OIL PIPE ANALYSIS OF LOW CYCLE FATIGUE AND FRACTURE UNDER RECIPROCATING BENDING LOAD

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ABSTRACT –Oil pipelines often subjected from the cyclic loading during its services, such as bending loading. So it is very significant for the oil pipe to carry out the fatigue life prediction under the reciprocating bending load and to investigate the damage and fracture in different cycle times by using of numerical analysis in the fields of oil and chemical industry. Low-cycle fatigue analysis using the direct cyclic approach was implemented in two different FEM models whether to consider the inner pressure in the pipe or not. The result indicated that there are almost the same cycle times, damage state and fracture morphology for the analysis and the experiments.

1. Introduction

The coiled tubing Drilling (CTD) is an advanced drilling technology by the use of the continuous tubes. Its development of the application began in the 90's. According to the different drilling methods, CTD is classified into directional well drilling and vertical shaft drilling. There are many advantages for coiled tubing Drilling, such as small footprint to suit for the many unlimited regions or operation on the sea, especially good in the slim hole and a method of drilling with low-cost and high-quality. The continuous tubes are also used in petroleum transmission pipeline. So its mechanics performance especially the low fatigue property is wildly concerned in the field of oil or chemical industry when suffering from the large bending and torsion deformation.

2. Experiment methods

The experiments of low fatigue of continuous tubes are commonly carried out before it is used. An experimental facility is designed and manufactured to test the low fatigue properties of coiled tube. The length and high of coiled tube experimental facility is 1300mm and 1500mm, respectively. The vertical frame support structure is used in this mechanical system (Fig. 1). There is "V"-shaped jig and fixture to fix the freedom on the facility, which consists of straightening module and flexural module. By changing the different flexural module, we can test the fatigue life of coiled tube with different diameters. In addition, because it is hard to remove, so a flange is designed to drive the flexural module along the horizontal direction. When the experiment is carried out, the bottom of coiled tube is fixed by the left and right holder, which can protect this region not suffering from the bending shear force and improve the reliability of experimental data. The top of coiled tube remove along the designed track by the hinged shaft installed on the frame, which consists of plate, sheet stiffener and base beam. An axial actuator is fixed on the piston rod. The coiled tube is installed on the position of hinged connection to make sure that the motion of piston rod is coincident to the linear track.

Two experiments of testing the fatigue of coiled tube were carried out. They are the bend along the designed track without or with the inner pressure in the coiled tube. The length of coiled tube is 1500mm, and the diameter of coiled tube is 38.1mm, the deflection of bending is about 30°. The experimental results indicated that the number failure cycling for the coiled tube without inner pressure is about 1000 times, and the number failure cycling for the coiled tube with inner pressure about 34.47MPa is about 264 times, respectively. There are almost positions of failure for the two different coiled tubes.

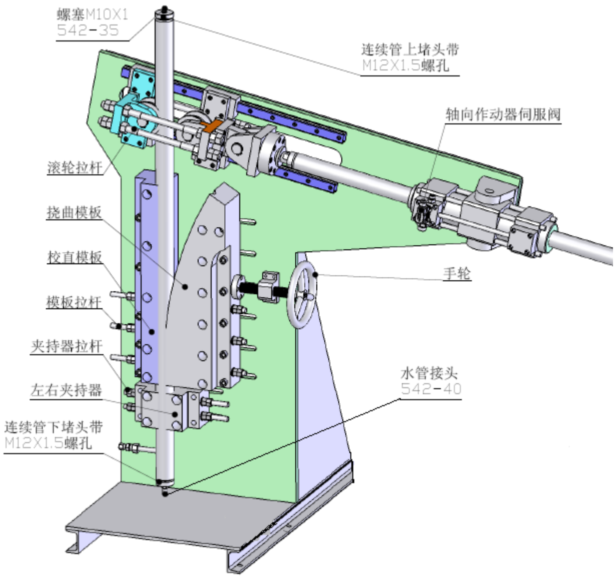
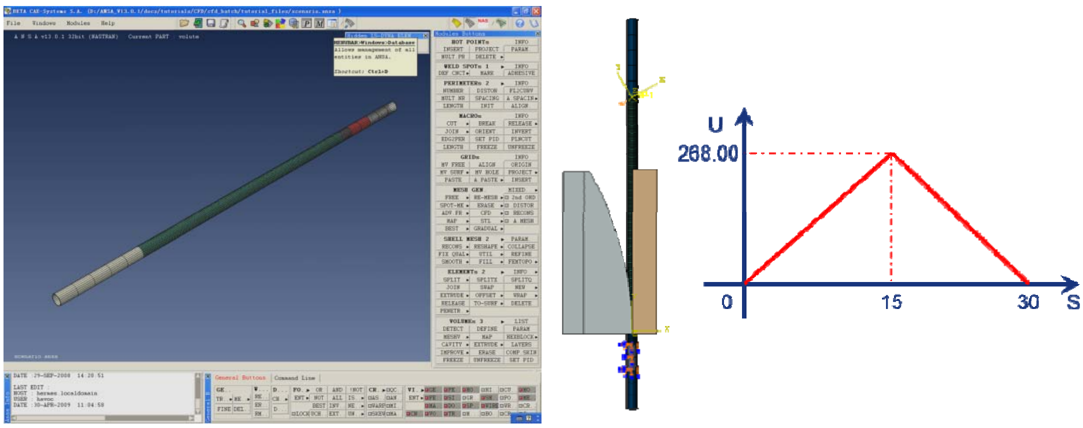


Fig. 1 The experimental facility of testing the fatigue life of coiled tube

3. FE modeling and low fatigue simulation

3.1 Method of FE modeling

Two kinds of software are used to carry out the low fatigue simulation of coiled tube bend. The whole preprocess of FE modeling was finished by use of ANSA. And the solve of models was finished by use of ABAQUS. According to the results of experiment, we find that the bottom is fixed and don't suffer form the shear force, so the mesh is coarse relative to the other regions. 4400 linear hexahedron elements were meshed by used of ANSA software as shown in Fig. 2a. The boundary condition is set up on the bottom of coiled tube, and the displacement of the coiled tube movement is shown in Fig. 2b.



(a) (b)

Fig. 2 The mesh of coiled tube (a) and boundary conditions (b)

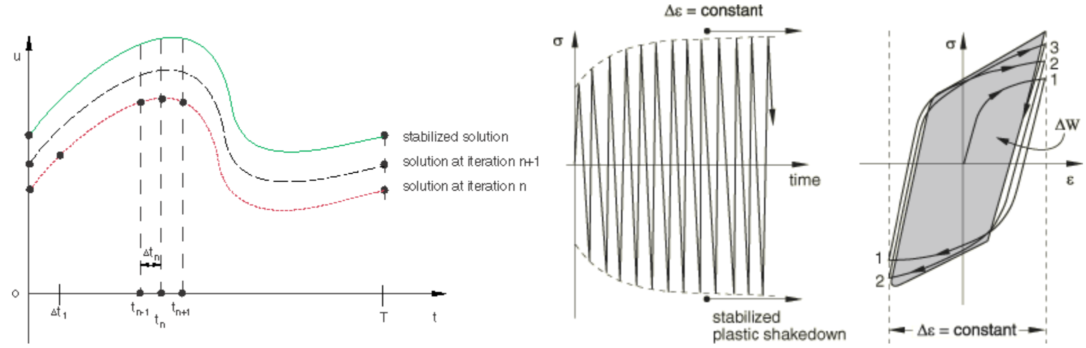
3.2 Direct cyclic analysis and low-cycle fatigue analysis

In order to investigate the damage and failure of coiled tube, three simulations were done, which are the static strength analysis to get the stress distribution and deformation, the direct cyclic analysis and low-cycle fatigue analysis using the direct cyclic approach to investigate the damage of material steel and the failure cycling numbers of coiled tube. The low fatigue and failure of coiled tube can simulated by using of ABQAUS software.

A direct cyclic analysis is a quasi-static analysis; uses a combination of Fourier series and time integration of the nonlinear material behavior to obtain the stabilized cyclic response of the structure iteratively; avoids the considerable numerical expense associated with a transient analysis; is ideally suited for very large problems in which many load cycles must be applied to obtain the stabilized response if transient analysis is performed; can be performed with linear or nonlinear material with localized plastic deformation; can be used to predict the likelihood of plastic ratchetting; assumes geometrically linear behavior and fixed contact conditions; uses the elastic stiffness, so the equation system is inverted only once; and can also be used to predict progressive damage and failure for ductile bulk materials and/or to predict delamination/debonding growth at the interfaces in laminated composites in a low-cycle fatigue analysis.

A low-cycle fatigue analysis is characterized by states of stress high enough for inelastic deformation to occur; is a quasi-static analysis on a structure subjected to sub-critical cyclic loading; can be associated with thermal as well as mechanical loading; uses the direct cyclic approach to obtain the stabilized cyclic response of the structure directly; models progressive damage and failure in bulk ductile material based on a continuum damage approach, in which case damage initiation and evolution are characterized by the accumulated inelastic hysteresis strain energy per stabilized cycle; models progressive delamination growth at the interfaces in laminated composites, in which case the onset and growth of fatigue delamination at the interfaces are characterized by the relative fracture energy release rate; uses the damage extrapolation technique to accelerate the low-cycle fatigue analysis; and assumes geometrically linear behavior and fixed contact conditions within each loading cycle.

It is well known that after a number of repetitive loading cycles, the response of an elastic-plastic structure, such as an automobile exhaust manifold subjected to large temperature fluctuations and clamping loads, may lead to a stabilized state in which the stress-strain relationship in each successive cycle is the same as in the previous one. The classical approach to obtain the response of such a structure is to apply the periodic loading repetitively to the structure until a stabilized state is obtained. This approach can be quite expensive, since it may require the application of many loading cycles before the stabilized response is obtained. To avoid the considerable numerical expense associated with a transient analysis, a direct cyclic analysis can be used to calculate the cyclic response of the structure directly. The basis of this method is to construct a displacement function $u(t)$ that describes the response of the structure at all times t during a load cycle with period T as shown in Fig. 3a. The direct cyclic analysis capability in Abaqus/Standard provides a computationally effective modeling technique to obtain the stabilized response of a structure subjected to periodic loading and is ideally suited to perform low-cycle fatigue calculations on a large structure. The capability uses a combination of Fourier series and time integration of the nonlinear material behavior to obtain the stabilized response of the structure directly. The direct cyclic low-cycle fatigue procedure models the progressive damage and failure both in bulk materials (such as in solder joints in an electronic chip packaging) and at material interfaces (such as in laminated composites). The response is obtained by evaluating the behavior of the structure at discrete points along the loading history. The solution at each of these points is used to predict the degradation and evolution of material properties that will take place during the next increment, which spans a number of load cycles, ΔN. The degraded material properties are then used to compute the solution at the next increment in the load history. Therefore, the crack/damage growth rate is updated continually throughout the analysis. The elastic material stiffness at a material point remains constant and contact conditions remain unchanged when the stabilized solution is computed at a given point in the loading history. Each of the solutions along the loading history represents the stabilized response of the structure subjected to the applied period loads, with a level of material damage at each point in the structure computed from the previous solution. This process is repeated up to a point in the loading history at which a fatigue life assessment can be made. In bulk material the cyclic loading leads to stress reversals and the accumulation of plastic strains, which in turn cause the initiation and propagation of cracks. The damage initiation and evolution are characterized by the stabilized accumulated inelastic hysteresis strain energy per cycle as illustrated in Fig. 3b.



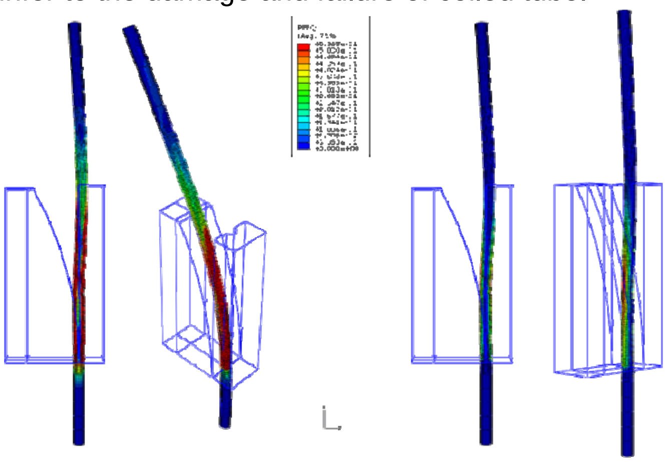
(a) (b)

Fig. 3 A displacement function at all times t during a load cycle with period T at different iterations (a) and Plastic shakedown in a direct cyclic analysis (b)

4. Results and discussions

4.1 The static analysis of coiled tube

A cycle of movement was simulated when the coiled tube driven by the axial actuators. The elastic-plastic material property of steel is defined as the coiled tubes. And Young's modulus E is about 210GPa, Passion's ratio is about 0.29, Yield stress σ_b is 550MPa, Tensile strength is 780MPa. The Mises stress contours and the deformations of coiled tube are shown in Fig. 4. It is easily seen that the maximum of stress lies on the bottom regions, the distance is about 300mm from the constraint position. The maximum value of Mises Stress is 600.5MPa. Because the plastic material property is considered in the model, so the equivalent plastic deformation exits at the position of the stress maximum. The maximum value of equivalent plastic strain (PEEQ) is about 0.39. According to the stress contours and the plastic deformation, we can infer to the damage and failure of coiled tube.



(a) (b)

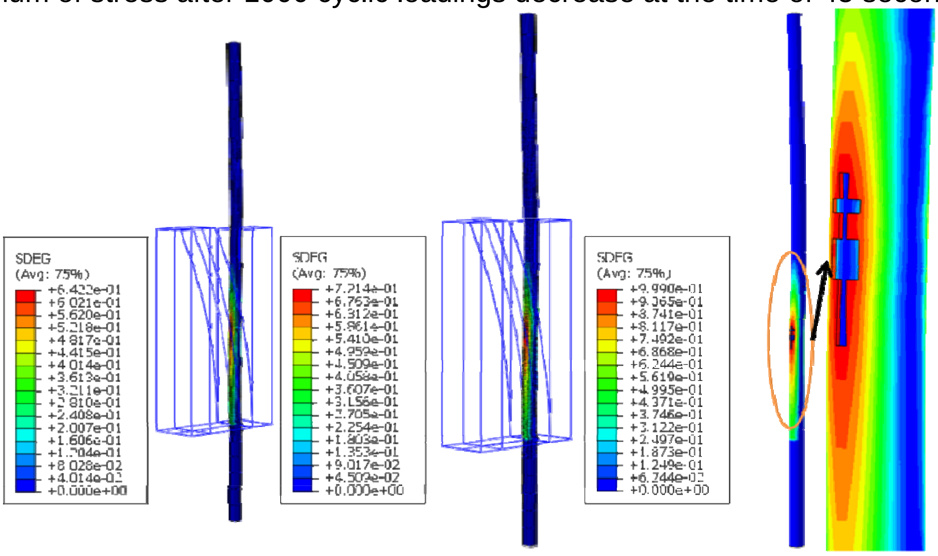
Fig. 4 The Mises contours (a) and the equivalent plastic strain (b) under one cycle movement

4.2 The results of direct cyclic analysis and low-cycle fatigue analysis

It is different from the static strength analysis, the direct cyclic analysis and the low-cycle fatigue analysis in Abaqus/Standard allow modeling of progressive damage and failure for ductile materials in any elements whose response is defined in terms of a continuum-based constitutive model. So the damage and failure of coiled tube need to be considered in the model. After damage initiation the elastic material stiffness is degraded progressively in each cycle based on the accumulated stabilized inelastic hysteresis energy. It is impractical and computationally expensive to perform a cycle-by-cycle simulation for a low-cycle fatigue analysis; Instead, to accelerate the low-cycle fatigue analysis, each increment extrapolates the current damaged state in the bulk material forward over many cycles to a new damaged state after the current loading cycle is stabilized.

In order to describe the damage of material steel, different types of output are available for postprocessing and for monitoring a low-cycle fatigue analysis using the direct cyclic approach. Abaqus/Standard also prints the number of Fourier terms used, the maximum residual coefficient, the maximum correction to displacement coefficients, and the maximum displacement coefficient in the Fourier series in the message file at the end of each iteration in each cycle. Meanwhile, some output parameters can be also printed in the output databases. These variables are STATUS (the status of an element is 1.0 if the element is active, 0.0 if the element is not), SDEG (Scalar stiffness degradation to describe the degree of damage and failure of an element), CYCLEINI (Number of cycles to initialize the damage at the material point), PENER (Energy dissipated by rate-independent and rate-dependent plasticity, per unit volume).

For the low-cycle fatigue analysis of coiled tubes without the inner pressure, three kinds of cycle times were considered to investigate the degree of damage, which are 300, 700 and 1000 cycle times, respectively. Compared with the static analysis and three cycle times fatigue analysis, we can find that there is almost the same as the stress contours and PEEQ in the model. The average stress is about 600MPa, and PEEQ is about 0.33. However, the SDEG is very different from three cycle models each other. The maximum of SDEG is about 0.642 after 300 cyclic loadings, which indicates that there is very large damage in the coiled tube (Fig. 5a). But the maximum of SDEG increases to be about 0.721 after 700 cyclic loadings, which is larger than that after 300 cyclic loadings (Fig. 5b). This is because the damage is accumulated, but the coiled tube is still failure destroyed. After 1000 cyclic loadings, the maximum of SDEG increases to be 1.0, and the destroyed elements have been killed and removed from the model (Fig. 5c). The status of failure is shown as a rectangular hole at the bottom of about 300mm from the fixed position. The stress value of node 40 changed with time at the opposite position of failure element was drawn (Fig. 6). There are almost the same stress changes for the model under the 300 and 700 cyclic loadings. But the maximum of stress after 1000 cyclic loadings decrease at the time of 45 second.



(a) (b) (c)

Fig. 5 The SDEG contours after the 300 (a), 700 (b) and 1000(c) cyclic loadings

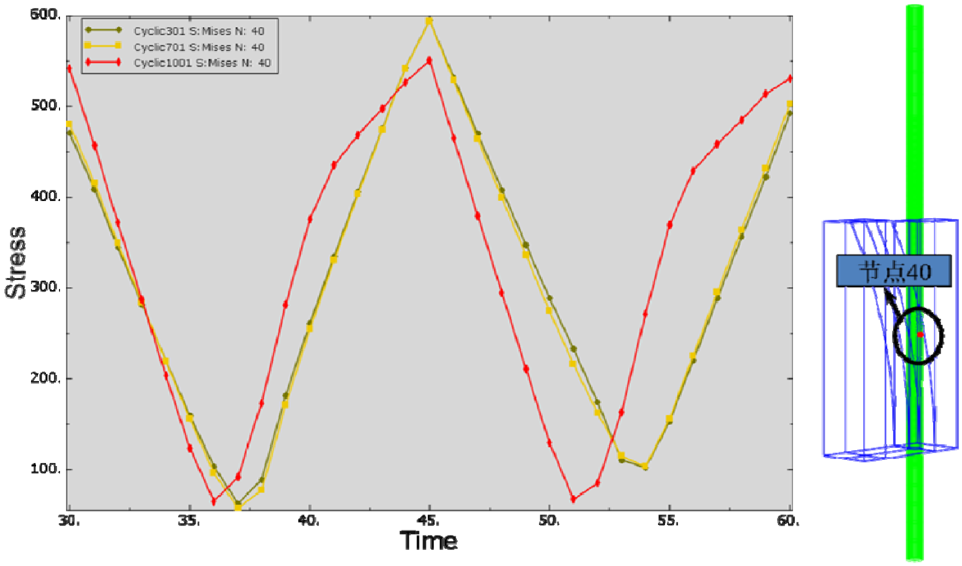
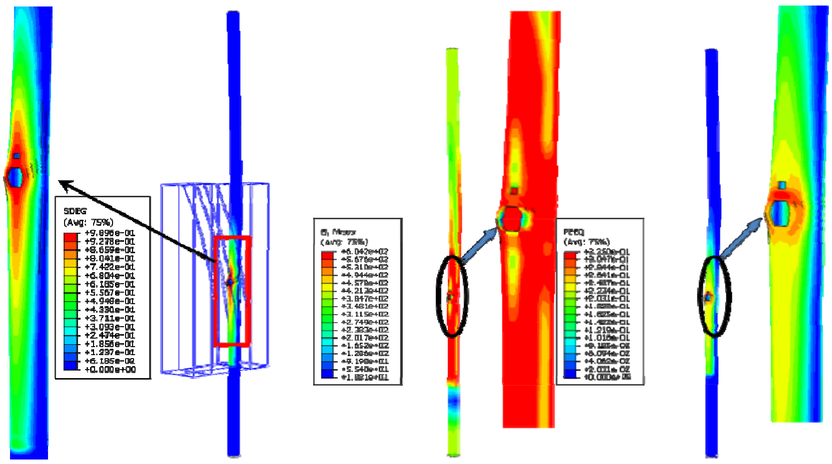


Fig. 6 The stress value change with time after the different cyclic loadings

For the low-cycle fatigue analysis of coiled tubes with the inner pressure of about 34.47MPa, the coiled tube was destroyed after about 260 cyclic loadings. The failure regions are still at the bottom of about 300mm from the fixed position. But the geometric shape of the failure regions is a circular notch, which is very different from the model without the inner pressure (Fig. 7). The elements were removed when their SDEG is equal to 1.0 (Fig. 7a). The stress of whole failure regions is very high (Fig. 7b) and the PEEQ nearby the failure elements is larger than the other regions. By comparing with experimental results, the deformation and the fracture shape are in good agreement with our numerical simulation (Fig. 8).



(a) (b) (c)

Fig .7 The SDEG contours of model with inner pressure after the 260 cyclic loadings (a); The stress contours (b) and PEEQ contours (c)

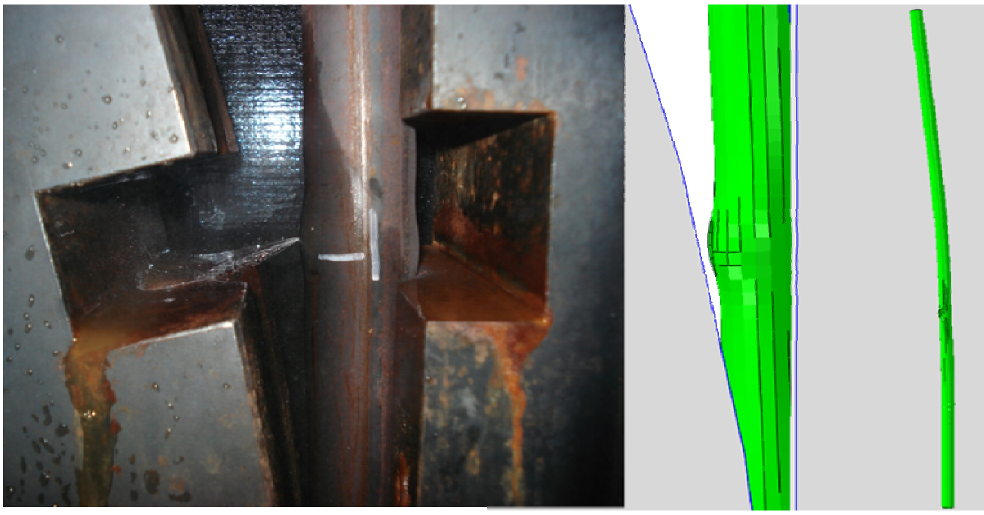


Fig. 8 Comparison of the experimental results and the simulation

5. Conclusions

The experimental investigations on low fatigue life prediction were carried out by use of the bending facility. Two kinds of experimental samples were done, which are the same coiled tubes without or with inner pressure. The experimental results indicate that the cyclic times of coiled tube without inner pressure are about 1000, the cyclic times of coiled tube with inner pressure of about 34.47MPa. According to the experimental results, the FE models of the life prediction of coiled tube were created by the software of ANSA and ABAQUS to verify the experiment. The static strength analysis, direct cyclic analysis and low-cycle fatigue analysis of two models, whether considering the inner pressure or not, are investigated respectively. The results of simulation indicate that by comparing with experimental results, the deformation and the fracture shape are in good agreement with our numerical simulation. For the low-cycle fatigue analysis of coiled tubes without the inner pressure, the maximum of SDEG increases to be 1.0, and the destroyed elements have been killed and removed from the model after 1000 cyclic loadings. The status of failure is shown as a rectangular hole at the bottom of about 300mm from the fixed position. For the low-cycle fatigue analysis of coiled tubes with the inner pressure of about 34.47MPa, the coiled tube was destroyed after about 260 cyclic loadings. The geometric fracture shape of the failure regions is a circular notch.

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