have used this approach to study the mechanical characteristics of RSCs. Stromeyer (1918), Den Hartog (1929), Goodier (1940) and Sopwith (1948) analyzed the threaded connections subjected to axial loads and found out that the load distribution on teeth is not uniform. The maximum stress occurs at the first tooth pair from the shoulder. Stall and Blenkarn (1962) calculated the allowable hook load and torque combinations for commonly used drill strings with simplified formulas, and the strengths are given for both new and used pipe, finally separate tables for yield and for ultimate strengths were given. As a standard, the limits for combined torsion and tension for RSCs were given by API (1998), which were derived under many assumptions, e.g. the tensile stress is considered uniform across the combined areas, the contribution of shear stress due to torsion is ignored, and the helix angle of the threads is neglected, etc. Based on equations from API RP 7G, Baryshnikov et al. (1994) developed a new method to optimize the selection of the most suitable RSCs in many different drilling situations, standard or abnormal as for example in stuck pipe conditions.

Although the analytical approximations are easy to use, the extremely nonlinear mechanics of thread interactions under complex load states cannot be captured due to the stringent assumptions of the analytical method. Fortunately, the finite element method (FEM) has been proved to be a powerful numerical method for solving this problem. Tafreshi (1999) analyzed the stress concentrations of drill string threaded joints under axial, bending and torsion loads with a 2D finite element model. In order to deal with the case of bending, axisymmetric solid elements with nonlinear, asymmetric deformation with Fourier interpolation are employed. Bahai (2001) proposed a 2D parametric model to study the variation of stress concentration factor in threaded connectors due to application of axial and bending loads. Takano et al. (2002) developed the premium connection "KSBEAR" for withstanding high compression, high pressure and severe bending. Thread form was optimized by 2D FEA and evaluation test. Han et al. (2003) analyzed the fatigue of drillstring threaded connections with 2D FEA and fatigue tests. It is found that the last engaged thread (LET) subjected to the highest preload stress and highest cyclic stress due to the stress concentration factor (SCF) distribution. Laboratory Soete (Ghent University) tested various designs with 2D parametric axisymmetric finite element models and compared the results with experimental data. They found that the fatigue life of the connections is dominated by the multiaxial stress distribution at the thread roots (Van Wittenberghe et al., 2011, 2010a, 2010b, 2010c; Meertens et al., 2010).

However, the helix angle of threads has been neglected for all above-mentioned computational models because these models were reduced to 2D axisymmetric. It is difficult to accurately predict the results with such models if the complex loaded conditions are considered, e.g. tension and torque coupled with bending moment (Di et al., 2012). With the progress of the modern finite element method, 3D analysis of the thread connections becomes possible. However, only a few of 3D finite element analyses for RSCs have been reported in literatures. Hua Zhao (1996) studied the load distribution law of threaded connections under the axial tension with 3D models, but the threads were simplified as triangular. With 3D finite element analysis, Fukuoka et al. (2008) found the maximum stress occurs at the bolt thread root located half a pitch from nut loaded surface. The axial load along engaged threads shows a different distribution pattern from those obtained by axisymmetric finite element analysis and elastic theory. Shahani and Sharifi (2009) obtained the location and the value of maximum SCF in the pin and the box. They analyzed the effect of preload on the SCF and the contact stress distribution on the threads. The results proved the necessity of the 3D analysis.

3D investigations have significant meaning in understanding the mechanism of the threaded connections. Note that materials used in above mentioned 3D analysis are elastic. In fact, stress concentration of threaded connection is very severe and plastic deformation will occur in local region. Moreover, the operating load limits has never been reported in these studies. In the present work, a nonlinear 3D elasto-plastic finite element model is established for threaded connections with the helix angle of the threads, and the ultimate working torque of RSCs combined with the impact of make-up torque and axial tension is calculated. Then the formulas are obtained by polynomial fitting to evaluate the ultimate working torque of the RSC under various axial tensions and two diagrams of determining the operating load limits were obtained for API RSC and DSC respectively. The comparison of operating load limits reported in this paper and API RP 7G shows the necessity of the 3D nonlinear analysis. The predicted operating load limits have been applied in Tarim oilfield, and the results are consistent well with the field application.

2. Three-dimensional elasto-plastic finite element model of RSCs

In the 3D finite element analysis of threaded connections, the contact region of the threads is a complex helical surface. Therefore, the implicit algorithm is difficult to converge due to the extremely discontinuous of the contact state. However, extremely discontinuous contact conditions are readily formulated in the explicit method. Therefore, ABAQUS/Explicit has been used to simulate the mechanical properties of the threaded connections.

2.1. Governing equations

Base on the principle of virtual work, the element control equation of threaded connections in Lagrangian coordinates can be expressed as (Yongqiang Meng, 2008)

$$\iiint_V S\delta Ed = \iint_A F\delta u dA \tag{1}$$

where, S is Kirchhoff stress tensor; E is Green strain tensor; F is the force vector on the element surface; δu is the virtual displacement; V is the volume base on initial configuration; A is the surface base on initial configuration.

Green strain tensor E can described as incremental form

$$\delta E = B\delta u_e \tag{2}$$

$$\delta u = N\delta u_e \tag{3}$$

where, B is the strain matrix of element, u_e is the displacement of node, N is shape function of element. Combined the control equations of all elements, the RSCs finite element equations can be described as

$$\sum c^T \iiint_V B^T S dV = \sum c^T \iint_A N^T F dA \tag{4}$$

where, c^T is the Boolean matrix which extended the element nodal displacement to the structure nodal displacements.

The displacement of each node can be obtained by solving Eq. (4), then the element strain can be obtained by geometric equations and the element stress can be obtained by constitutive relation of the material.