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Fracture Probability Analysis of Crack Occurrence on a Floating Roof due to Thermal Stress

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Abstract. Several cracks were found on some actual floating roofs of a crude oil tank in the oil refinery located in southern Japan. We assumed that one of reasons would be due to thermal stress caused by temperature changes during the day. In order to consider whether the thermal stress could the cause damages on the floating roof, strain and temperature were measured on the actual floating roof by using optical fiber gauges. Furthermore, fracture possibility due to thermal stress was calculated to discuss whether thermal stress could cause fracture or not. As a result, the probability showed that thermal stresswasnot enough to cause fracture. Anotherexternal factor such as Typhoon could be related.

Introduction

An oil storage tank equipped with a floating roof is called a floating roof tank [1]. The floating roof covers the oil surface in order to prevent volatilization and contamination into the products such as heavy oil, light oil, naphsa, etc. The single-deck type floating roof mainly assembles from a thin deck and a pontoon maintaining buoyancy. The deck thickness does not depend on tank size and approximately 5mm thick steel plate is used even if the diameter is as much as 100meters length. Therefore, the floating roof is likely tobe vulnerable to the external factor such as earthquake groud motion[2].

According to the recent investigation conducted by the authors, several cracks were found on the floating roof of the crude oil tank located in southern Japan[3]. In order to prevent the potential serious incident, it is necessary to investigate causes of the cracks on the floating roof.

In this study, we assumed that one of causes was due to thermal stress on the floating roof tank during the day. Strain and temperature on the floating roof were measured by using an optical fiber gauge in order to comprehend the floating roof during the day.Furthermore, fracture possibility due to thermal stress was calculated to discuss whether initial crack could cause fracture.

1. *Measure*ments on the Actual Floating Roof

1.1 Sensor layout. floating roof on which several cracks were found is the single-deck type floating roof with an additional center pontoon. The tank has a diameter of 80m and height of 22m with a 100,000 kL capacity. The thickness of the deck plate of the roof is 4.8mm. The tank was built in 1980.

In order to measure thermal stress amplitude during the day, optical fiber gauges equipping with the explosion-proof were adhered to the roof surface. Figigure1 and Figure2 show the actual floating roof and layout optical fiber gauges to measure strain and temperature amplitude. Abbreviation, “STR#” in Fig. 2 shows the stiffener rings attached to the liquid side of the deck plate. Table 1 shows the distance of strain gauges from the wall of the center pontoon. Temperature gauges were set in between STR2 and STR3 beside the line of the strain gauge sensor.

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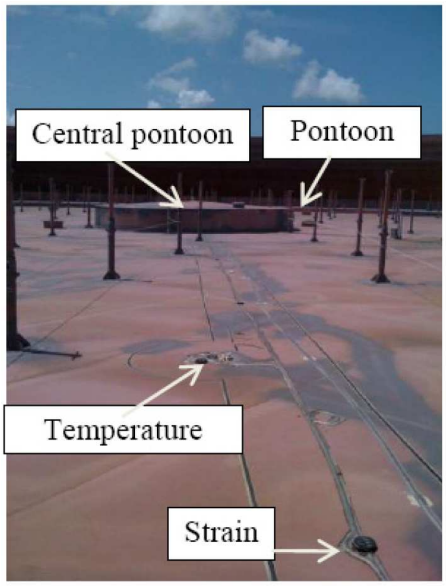

Figure 1 Actual floating roof equipped with pontoon and center pontoon.

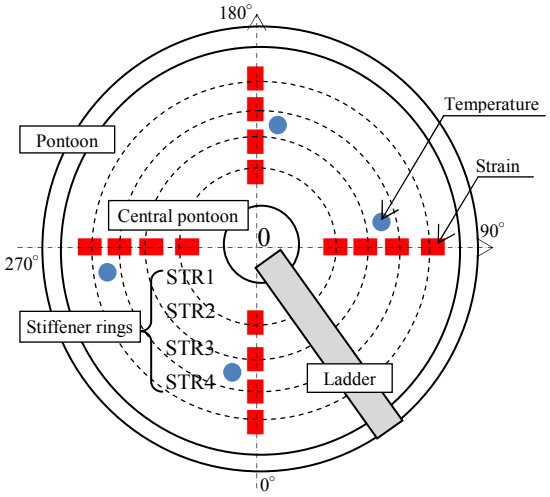

Figure 2 Layout of optical fiber gauges adhered to the floating roof.

Table 1 Sensor location on the floating roof.

	Distance from the wall of the center pontoon in each direction (meter)			
	0°	***90°***	***180°***	***270°***
STR1	11.8	12.1	12.0	12.0
STR2	18.0	18.0	18.0	18.0
STR3	24.1	24.0	24.0	24.0
STR4	29.5	29.5	29.5	29.5

1.2 Measurement Results. Figure 3 and Figure 4 show strain and temperature amplitude histories in 0^{o} direction during the day, respectively. The origin of the holizontal axis in both figures means 12A.M. Figure 3 shows that 412μStrain amplitude occurred at STR 1 in 12 hours when temperature amplitude was 56 degree Celsius. 83MPa stress amplitude would occur if Young's module shall be 206GPa. This value is less than that of yield stress of general structure steel which shows around 245MPa [4]. As for the result of STR4 in Fig. 3, the buckling mihgt occur in 9 hours. This point will be discussed in the section 2.2 later

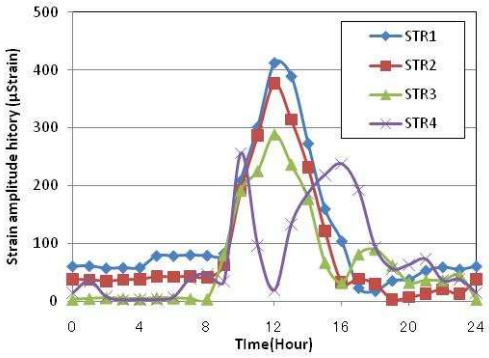

Figure 3 Strain amplitude history in 0° direction.

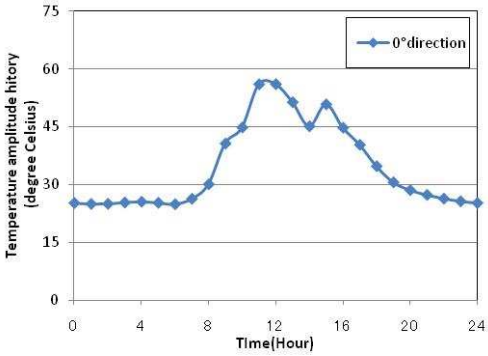

Figure 4 Temperature amplitude history in 0° direction.

2. Acture `Possibility due to Thermal Stress

Next, initial cracks which occurred from any cause were discussed as to whether thermal stress allowed cracks to propagate or not. However, the crack occurrence involves a variety of uncertainties. Therefore, the fracture probability due to the thermal stress was considered by using probabilistic facture mechanics approach [5].

2.1 Fracture probability. The fracture probability P_f is shown in Eq.(1). In this study, P_f was calculated by means of Monte Carlo Method that is the way to estimate the probability of a certain event subject to the probability density function [6]. N_f and N_t describe the total number of the fracture and the event, respectively. The event was randomly given according to the random function [7].

$$P_f = N_f/N_t \quad (1)$$

2.2 Flow chart to estimate fracture probability. Figure 5 shows the flow chart to estimate the fracture probability. As for an initial crack a_0, it shall be defined as a two dimensional surface crack shown in Fig. 6. The crack length a and thickness of the deck plate h have a dimension in mm. Details of the flow chart are described as follows:

1) *Initial crack*: An initial crack a_0 shall be subject to the probability density function p in Eq.(2). μ is the mean of the crack length in mm. Three cases (μ=h/3=1.6mm, h/4=1.2mm, and h/5=0.96mm) were considered. The number of the initial cracks given to the calculation process was 1,000 in each case. All cracks were assumed to pass through the inspection process. The relatively large cracks that could be detected by the inspection were rejected and replaced. The probability function B(a), which describes that the inspection fails to detect the cracks, is given in Eq.(3) [8]. The function was referredfrom the nuclear safety study because it has never been proposed in the study field of the oil storage tank.The coefficients α and β are 0.113 and 0.005, respectively.

2) *Crack propagation*: As for the crack propagation criteria, Paris law given in Eq.(4) was applied [5]. ΔK is st`ress intensity factor range in $MPa(m)^{1/2}$. Constant numbers C and m are 5.21×10^{-13} and 3.0, respectively [9]. The crack shall propagate in case that ΔK is larger than threshold ΔK_{th} equal to $2MPa(m)^{1/2}$ [9]. The stress intensity factor rangeΔK is given as difference between maximum stress intensity factor K_{max} and minimum intensity factor K_{min} in Eq.(5). The stress intensity factor K is determined by using the cubic stress function shown in Eq.(6) [10]. The variable ξ is shown in Fig. 7 as the ratio of the crack length a to the deck thickness h. Coefficients A_i in Eq.(6) were decided to fit the stress distribution. Maximum effective stress was 27.4MP on the deck surface attached with the stiffener ring #1[12]. Also, the effective stress on the opposed side of the deck surface was 13.2MPa. Here, the stress function was simply defined as the linear function showing in Fig. 7 as the red dotted line. The stress intensity factor K is given as Eq.(7) based on the principle of superposition. The coefficient F_0 and F_1 are give as Eq.(8) and Eq.(9) according to the ratio a/t [10, 11]. Also, the periodic inspection subject to the probability function shown in Eq.(3) shall be conducted every several years. In this simulation, the four cases (no periodic inspection, every 5 years, every 8 years and every 10 years) were carried out.

3) *Fracture probability*: Fracture probability was calculated by Eq.(1). The fracture condition in this calculation is defined if the initial crack length a_0 becomes equivalent to the plate thickness h.

$$p=(1/\mu)\exp(-a_0/\mu) \quad (2)$$

$$B(a)=\beta+(1-\beta)\exp(-\alpha a) \quad (3)$$

$$da/dN=C(\Delta K)^m,\ \Delta K_{th}<\Delta K \quad (4)$$

$$\Delta K=K_{max}-K_{min} \quad (5)$$

$$\sigma(\xi) = A_0+ A_1\xi + A_2\xi^2 + A_3\xi^3 \quad (6)$$

$$K=(\pi a)^{1/2}(A_0F_0+2\xi A_1F_1/\pi) \quad (7)$$

At a/t<=0.7

$$F_0=0.6820\xi^4-1.8283\xi^3+3.4051\xi^2+0.0209\xi+1.1215$$

$$F_1=1.2402\xi^4-2.2730\xi^3+2.5718\xi^2-0.0578\xi+1.0727 \quad (8)$$

At a/t>0.7

$$F_0=4729.3333-17919.6364+27100.4530-20442.3042+7692.5106-1153.4967$$

$$F_1=2688.0000-10106.3636+15174.8303-11369.3741+4250.9351-633.0513 \quad (9)$$

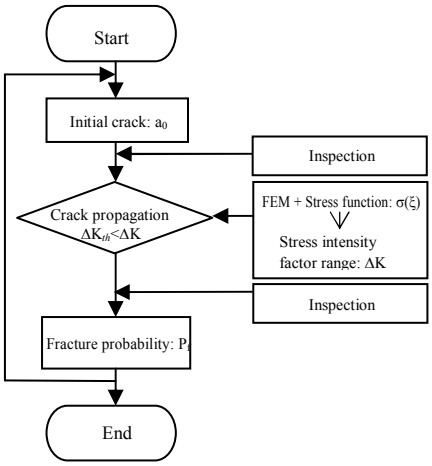

Figure 5 Flow chart for estimating fracture Probability.

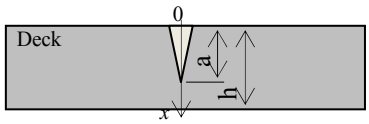

Figure 6 Two dimensional surface crack.

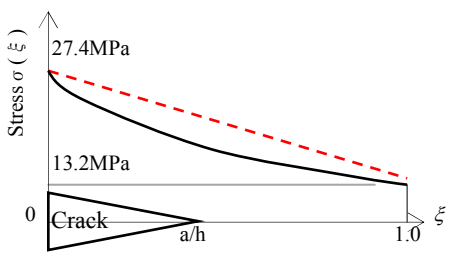

Figure 7 Coordinate system and stress function along the crack.

2.3cture Probability Results. Figure 8 shows the fracture probability in case that average crack lengths are h/3, h/4, and h/5 without any of the initial inspection or the periodic. According to Fig. 8, the larger the average crack length was, the earlier the fracture began to occur. In the case of h/3, the fracture begins to cause in 7.2 years and the fracture probability could attain to 0.45 in 30 years. Similarly, in the case of h/4, fracture would begin to occur in 13.0 years and the fracture probability could attain to 0.39 in 30 years. In the case of h/5, the fracture probability could attain to 0.21 within 18.8 years to 30 years.

Figure 9 shows the fracture probability considering the periodic inspection (every 5, 8 and 10 years) in case of h/3. Figure9 illustrates that the fracture probability can become approximately zero right after the periodic inspection. This result does not depend on the period of the inspection. The shorter the interval of the inspection was, the lower the maximum value of the facture probability became.

The actual tank shall be inspected every 8 years. Based on the period of service (about 30 years), the facture probability was supposed to be 4.3e-2 when the cracks on the floating roof were detected.

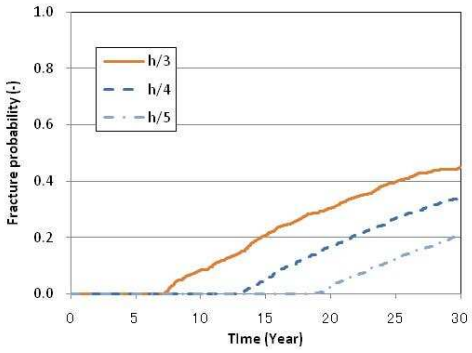

Figure 8 Fracture probability (average crack length: h/3, h/4, h/5without inspections).

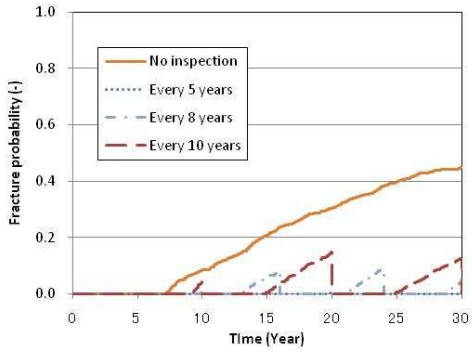

Figure 9 Fracture probability considering the periodic inspection (average crack length: h/3)

Conclusion

In order to investigate the cause of the crack occurrence on the floating roof, the measurement on the actual floating roofand the fracture probabilistic estimation were carried out. Conclusions are shown as follows:

(1) Strain and temperature amplitude history on the floating roof were measured by using optical fiber gauges. The maximum strain around the stiffener rings was around 400μStrain. However, the value of the estimated maximum stress was much smaller than the value of tensile strength of the general structure steel.

(2) The initial cracks which occurred from any causes were discussed by probabilistic fracture mechanics approach. Even though there were initial cracks on the deck surface, they were unlikely to propagate and penetrate through the deck due to cyclic thermal stress.

(3) Considering the cases in this study, the facture probability can be estimated to be 4.3e-2 if the inspection shall be implemented every 8 years. Generally speaking, this probability would be relatively small, while the results depend on the probability function. Hence, anotherpossibility caused by the external factor such as Typhoon should be discussed in the future.

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