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Reliability Analysis of Ice-Induced Fatigue and Damage in Offshore Engineering Structures*

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Abstract — In Bohai Gulf, offshore and other installations have collapsed by sea ice due to the fatigue and fracture of the main supporting components in the ice environments. In this paper presented are some results on fatigue reliability of these structures in the Gulf by investigating the distributions of ice parameters such as its floating direction and speed, sheet thickness, compressive strength, ice forces on the structures, and hot spot stress in the structure. The low temperature, ice breaking modes and component fatigue failure modes are also taken into account in the analysis of the fatigue reliability of the offshore structures experiencing both random ice loading and low temperatures. The results could be applied to the design and operation of offshore platforms in the Bohai Gulf.

Key words: *reliability*; *fatigue*; *ice*; *offshore structure*; *crack*

1. Introduction

Offshore engineering structures in ice environment in Bohai Gulf experience not only ice loading but also temperatures as low as nearly 243 K. The interaction of sea ice and low temperatures on structures caused the collapse of a fixed offshore platform in 1969 in the Gulf (Fang *et al.*, 1995; Duan, Wu and Gao, 1999). The investigations on the collapse show that the main cause leading to the collapse is the fatigue and fracture of components of the platform, especially the legs for the final fracture (Duan, 1997; Duan , Wu and Gao, 1999).

Structural reliability of the platforms is one of the main concerns of offshore oil companies, and the fatigue reliability is taken for an important item to assess the safety of the structures receiving ice loads, which are considered as random variables. In order to obtain the strength probability distribution of the structural materials, 200 specimens were tested to investigate the fatigue strength and fracture toughness under low temperature and random ice load (Fang, 1996).

Ice loads on structures are mainly controlled by ice thickness, ice compression strength, shape and size of the ice-contact area of the structures, *etc.* (Johnston *et al.*, 1999; Croasdale, 1980; Sanderson, 1988; Cammaert and Muggeridge, 1988). The probability distributions of ice thickness and ice compression strength are presented according to the field-recorded data of 20 years in Bohai Gulf. The frequency distributions of ice velocity and floating direction, which affect ice-structure interaction, are also given.

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Two failure modes for structural components of offshore platforms in ice areas, fatigue failure by daily ice and fracture failure by extreme ice loading, are investigated. The reliability models and failure functions for these two modes are developed based on reliability theory, and a corresponding assessment software OSFAC is developed to evaluate the structural safety of offshore platforms.

2. Strength Probability Characters of Offshore Structural Steels

To investigate the fatigue and fracture of structural components or materials under field ice loading and low temperatures, a testing system was established (Fang and Duan, 1995; Duan, 1997) and three key problems were solved, i. e., low temperature automatic controlling, fatigue crack propagation monitoring in hermetic low temperature chamber, and random field ice load simulating 200 specimens were tested by the system in order to obtain the $S-N$ curve and fatigue life probability distribution.

The S-N curves for A537 steel at room and low temperatures are shown in Fig. 1. They can be expressed as:

$$\lg N = 14.097 - 3.62 \lg S \qquad \text{(low temperature)}; \tag{1}$$

$$\lg N = 12.097 - 2.99 \lg S \qquad \text{(room temperature)}. \tag{2}$$

where S is the stress rang in MPa, N the number of stress cycles till crack initiation in 10^5 cycles.

It is shown that the probability of fatigue life follows logarithmic Gaussian distribution.

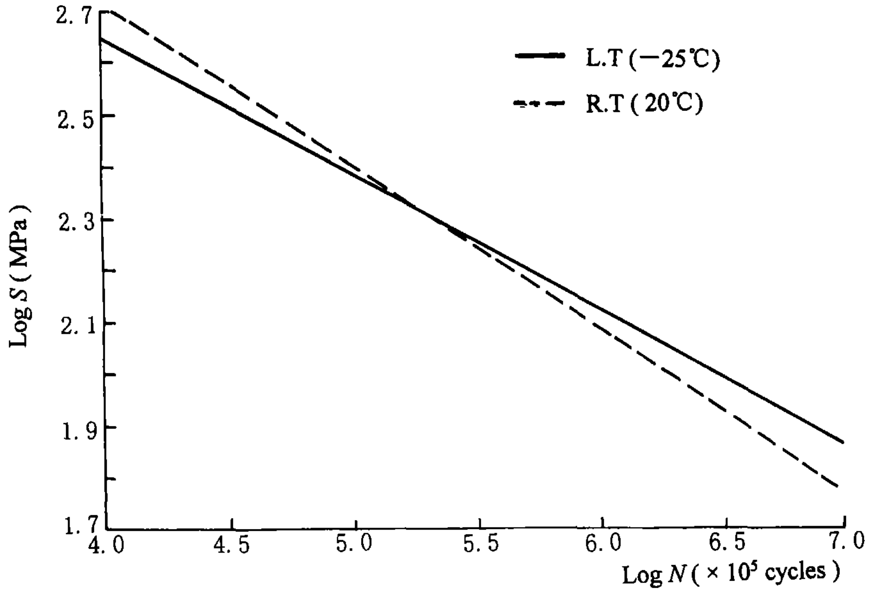

Fig. 1. S-N curves of tubular joint (T-type) at low and room temperature.

Fig. 2 shows the (da/dN) versus ΔK correlation for A537 steel under random ice loads and at room and low temperatures, where (da/dN) is the crack growth rate, and ΔK the stress intensity factor range. The experimental coefficients C and m in the (da/dN) versus ΔK correlation for different breaking modes of ice sheets are listed in Table 1., where C and m are test constants defined by material parameters, environment temperatures and loading frequencies as well (Duan, Li and Li, 1999; Duan, Gao, Li *et al.*, 1999). They are random variables defined by some specified distributions (Ding *et al.*, 1999).

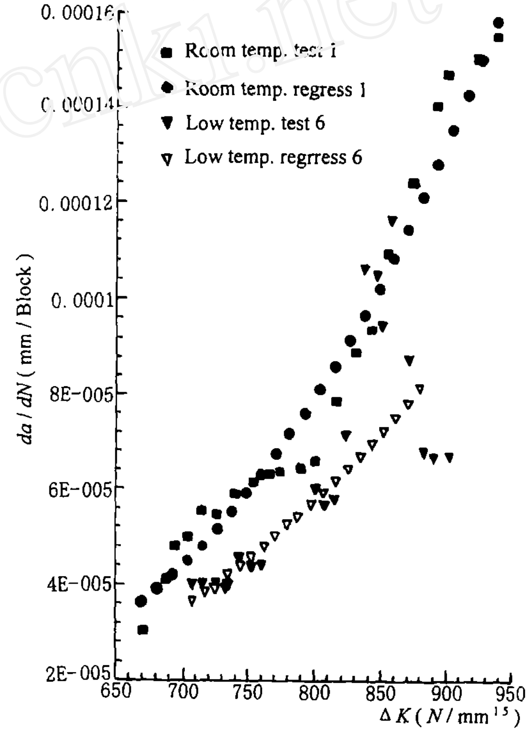

Fig. 2. Fatigue crack propagation curves of A131 steel welding joint under random bending ice load and low or room temperature.

Table 1 C and m in the (da/dN) versus ΔK correlation

Breaking modes of sea ices sheet	$T = 20$℃		$T = -25$℃	
	C	m	C	m
Bending	1.726E − 17	4.36	2.1405E − 15	2.59
Crushing	1.61E − 12	2.559	5.972E − 11	2.02
Bucking	2.8177E − 12	2.448	2.745E − 13	2.8255

The crack tip opening displacement (CTOD, δ_c), experiments at different temperatures are conducted and the probability characters are obtained. The $R-\delta_c-T$ curves for δ_c at five different reliabilities RK are shown in Fig. 3. The probability density functions (PDF) at different temperatures for steel A131 are shown in Fig. 4. It can be seen that the probability distribution of CTOD follows the Weibull distribution and its three parameters α, β and η as well as the corresponding statistical characteristic values of CTOD are shown in Table 2.

Table 2 α, β and η in the Weibull distribution and statistical values of δ_c

Temperature (℃)	26	0	−20	−40	−60
α	0.58241	0.012345	2.49E−05	2.22E−05	8.58E−06
η	0.37008	0.683151	0.606947	0.539569	0.196225
β	3.54413	2.004329	1.623951	1.578049	1.260967
Mean value (mm)	0.915006	0.606187	0.522806	0.466321	0.168927
Standard deviation	0.090921	0.275408	0.300359	0.276226	0.106155
Variation coefficient	0.099367	0.454328	0.574513	0.59235	0.628408

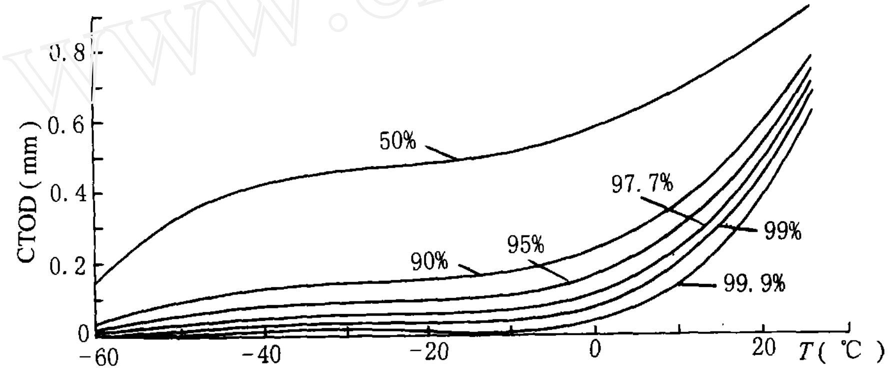

Fig. 3. CTOD at different temperatures (*T*) and reliability (*R*).

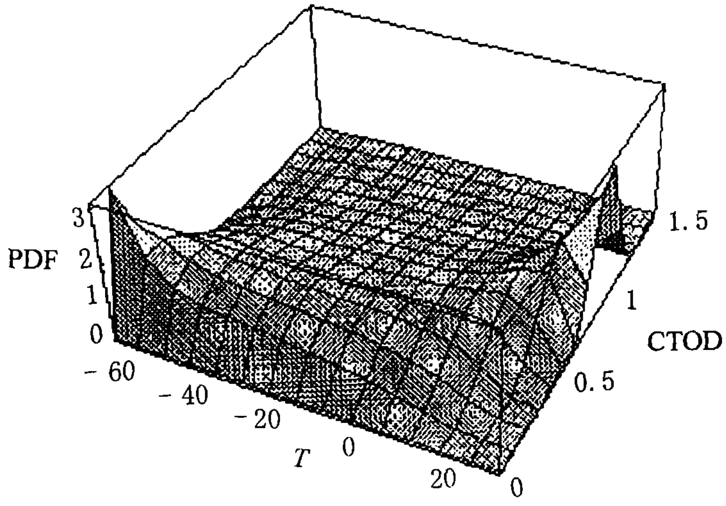

Fig. 4. Probability density function (PDF) of CTOD of A131 steel welding joint at different temperatures.

3. Ice Load and Its Probability Distribution

Ice load acting on a circular component of the offshore structure F_c can be expressed as follows (Fang, 1996)

$$F_c = \alpha_1 \sigma_c D^{0.5} H^n \tag{3}$$

where σ_c stands for the compressive strength of the ice sheet; H the ice thickness; D the diameter of the circular component; and α_1 and n are two coefficients related to the ice state. For the Bohai Gulf, $\alpha_1 = 0.628$ and $n = 1.176$ for single level ice sheet. Eq. (3) shows that the ice load F_c is directly proportional to the ice compressive strength σ_c and increases with the ice thickness H.

Fig. 5 presents the probability density function (PDF) of the annual maximum ice thickness distribution, and Fig. 6 the PDF of ultimate compressive strength distribution for the single ice sheet in Bohai Gulf. The probability distribution function $P(H)$ can be expressed as

$$P(H) = \exp\left[-\exp\left(-\alpha_2 (H-k)\right)\right] \tag{4}$$

where coefficients α_2 and k for the Bohai Gulf are shown in Table. 3.

Table 3 List of the coefficients for different regions

	North ice region	South ice region	East ice region
Coefficient k	31.081789	23.039715	31.180676
Coefficient α_2	0.25902	0.258525	0.307874
Relative coefficient γ	−0.976156	0.978571	0.967279
K–S inspection value D_n	0.106576	0.133274	0.114811

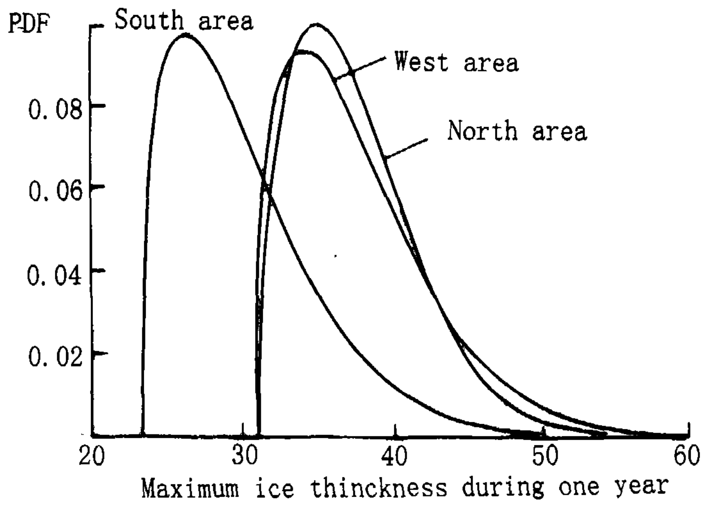

Fig. 5. PDF of maximum ice thickness per year in Bohai Gulf.

4. Reliability Analysis or Fracture Failure Under Extreme Ice Load

According to the residual strength model, the failure function Y_{ex} for this failure mode can be expressed by

$$Y_{ex} = R_f - BS_{\max} \tag{5}$$

where R_f is the residual strength of material, B is a coefficient, and $S_{\max}$ is the maximum hot spot stress in the structure generated by extreme ice load in one year.

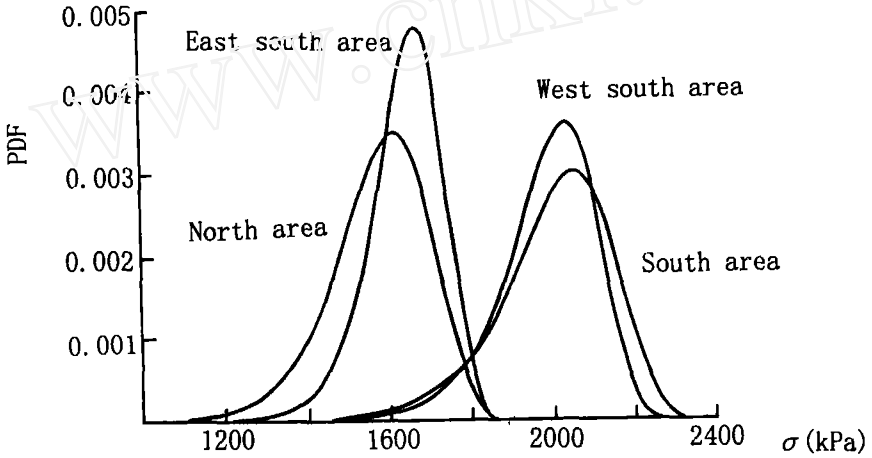

Fig. 6. Frequency distribution of direction and speed of floating ice.

Based upon the theory of fracture, the residual strength R_f can be expressed as (BSI PD6493, 1991)

$$R_f = \begin{cases} \left(\dfrac{\delta_c E \sigma_y}{2\pi a}\right)^{1/2}, & R_f \leqslant 0.5\,\sigma_y\,; \\ \left(\dfrac{\delta_c \sigma_y}{2\pi a}\right) + 0.25\sigma_y\,, & R_f > 0.5\,\sigma_y\,. \end{cases} \tag{6}$$

In the above formulas, R_f is a function of random variables δ_c (crack tip opening displacement) and a. The crack size a can be calculated by means of the initial crack size a_0

$$a = a_0 + \Delta a \tag{7}$$

where Δa indicates the crack propagation depending upon da/dN which is calculated by the Paris Equation

$$\frac{da}{dN} = C\,(\Delta K)^m = C\left[Y_1\,B\,(\Delta\sigma)\sqrt{\pi a}\right]^m \tag{8}$$

where Y_1 is a constant presenting the effect of the shape and geometry of the ice structure contacting surface, $\Delta\sigma$ is the stress range at the crack tip.

In general, a_0 follows the Weibull distribution with its three parameters being $\alpha = 1.12$, $\eta = 0.1$ and $\beta = 0.8$. Hence the crack size a also follows the Weibull distribution. Although the probability of δ_c and a are Weibull distribution. More work has to be done to determine if R_f also follows the same distribution.

The maximum stress $S_{\max}$ excited by extreme ice has a linear relation with the extreme ice load F_c which is a function of ice thickness H, the probability distribution function of $S_{\max}$ thus follows the same distribution as ice thickness H. Let x stand for the variable $S_{\max}$, the probability distribution function of $S_{\max}$ according to Eq. (4) can be expressed by

$$P(x)= \exp\left[-\exp(-\alpha_2(x-k))\right] \tag{9}$$

where coefficients α_2 and k can also be found from Table 3.

5. Reliability Analysis of Fatigue Failure Under Ice-Induced Vibration

According to a life model, the fatigue failure function Y_f can be expressed by

$$Y_f = N_t - N_d \tag{10}$$

where N_d is the design life taken as a constant, N_t the sum of crack initiation life N_c and fatigue crack propagation life N_p. N_c can be obtained from the S-N curve of the material as shown in Fig. 1, and N_p from the Paris Equation as discussed in fracture mechanics (Duan, Li and Li, 1999; Duan, Gao and Li *et al.*, 1999) or Eq. (8). Because the fatigue life N follows logarithmic Gaussian distribution, the fatigue reliability $R(t)$ can be expressed as

$$R(t)= P(Y_f > 0)= \frac{1}{S_{\lg Y_f}\sqrt{2\pi}}\int_0^{\infty} e^{\frac{1}{2}}\left(\frac{\lg y-\mu_{\lg Y_f}}{S_{\lg Y_f}}\right)^2 \mathrm{d}y$$

$$= \frac{1}{\sqrt{2\pi}}\int_{-\frac{\mu_{\lg Y_f}}{S_{\lg Y_f}}}^{\infty} e^{-\frac{1}{2}z^2}\,\mathrm{d}z = \Phi(Z) \tag{11}$$

where $Y_f = 0$,

$$Z= -\frac{\mu_{\lg y}}{S_{\lg y}} = -\frac{\mu_{\lg N_c}+\mu_{\lg N_p}-\mu_{\lg N_d}}{S_{\lg N_c}+S_{\lg N_p}}\,. \tag{12}$$

In order to obtain the logarithmic mean value of N_c, N_p ($\mu_{\lg N_c}$, $\mu_{\lg N_p}$) and standard deviation ($S_{\lg N_c}$, $S_{\lg N_p}$) from the S–N curve and the Paris Equation, the equivalent stress range S of random ice-induced vibration response must be obtained. This equivalent stress range S not only depends on the breaking modes of the ice sheet, but also on the fatigue of the acting ice sheet which is affected by ice floating direction and speed, ice thickness, and ice compressive strength. So an ice floating direction represents a fatigue environment in this paper, and the ice thickness or compressive strength the fatigue subenvironment. The probability distributions of maximum ice thickness per year and ice compressive strength are given in Fig. 5 and Fig. 6, and the distributions of ice floating speed are shown in Fig. 7 respectively for Bohai Gulf.

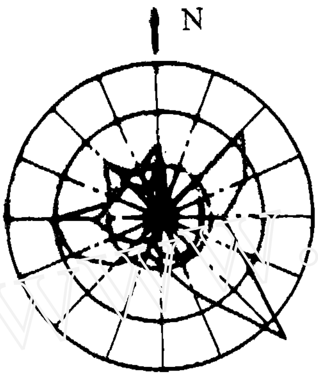

Fig. 7. Frequency distribution of speed of floating ice sheet.

Based on the Miner's cumulative damage rule, the equivalent stress range of S_e can be calculated according to the definitions of fatigue environment and subenvironments as discussed above

$$S_e = \left[\sum_{i=1}^{N_e} \sum_{j=1}^{n_i} \alpha_{ij} S_{e_{ij}} \right]^{\frac{1}{m}} \tag{13}$$

$$S_{e_{ij}} = \left[\frac{1}{N_{ij}} \sum_{p=1}^{N_{ij}} S_p^m \right]^{\frac{1}{m}} \tag{14}$$

where $S_{e_{ij}}$ is the equivalent stress range of the i-th fatigue environment and the j-th sub-environment which can be obtained from Eq. (14); N_e the number of fatigue environments; n_i the number of sub-environments of the i-th fatigue environment; α_{ij} is the percentage of the j-th sub-environment of the i-th fatigue environment; m the coefficients of the S-N curve (for regular fatigue analysis based on on S-N curve) or the $(da/\,dN) \sim \Delta K$ curve (for crack propagation analysis); N_{ij} the total number of cycles in the j-th sub-environment of the i-th fatigue environment, and S_p the stress range corresponding to each cycle.

6. Reliability Assessment of No. 8 Production Platform in Bohai-Gulf

Production platform No. 8 of 15-year design life was constructed in 1976. In 1991, underwater inspection detected many cracks in structural components. Bohai Oil Company wanted to prolong its service life to 1996, thus, assessment on the safety and reliability of the platform was carried out by means of the OSFAC software.

Table 4 shows part of the assessment results by extreme ice load (ice thickness 0.3 m), where a_t stands for the measured crack size in depth, a_c the one calculated by the Paris Equation, and the symbol ″ × ″ means that the existing measured crack size B_t is larger than the allowable crack size B_c as calculated on the basis of the Standard BSI PD6493 (BSI, 1991).

Table 5 shows the fatigue life of some structural components at given reliability due to ice-induced vibration under crushing ice loading. These results are also obtained by means of OSFAC.

Table 4 Assessment results for extreme ice load

Node No.	Element	Maximum stress (MPa)	Wall thickness (mm)	B_t (mm)	B_c (mm)	a_t (mm)	a_c (mm)	Assessment results
531	433~531	148.701	6.5	30	24.537	3	5.86	×
617	718~617	226.530	4.6	19	19.837	2	3.70	
633	625~633	98.421	3.5	20	28.968	2	4.97	
633	644~633	139.203	3.5	110	25.267			×
653	645~653	114.512	3.5	150	27.385			×
653	664~653	335.513	3.5	45	15.645			×
675	774~675	−134.963	10	1	178.96	1.21	1.21	
677	666~677	39.144	3.5	20	57.259	2	4.97	
732	631~732	−497.221	6.25	210	999.00			

Table 5 Fatigue life and reliability

Element No.	Node number	Failure node No.	Fatigue life (year)	Reliability
539	119~221	221	46.8991	0.67515
256	521~523	523	48.5761	0.716307
232	525~535	525	51.3691	0.774851
235	551~564	564	56.6195	0.876764
275	555~557	555	56.8148	0.880369
231	524~531	524	58.981	0.919556
262	551~656	565	60.2027	0.941025
236	555~565	565	60.2178	0.941288
273	535~537	535	62.38	0.97823

According to the assessment results, it is suggested that the service period of production platform No. 8 could be prolonged three years, and only a few structural components need to be repaired. The operation of production platform No. 8 in the prolonged years supports the above conclusions. The OSFAC software has been successfully applied to offshore engineering.

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