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The crack growth simulations using XFEM of composite riser bonded joint in deep water

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ABSTRACT

With the developing of deep water oil and gas resources, technologies and equipment are facing new challenges. The composite risers are increasingly used for deep water as its advantage. The joint in the pipeline system is the most prone to break. Generally, the joint's actual carrying capacity is less than the theoretical carrying capacity. A very important factor is the prevalence of various defects in bonding interface. In this paper, based on the mechanical analysis model of composite riser bonded joint, a simple and efficient approach based on extended finite element method (XFEM) has been presented to simulate cracks terminating at a bimaterial interface growth simulations. The proposed underwater depth is 1500m, through the overall analysis of the riser under the condition that it encountered storm once a year to get the critical load conditions which is used as the riser's joint boundary conditions for local analysis later. On this condition,set an initial crack terminating at a biomaterial interface based on extended finite element method (XFEM).By changing the ratio of elasticity modulus and the Poisson's ratio, we can get the trend of crack propagation angle of bonded joint.

Keywords: bonded joint, overall analysis, XFEM, bimaterial interface, crack propagation angle

1. INTRODUCTION

Ideally, a piping system would be designed without joints, since joints could be a source of weakness or excess weight. However, limitations on component size imposed by manufacturing process and the requirement of inspection, accessibility, repair, and transportation/assembly necessitates some load carrying joints in most piping systems. Generally, joints are divided into two main categories in piping systems: adhesively bonded joints and flanged joints. For the traditional flanged connection,

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which is based on the shear connection through bolt, fatigue of the connection members is a concern, especially under high stress concentration on the bolts. Another serious problem is the corrosion of connecting bolts. In most adhesively bonded joints, whether metallic or composite, a coupler usually butt-welds the two pipes together. The loading is transferred by means of the adhesive layer between the two contacting surfaces of the pipe and the coupler. Adhesive bonding is becoming a primary connection method because it can not only effectively lower the stress concentration, but also generally corrosion-free.

Nowadays, the adhesive pipe joint constructions are successfully used in the repair of offshore pipes such as risers (see Fig.1 (a)), which are subjected to complex combined load in deep water. The schematic diagram of the repairing system is shown in Fig.1 (b), the corroded region in the pipelines are winded with adhesive and composite coupler. (C. Alexander 2010)

Fig.1 Riser repair(a)outside view,(b)schematic diagram

In the adhesive joint there are two pieces essentially of pipes to be joined, a coupling to carry the load at the connection, and a medium (adhesive) to transfer the load from the pipes to the coupling. Generally, the joint's actual carrying capacity is less than the theoretical carrying capacity. A very important factor is the prevalence various defects in bonding interface, including micro holes, micro cracks and inclusions, and partial deboning (De Moura 2006). And composite material is easy to form the initial crack because of its adverse operation circumstances, especially at the interface between materials (Yang, F.S. 2011). In those crack propagation problems, an initial crack terminating at a biomaterial interface is often occurred. Therefore, researching this kind of crack in bonded joint is of great significance (see Fig.2).

Over the years, a number of numerical techniques have been developed to simulate the fracture mechanics problems. Among these, the extended finite element method (XFEM) has gained enormous attention in stress analysis around a crack without using a mesh conforming to the crack. Unlike the crack modeling in FEM, XFEM allows for mesh independent modeling of discontinuities and eliminates the requirement for a discontinuity to conform to element boundaries. This allows a discontinuity to be arbitrarily placed in an element, thus enabling the domain to be discretized without explicitly meshing the discontinuity.

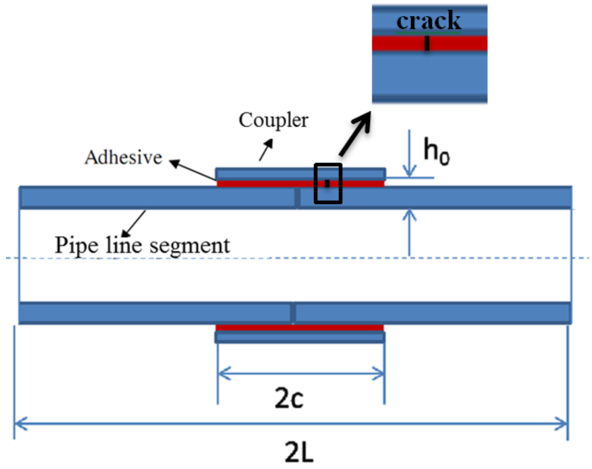

Fig.2 The proposed construction of adhesive joint used in pipe lines in deep sea

Chadegani etc (2011)using the first-order shear deformation theory (FSDT) to analyze the stress and displacement of bonded joint including initial interface cracks and holes. Sukumar (2003) and Huang (2003) give the enhancement function of crack terminating at a biomaterial interface, which composed of four items,and then Sukumar (2004)give the enhancement function of interface crack along the two materials' interface, which consists of 12 items. Bouhala (2013) using Airy stress function to derive the crack tip displacement enhancement function of interface crack with arbitrary angle, and also using body force method to calculate the stress intensity factor. But the above problem does not take into accounting the propagation of the crack.

In this paper, based on the mechanical analysis model of composite riser bonded joint, a simple and efficient approach based on extended finite element method (XFEM) has been presented to simulate cracks terminating at a biomaterial interface growth simulations. The proposed underwater depth is 1500m, and though the overall analysis of the riser under 1 year storm so that to get the most dangerous load conditions as the riser's joint boundary conditions of local analysis. On this condition, to set a initial crack terminating at a biomaterial interface based on extended finite element method(XFEM).By changing the ratios of elasticity modulus and the Poisson's ratios, we can get the trend of crack propagation angle of bonded joint.

2. THE OVERALL ANALYSIS OF THE RISER

This chapter mainly studies the single riser string system of TLP platform in 1500 m water depth. The riser system mainly includes the wellhead, the stress joint, tensioner joints, the X-mas tree and riser joints.Fig.3 shows the riser system schematic diagram that will be analyzed by ABAQUS software.

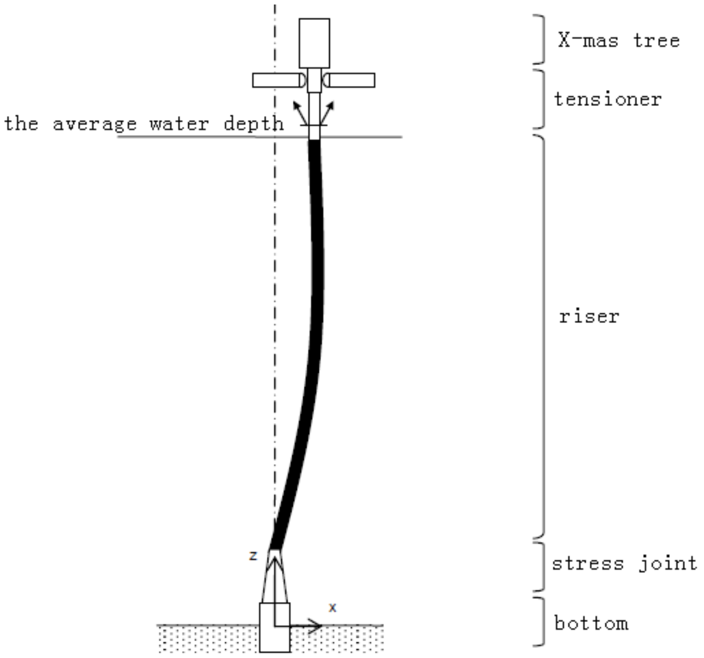

Fig. 3 Composite riser system configuration

2.1 Load Condition

The loads mainly include working loads and environmental loads, working loads are divided into loads during installation and operation. This paper mainly studies the working loads during operation, which include top tension, gravity, buoyancy and the design pressure as well as the force caused by the temperature variation. The maximal external pressure mainly determined by the limit operation depth, in this paper, the external pressure is 15 MPa in 1500 m depth.

The weight of the riser mainly includes itself weight and internal mud weight, in addition, for the convenience of calculation. This paper use wet weight, which is riser weight minusing the buoyancy of the riser. At the general operating conditions, the density of mud is 1600 kg/m3, according to the following formula:

$$\mathrm{G}_D = \rho_m \pi r_0^2 L_1 g + \sum_{i=1}^{n} \rho_i \pi (r_i^2 - r_{i-1}^2) L_1 g \quad (1)$$

$$\mathrm{G}wet = \rho_m \pi r_0^2 L_1 g + \sum_{i=1}^{n} \rho_i \pi (r_i^2 - r_{i-1}^2) L_1 g - \rho_w \pi R^2 L_2 g \quad (2)$$

Where GD: riser weight; Gwet: riser wet weight; am : mud density; ρw: the density of sea water; ρi: the density of the ith layer material;r0: riser inner diameter; R: riser outer diameter;L1.Riser string length, 1530 m;In L2: riser string length under water, 1500 m;I - n: composite riser layer number; g: acceleration of gravity, 9.8 m/s^2.

According to the working conditions of the riser and the density of different materials, the riser weight and riser wet weight can be got as:

$$G_D = 8.223 \times 10^6 N$$

$$Gwet = 3.176 \times 10^6 N$$

The top tension of riser is general calculated according to the formula .

$$T_{\mathrm{real}} = T_{\mathrm{eff}} + P_{\mathrm{i}} A_{\mathrm{i}} - P_{\mathrm{o}} A_{\mathrm{o}} \tag{3}$$

Where T_{real}: the actual tension of riser top; T_{eff}: the effective tension according to different situations, general, it is a function of the riser weight. For steel riser ,taking 1.18 times the weight of the steel riser, for composite riser, taking 1.55 times the weight of the riser (Swanson 1988);Pi: internal pressure; Po: outside pressure; Ai, Ao: cross-sectional area of the inside and outside.

Environmental loads mainly refers to the effect wave and current. Wave enhanced the hydrodynamic loads on the riser, and through the RAO to influence the movement at the top of the riser. The more important movements caused by Waves contain (Qi,B. 2011) : surge, heave and pitch. This paper selects the wave conditions occurred per year in South China Sea, respectively, the wave period is 5.23s, the significant wave height is1.22 m.

2.2 Overall Analysis By FEM

The length of the riser underwater is 1500m, the length above water is 30m, with 501 nodes and 500 units. In equivalent beam element model of the composite riser, the load conditions: the top tension is directly applied at the top of the riser as a concentrated force, otherwise the riser's wet weight is applied along the equivalent beam unit as a line load, besides, the wave and current are applied using the AQUA module of ABAQUS. In addition, it's necessary to set boundary conditions at the top and bottom of the riser. The riser's bottom is connected with blowout preventer by stress joint, so to set the riser's bottom as fixed boundary condition. The movement of the riser top is synchronized with the platform movement. The platform motion under the condition of storm encountered once a year are as follows:

Platform surge: $\mathrm{x} = 21.81 + 0.69\sin\left(\frac{2 \cdot \pi}{5.23} t\right)$

Platform heaving: $\mathrm{y{=}1530{-}}\sqrt{((21.81{+}0.69\sin(\frac{2\pi}{5.23}\mathrm{t}))^2 {+}15302)}$

According to the above contents,the equivalent beam element model of the composite riser can be established with loads and boundary conditions applied. The model is shown in Fig.4. Fig.5 shows the dynamic analysis stress nephogram of the riser overall equivalent beam model under the condition of storm encountered once a year, the bottom's stress is more concentrated.

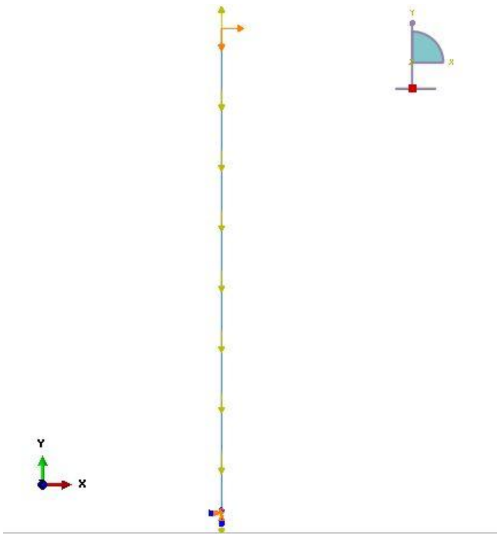

Fig. 4 Equivalent beam model of whole riser

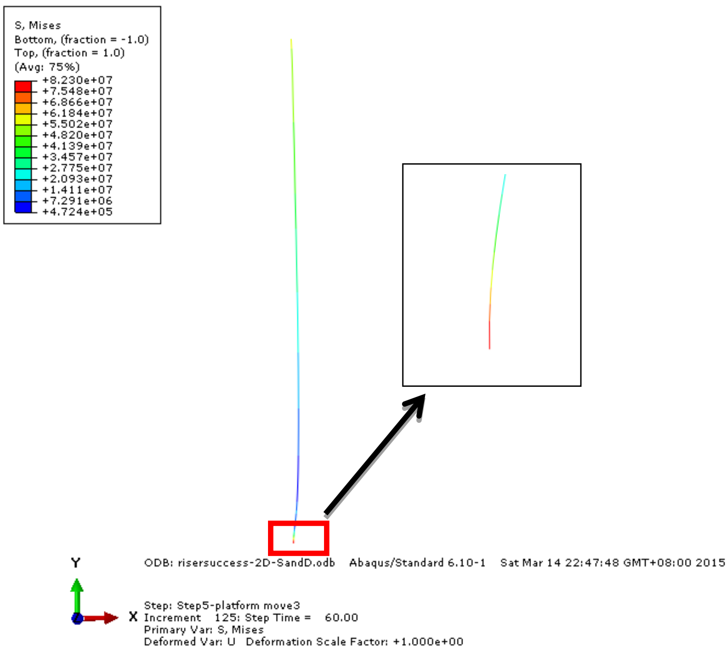

Fig. 5 Mises stress under 1 year storm

Fig.6 is bending moment nephogram, the bottom is of the largest value, and the riser's top and the upper position of the riser's bottom also have certain bending moment, however the values at these position are significantly lower than the riser's bottom moment. This is due to the fixed boundary condition of the bottom and material geometric nonlinearity. Fig.7 is the equivalent stress of composite riser, moreover, extracting the mises stress of two key sections (top and bottom), as is shown in Fig.8. It can be seen the top and bottom's mises stress is larger, but the bottom stress is significantly higher than the top, which is because the bottom moment caused by platform movement under 1 year and the storm is very big. Therefore, the riser bottom section is the most dangerous position of whole structure, which must be considered in the analysis of riser. In this paper, extracting the load conditions at the bottom of the riser as the load and boundary conditions for later XFEM analysis of bonded joint model.

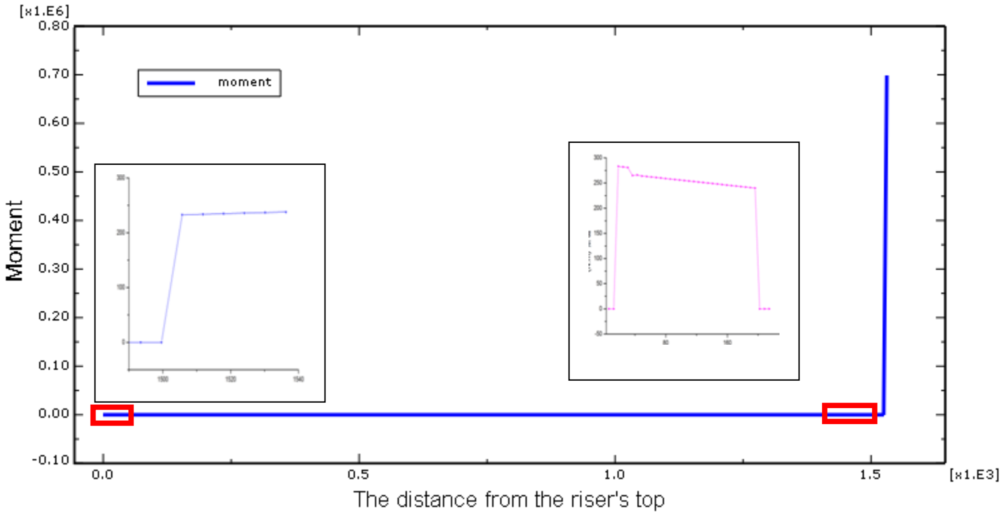

Fig. 6 Bending moment along riser

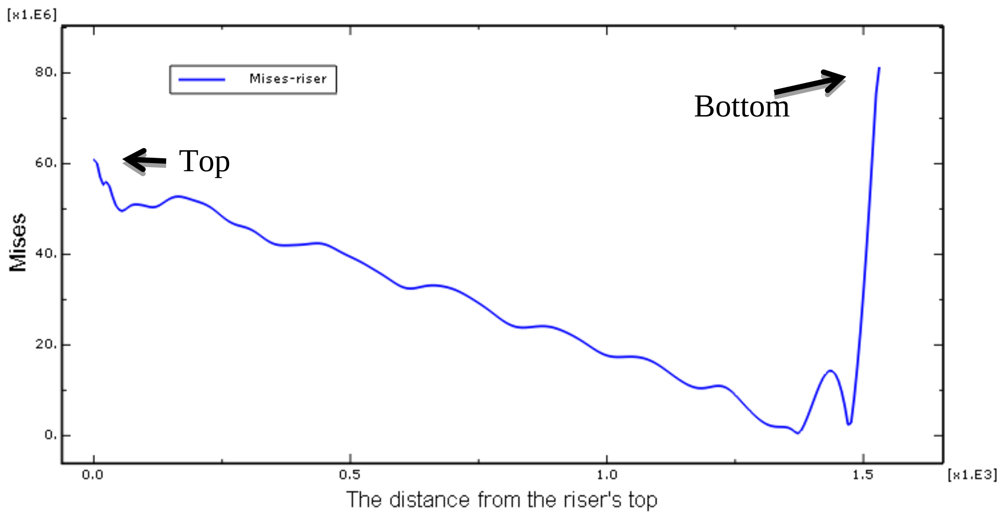

Fig.7 Equivalent stress along riser

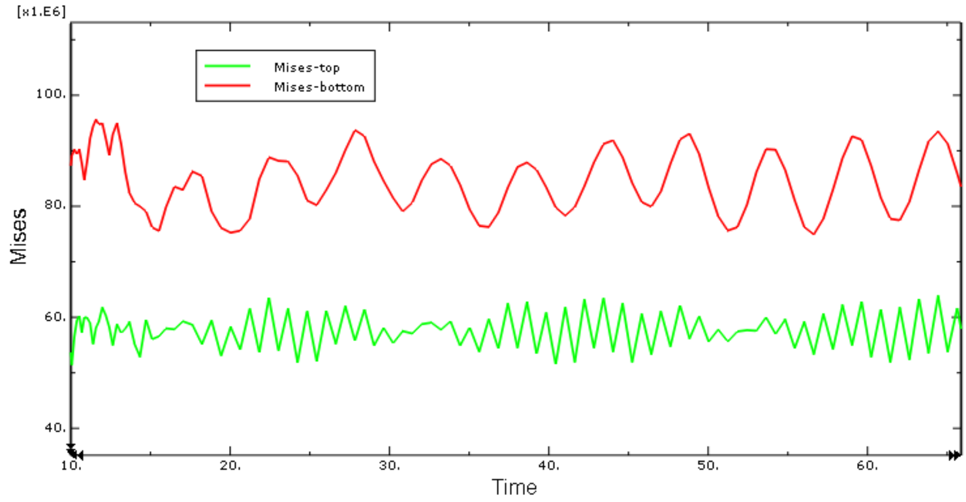

Fig.8 Mises stress of riser's top and bottom

Table 1 The dimension of the adhesive pipe joint

	Length (mm)	Thickness (mm)	External diameter (mm)
Pipe line	650	30	620
Adhesive	250	3	626
Cover	250	30	686

3. XFEM ANALYSIS OF BONDED JOINT

A qualitative simulation research under ideal conditions is made in this paper, proposed adhesive joint for use in pipe lines is analysed with finite element analysis. The dimensions of the joint are shown in Table 1. Choose the maximum principal stress failure criterion in the process of damage, and select the mixed model and damage evolution law of energy to determine the crack propagation behaviour in damage extension process. Initial damage corresponds to the material properties initial damage, when the stress or strain content to define initial critical damage criterion, then damage begans to start at this time.

The pipe line material is made of material A, and the adhesive material is made of material B.The material parameters are shown in Table2. Generally, the coupler material is composite material, but to simplify the analytical model, the coupler is proposed to be the same material as the pipe lines. Material A's damage parameters as follows: $\sigma_{max} = 84.4\text{MPa}$, $G_{1C} = 4.22 \times 10^3 N/m$, $G_{2C} = 4.22 \times 10^3 N/m$, $G_{3C} = 4.22 \times 10^3 N/m$, Damage coefficient $\alpha = 1$.Material B's damage parameters as follows:$\sigma_{max} =$

22MPa, $G_{1C} = 2.87 \times 10^3 N/m$, $G_{2C} = 2.87 \times 10^3 N/m$, $G_{3C} = 2.87 \times 10^3 N/m$, Damage coefficient $\alpha = 1$.

Table 2 The material parameters

Material parameters	Material A	Material B
Young's modulus(Gpa)	210	3.43
Poisson's ratio	0.30	0.30

Due to the symmetry of the model, in order to reducing the amount of calculation, this paper selects half of the axial cross section of the bonding joint as the research object. Applying fixed constraint on one end of model and another end is coupled with the centre axis of the bonding joint, then applying load conditions extracting from overall analysis and internal pressure and external pressure under 1500m water depth. Model diagram and local meshing diagram is shown in Fig.9. The crack is located between the grid of adhesive layer.

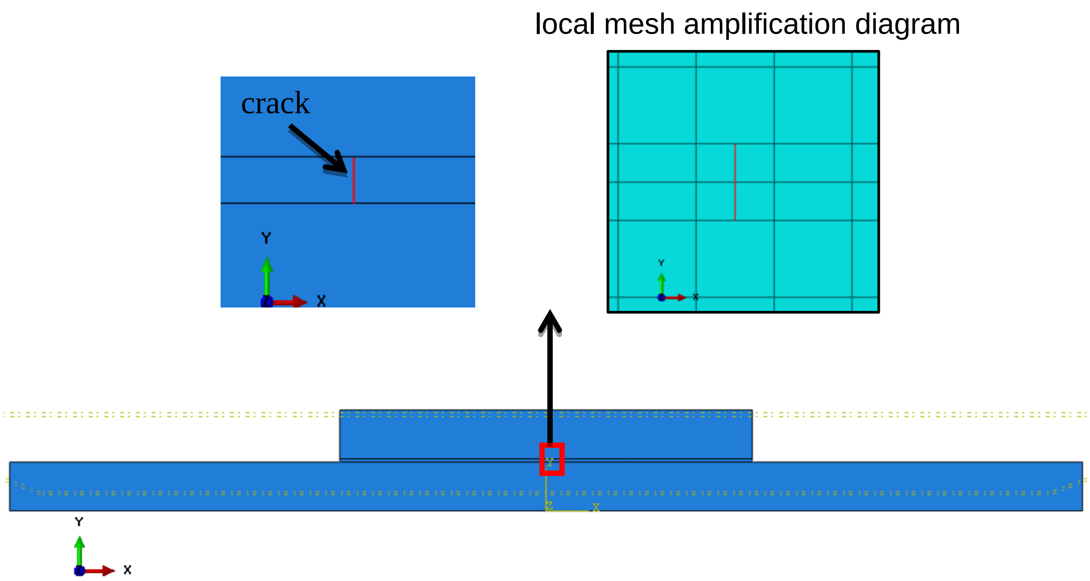

Fig.9 Model diagram and local meshing diagram

Make material B' elastic modulus and Poisson's ratio as E1, υ_1, material A' elastic modulus and Poisson's ratio as E2, υ_2. The results of numerical simulation: E2/E1= 60, crack propagation path and extension finite element mesh is shown in Fig.10, and the crack extend in the direction of pipeline, θ_p = 27 °. It can be seen that the crack propagation process is completely dependent on the grid, which means the grid once divided, the grid without any change in subsequent iterations. This is very different with the traditional finite element method (FEM), thus XFEM has obvious advantages.

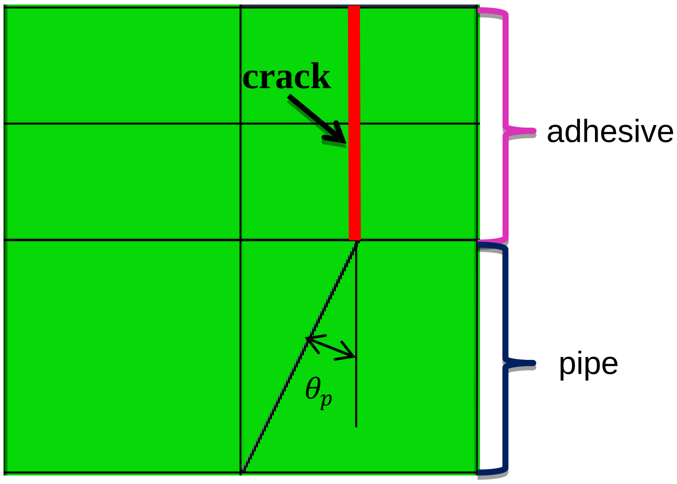

Fig.10 The crack propagation path diagram(E2/E1=60)

To keep E2 = 206 GPa and $\upsilon_1 = \upsilon_2$=0.3 unchanged, then take different E1 values to calculate, investigating the changes of crack propagation angle. With the change of the E2 / E1, the change of crack propagation Angle is shown in Fig.11~12 and Table 3~4. It is shown that as the change of the ratio of elasticity modulus, not only the change of the crack propagation angle presents a certain regularity, but also the propagation direction changes. When the ratio between 50 ~ 100, the crack propagates in the direction of pipeline, and the crack propagation angle decreases with the increase of the ratio. Besides, when the ratio is within 2 ~ 9, the crack propagates in the direction of coupling and the change law of crack propagation angle is similar, which also decreases with increasing of the ratio. While when ratio is within a certain range (10 ~ 40), after analysing by XFEM, it can be seen that the crack is not to propagate to the pipe or coupling. For this situation, we extracted and examined the stress of initial crack unit during the process, founding that the stress has not reached the critical propagation stress value, so there is no obvious propagation. Therefore, the elastic

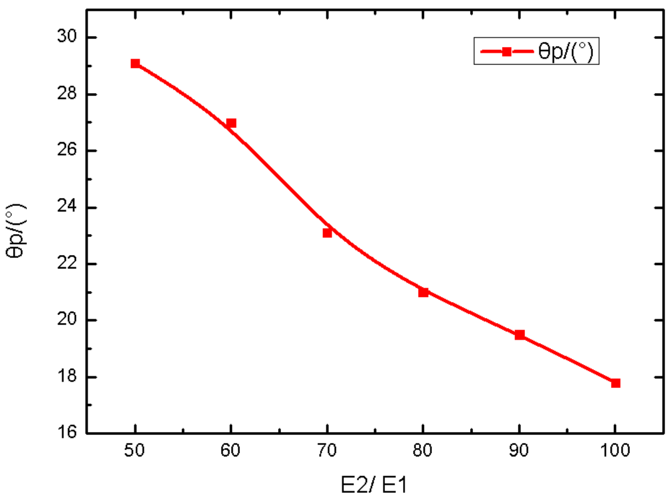

Fig.11 Variations of crack propagation angle versus E2/E1(50~100)

Table 3 The crack propagation angle(E2/E1=50~100)

E2/ E1	100	90	80	70	60	50
$\theta_p/(°)$	17.8	19.5	21.0	23.1	27.0	29.1
direction	down	down	down	down	down	down

Table 4 The crack propagation angle(E2/E1=2~9)

E2/ E1	9	8	6.36	4	2
$\theta_p/(°)$	30.7	31.2	31.7	32.0	32.9
direction	up	up	up	up	up

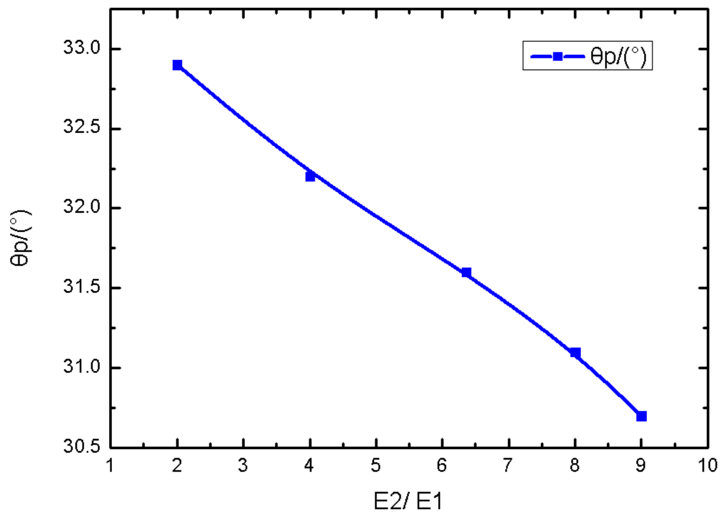

Fig.12 Variations of crack propagation angle versus E2/E1(2~9)

Table 5　Influence of Poisson's ratio on the crack propagation angle

ν_1	0.2	0.25	0.3	0.35	0.4
$\theta_p/(°)$	27.09	27.04	27.05	27.04	27.02

modulus has a certain influence on crack propagation of bonded joint. Choosing the proper adhesive material can reduce or even avoid the initial crack propagation. It has an important guiding significance for deep water structures.

Keep E1 = E2 = 206 GPa, υ_2 = 0.3,and take different $\upsilon_1$values to calculate, the calculation results are shown in Table 5, visibly, the crack propagation angle θp is independent of the ratio of the Poisson's ratios υ_1/υ_2) of materials on both sides of the interface.

4. CONCLUSIONS

1) Based on the overall analysis of riser, the riser's top and bottom are two key points which be considered in riser design under the condition of 1 year storm and 1500m water depth.
2) Because of excessive bending moment and material nonlinearity, the riser bottom becomes the most dangerous section in overall analysis.
3) Through XFEM analysis of bonded joint, the crack propagation angle θp is independent of the ratio of the Poisson's ratios (υ_1/υ_2) of materials on both sides of the interface.
4) While the elastic modulus has a certain influence on bonded joint crack propagation. That crack propagation angle decreases with the increase of elastic modulus ratio, and the crack propagation direction also changes during analysis process. Besides, when the elastic modulus ratio within a certain range, the initial crack does not propagate. Thus, It has an important guiding significance for deepwater structures to choose the proper adhesive material, which can reduce or even avoid the initial crack propagation.

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