Three-Dimensional Fracture Analysis in Gravity Ocean Platforms

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ABSTRACT

This paper presents a study of the fracture problem in gravity ocean platforms. We considered that there was a three-dimensional crack at the intersection of deck and columns. We used finite element method to take the static analysis for platform with no crack, got the tensile stress which corresponding to the crack location. We then calculated the stress intensity factor of the crack tips, got the maximum depth of crack at the intersection of deck and columns under marine environment loads. The results could provide a reference for the design of the ocean platforms to be built in the future.

KEYWORDS: gravity ocean platform; crack; crack tip; stress intensity factor

INTRODUCTION

Along with the development of offshore oil and gas resources, ocean platform structures are growing rapidly and getting more and more widely in ocean engineering. Ocean platforms are mainly divided into mobile platforms and fixed platform. Now, mobile platforms we are using and researching mainly have sit sea platforms, jack-up platforms, floating boat drilling platforms, semi-submersible platforms, cable tower platforms, tension legged platforms, etc. Fixed platforms basically have steel tube platforms and gravity platforms [1]. According to the difference of the materials, gravity platforms are divided into three categories: reinforced concrete gravity platforms, steel gravity platforms, steel and concrete mixing platforms [2]. Ocean gravity platform in shallow sea is reinforced concrete structures which kept stable by it's weight. Its bottom is a massive concrete foundation (caissons), In the middle of the platform, concrete or steel columns are used to support the deck, bottom of the basis is divided into many cylinder storage and ballast tanks. The weight of this platform can be up to hundreds of thousands tons. Due to rely on its own enormous weight, the platform is embedded in the bottom of the sea directly, different structures among platform would be produced cracks inevitably, especially concrete material could bear compressive, but not tensile, it could be ruptured when bear stress. At present, there are many researches on two-dimensional fracture analysis of the gravity ocean platforms [3], but rarely related literatures of fracture problems in three-dimensional. Three-dimensional crack problems of platform are very important in engineering, it directly affect the service life of the ocean platforms. Therefore this paper studied the three-dimensional fracture problem of ocean gravity platform, supposed there was a three-dimensional crack at the intersection of deck and columns, firstly used finite element methods to take static analysis for gravity ocean platform with no crack, got ring stress σ which corresponding to the crack location. And then calculated the stress intensity factor of the crack tips, got the maximum depth of crack at the intersection of deck and columns. The results could provide reference for the design of the ocean platforms.

FRACTURE MODEL OF GRAVITY OCEAN PLATFORM

Based on the marginal oilfield in shallow sea of the Bohai sea, consider the small gravity ocean platform as shown in figure 1, the platform is mainly composed of bottom storage tank (caissons), support columns, the upper deck and skirt board. Among them, the deck, columns and bucket skirt board are made by steel, the bottom of the storage tank is made by concrete. Each component size is as follows: Deck: long 12 meters, width 12 meters, thick 15 millimeters; Columns: outer radius 0.6 meters, wall thickness 24 millimeters, height 33.6 meters; Caissons: inside radius 8 meters, wall thickness 40 centimeters, Internal height 3 meters, Floor and roof: thickness 40 cm; Skirt board: outer radius 8.4 meters, wall thickness 12 millimeters, height 5 meters.

Ocean platform structures are made of different structures welded together, under the marine environmental loads, there are serious stress concentration and local triaxial stress between the deck and columns. These places usually easy have cracks. Suppose point D at the intersection of deck and columns (see Figure 1) is the flow direction, according to the results with finite element calculation (see next section), tensile stress σ of point D is bigger, this location easy to produce crack similar to circular shape, That is to say, point D has typicality, its fracture characteristics has no difference with general plates. This paper will consider the three-dimensional fracture problem of the crack under marine environment loads.

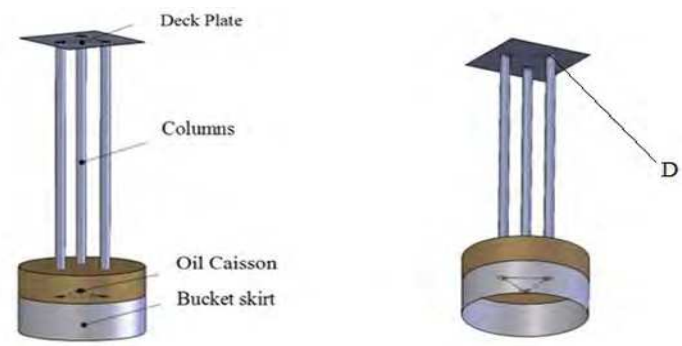

Figure 1: Gravity ocean platform

FINITE ELEMENT ANALYSIS OF OFFSHORE PLATFORM STRUCTURES WITH NO CRACKS

Fracture of gravity ocean platform structure is three-dimensional fracture mechanics problem, use the finite element method to take numerical solution. During solution process, grid partition of finite element is very complicated, because the crack size is too small relative to deck, the grid division is hard to meet the accuracy requirement of the crack tip, it is too hard to reach the purpose of fracture analysis. Therefore, we take local structure contains of crack during analysis.

This section is static analysis of ocean platform structure with no cracks under marine environment load (wind, wave, flow and ice, etc.). Finite element mesh as shown in figure 2, the upper deck and the outer wall of storage tank in the bottom is SHELL63 unit. For the thin-walled structure (caissons) in this paper we studied, it had better choose the SHELL63 unit, the main advantage is that it can reduce computation cost, save calculation time, and increase the accuracy of solutions. Frame beams of the deck is BEAM4 unit, columns submerged in the water is PIPE59 unit, the other parts of columns is PIPE16 unit.

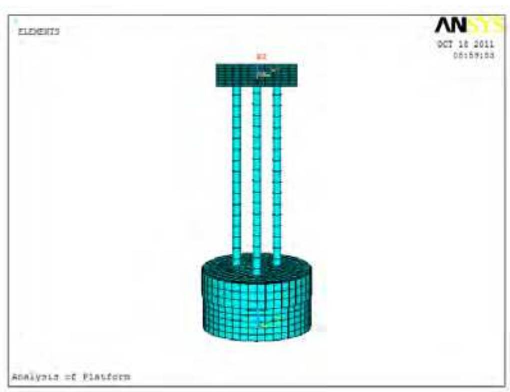

Figure 2: Finite element model of gravity platform

In calculation, the wind load formula is as follows [4]:

$$F = k \cdot k_z \cdot \beta_z \cdot P_0 \cdot A \tag{1}$$

where, k is shape coefficient of wind load, for buildings wall, it is 1.5, for cylinder wall, it is 0.5, in this paper, for the total projection area of platform, it is 1.0; k_z is wind pressure height coefficient on offshore, it is 1.0; β_z is wind array coefficient, take 1.70; P_0 is fundamental wind pressure, and $P_0 = \alpha \cdot V_t^2$, α is coefficient of wind pressure, generally take 0.613N·s2/m4, V_t is designing wind speed as time interval is *t* minutes, through calculation we got $P_0 = 5.21 \times 10^4 N/m^2$; A is area by the wind, it is outline projection area of perpendicular to the wind videlicet, take 0.18m2; Calculation model of the waves load take stokes five order wave to determine the speed of water particle, Stokes five order wave theory especially suitable for wave force calculation of all kinds of ocean platforms [5]; When only the ocean current effected (don't consider the waves load), calculation formula is [6]:

$$f_D = \frac{1}{2} C_D \rho A u_c^2 \tag{2}$$

where, C_D is the drag coefficient of perpendicular to axis in the component, its value should be determined by experiment as far as possible, take it for 0.6 to 1.0 when the experiment material shortage, this article take for 1.0; ρ is density of sea water $1.028 \times 10^3 kg/m^3$; u_c is designing ocean flow velocity 1.03*m*/*s*, *A* is projective area which perpendicular to ocean flow of member bar with Unit length, take 24m^2. There are a lot of calculation model of extrusion failure between Ice and vertical structure. The most basic expression based on the theory and experience is [7]:

$$F_c = m k_1 k_2 R_c D h \tag{3}$$

where, *m* is *shape factor*, for cylinder, it is 0.9; k_1 is *local extrusion coefficient*, take $k_1 = 2.5$ generally; k_2 is *contact coefficient* (0.4-0.7), take minimum when high ice speed, this article take 0.45; $R_c = 2.085\text{MPa}$; *D* is structure width, in this paper, structure width is the outer diameter of columns which contact with ice, take *D*=1.248 meters; *h* is ice thickness, according to the actual situation of the Bohai sea, take *h*=32 centimeters.

In ANSYS calculation, the total wind, the biggest wave-flow coupled, the total ice force and self-gravity of the structure as follows respectively:

The total wind: *F*=15.942*kN*;

The biggest wave-flow coupled: 387.1650*kN* ;

The total ice force: $F = 2276.299$ *kN*;

Self-gravity: *G*=7230.781*kN*.

Through the ANSYS calculation, we get stress distribution of the platform under the coupling of wind, wave flow and ice, etc., as shown in figure 3. Observe the calculation results, we find that the maximum stress appears in the junction of deck and columns, this is because there are discontinuous processing and welding defects among different structures of the ocean platform inevitably, high stress concentration exist near the junction of the deck and columns, we must pay more attention in designing and using.

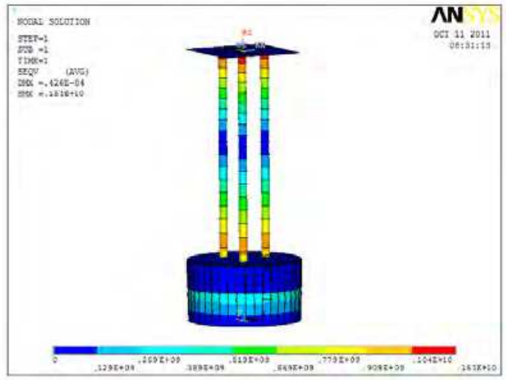

Figure 3: Stress distribution of the platform

From figure 3, we get the ring tensile stress intersected deck and columns $\sigma = 1510\,MPa$. Crack's surface is freedom, but intersection of deck and columns (with no cracks) have influence of tensile stress σ , In order to eliminate the tensile stress, we will effect equivalent and reverse pressure stress on the crack surface according to the superposition principle, ring tensile stress σ with no crack in this section is pressure stress on crack surface in the next.

THREE DIMENSIONAL FRACTURE ANALYSIS OF THE PLATFORM STRUCTURE

It is very difficult to take accurate calculation for three-dimensional fracture analysis, we must Simplified simplify the whole platform structure. We only consider the three dimensional crack model as shown in figure 4, take the bottom of the deck along with the columns top (including crack) from the whole structure, see figure 5. Research the crack tip A, B and crack center C, where, *a* is depth of the surface crack, the pressure stress σ in crack surface is seen in the section of previous calculation results.

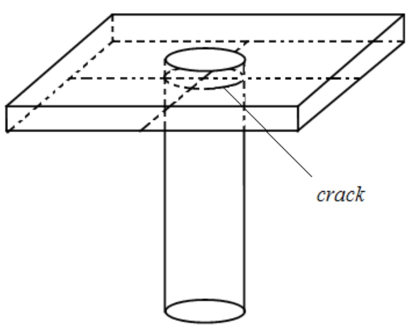

Figure 4: The whole three-dimensional mode

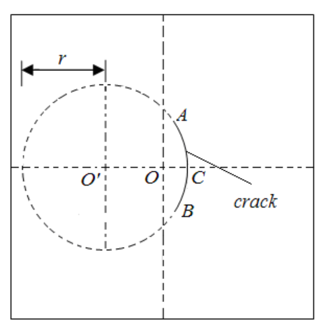

Figure 5: The crack model

According to the theory of fracture mechanics [8-9], as shown in figure 7, the approximate formulas of Ⅰ type of stress intensity factor in the crack tip is [9]:

$$K_{\mathrm{I}} = F\sigma \frac{2}{\pi}\sqrt{\pi r} \tag{4}$$

where, r is the radius of the circular crack; F is geometric factor, it has relations with the depth of crack a and the deck thickness h, F value of the crack tip A and B see table 1 [8], and F value of point C see table 2 [8]:

Table 1: *F* value of the crack tip A and B

$(r\text{-}a)/r$ \ a/h	0.85	0.8	0.7	0.5
0.2	1.05	-	1.02	-
0.4	0.98	0.96	0.95	0.90
0.6	0.75	-	0.73	0.70

Table 2: *F* value of the crack center C

$(r\text{-}a)/r$ \ a/h	0.85	0.8	0.7	0.5
0.2	1.18	-	1.07	-
0.4	1.12	1.07	1.0	0.92
0.6	1.01	-	0.92	0.83

First, we take calculus of interpolation use Table 1:

For $(r\text{-}a)/r$=0.2(r=1.25a), we can get the 1 time Lagrange interpolation polynomials:

$$F = 0.88 + 0.2\frac{a}{h} \tag{5}$$

For $(r\text{-}a)/r$=0.4($r=\frac{5}{3}a$), we can get the 3 times Lagrange interpolation polynomials:

$$F = -1.4 + 10.21\frac{a}{h} - 14.78(\frac{a}{h})^2 + 7.14(\frac{a}{h})^3 \tag{6}$$

For $(r\text{-}a)/r$=0.6(r=2.5a), we can get the 2 times Lagrange interpolation polynomials:

$$F = 0.6083 + 0.2071\frac{a}{h} - 0.0476(\frac{a}{h})^2 \tag{7}$$

Then we take calculus of interpolation use Table 2:

For $(r\text{-}a)/r$=0.2(r=1.25a), we can get the 1 time Lagrange interpolation polynomials:

$$F = 0.734\frac{a}{h} + 0.556 \tag{8}$$

For $(r\text{-}a)/r$=0.4($r=\frac{5}{3}a$), we can get the 3 times Lagrange interpolation polynomials:

$$F = 0.27 + 2.94\frac{a}{h} - 4.71(\frac{a}{h})^2 + 2.86(\frac{a}{h})^3 \tag{9}$$

For $(r\text{-}a)/r$=0.6(r=2.5a), we can get the 2 times Lagrange interpolation polynomials:

$$F = 0.755 - 0.0643\frac{a}{h} + 0.4286(\frac{a}{h})^2 \tag{10}$$

We calculate the allowed largest crack depth a_c using fracture criterion next.

Crack fracture criterion of Type I (K criteria) is [9]:

$$K_{\mathrm{I}} \le K_{\mathrm{I}C} \tag{11}$$

where, $K_{\mathrm{I}C}$ is fracture toughness, which reflects the ability of material's resistance to crack propagation. Fracture toughness is higher, the allowed crack size is greater when the material fracture, according to the experiment [10], fracture toughness of F206 steel is:

$$K_{\mathrm{I}C} = 175 \sim 184 MPa\sqrt{m} \tag{12}$$

We take $K_{\mathrm{I}C} = 184 MPa\sqrt{m}$ to calculate, from the formula (4), $\sigma = 1515\,MPa$, h=15mm and crack propagation conditions $K_{\mathrm{I}} = K_{\mathrm{I}C}$,we obtain:

$$F\sqrt{r} - 0.1076 = 0 \tag{13}$$

Substitution formula (5) to (10) into (13) respectively, we got the biggest crack depth according to the nonlinear equation listed in table 3 and 4.

Table 3: a_c value of the crack tip A and B (millimeters)

a/h $(r$-	0.85	0.8	0.7	0.5
0.2	0.0084	-	0.0089	-
0.4	0.0072	0.0075	0.0076	0.0085
0.6	0.0082	-	0.0087	0.0094

Table 4: a_c value of the crack center C (millimeters)

a/h / $(r-$	0.85	0.8	0.7	0.5
0.2	0.0066	-	0.0081	-
0.4	0.0055	0.0060	0.0069	0.0082
0.6	0.0045	-	0.0055	0.0067

From the above two table results we can see, when $(r\text{-}a)/r$ *is* constant, a_c is reduce along with a/h increases; Also, when a/h *is* constant, a_c is reduce along with $(r\text{-}a)/r$ increases.

In order to validate the effectiveness of the results, we take a/h=0.8 and a=0.0075 meters and use ANSYS to calculate the crack as shown in Figure 3, The finite element model are as follows. Where, local crack model of ocean platform are shown as Figure 6, 7, 8; finite element mesh of crack body as shown in Figure 9:

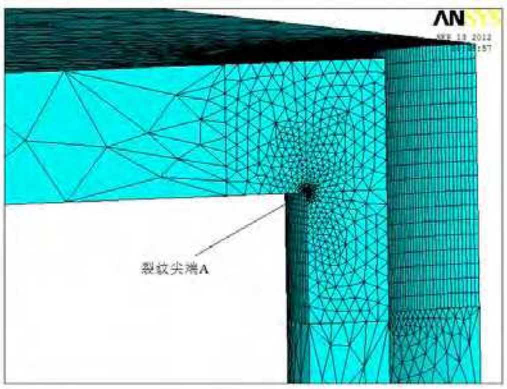

Figure 6: Local crack model of platform

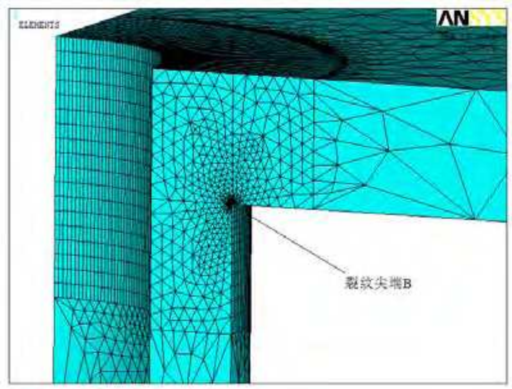

Figure 7: Local crack model of platform

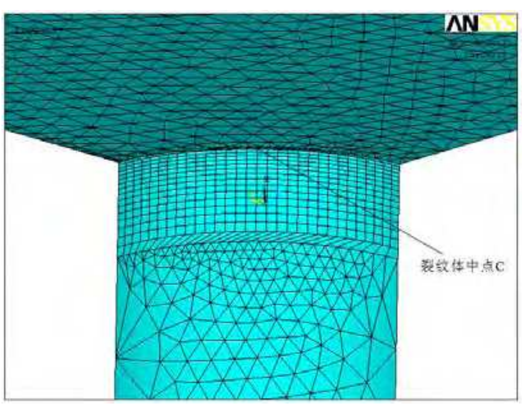

Figure 8: Neutral position of crack

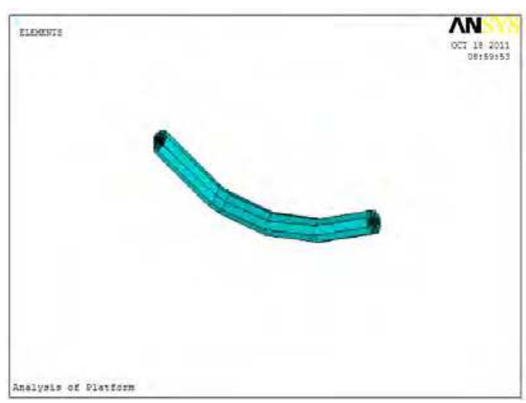

Figure 9: Finite element model of crack body

Through applied loads σ (calculated by wind, wave, flow, ice and self gravity G of the model, etc.) on the crack surface we get the following results:

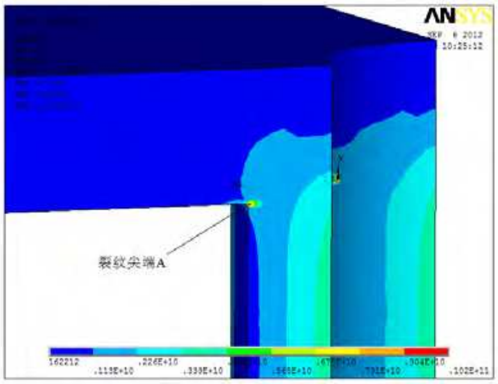

Figure 10: Equivalent stress of crack tip A

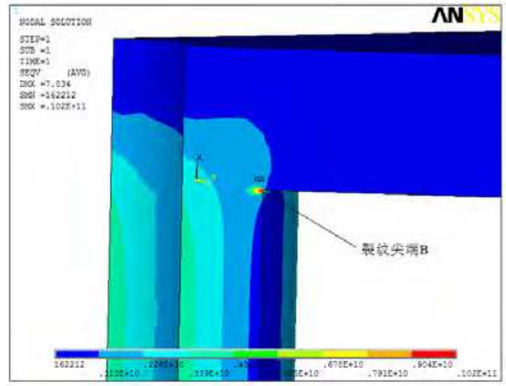

Figure 11: Equivalent stress of crack tip B

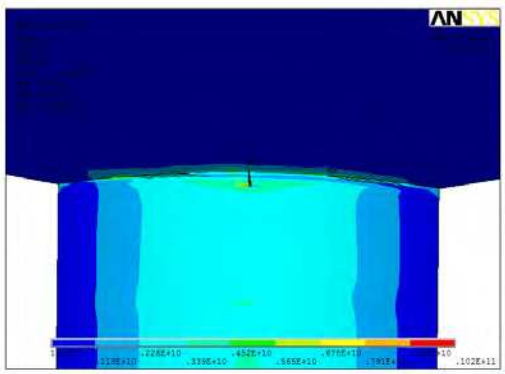

Figure 12: Stress concentration between deck and columns

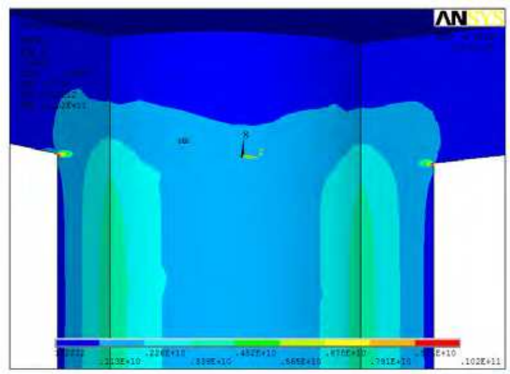

Figure 13: Equivalent stress of column section

From Figures 10 through 13, strong stress concentration appeared in crack, the maximum stress locates on the crack tip, and changes along with the load. this is consistent with the engineering actual situation.

Define local coordinate system which describe the crack tip, and then define crack path through the node, finally calculate using KCALC command, get stress intensity factors (*K*) of crack tip A and B as follows (Stress intensity factor of point C is 0):

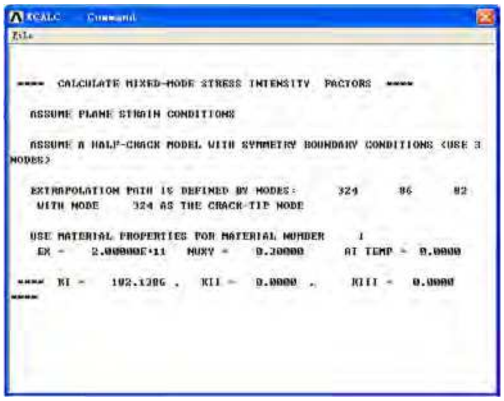

Figure 14: Stress intensity factor of crack tip A

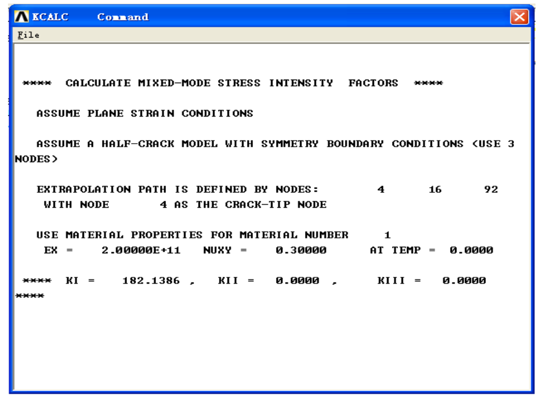

Figure 15: Stress intensity factor of crack tip B

The results concluded that stress intensity factor for type I of the crack tip is $K_{\mathrm{I}} = 182.1386 MPa\sqrt{m}$, which is consistent with the calculation value of approximate formula. This shows that in this article, the grid partition is reasonable when we use finite element method to calculate stress intensity factor of the crack tip. And we can see, the results accord with the approximate formula calculation value.

CONCLUSIONS

(1) Put forward 3D fracture model of gravity ocean platform. Used finite element method to take the static analysis for platform with no crack, got the maximum tensile stress of the junction between deck and columns which corresponding to the crack location.

(2) Calculated the maximum permissible crack depth of the junction between deck and columns which under the marine environmental loads according to the theory of fracture mechanics. Due to tensile stress caused by the platform structure under loads is small, the allowed crack size is large.

(3) Calculate the stress intensity factor of the three-dimensional ocean platform structure with finite element method, the results accord with engineering standards.

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