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Ice Induced Low Temperature Fatigue Crack Propagation in Offshore Structural Steel A131

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Abstract — To investigate the low temperature fatigue crack propagation behavior of offshore structural steel A131 under random ice loading, three ice failure modes that are commonly present in the Bohai Gulf are simulated according to the vibration stress responses induced by real ice loading. The test data are processed by a universal software FCPUSL developed on the basis of the theory of fatigue crack propagation and statistics. The fundamental parameter controlling the fatigue crack propagation induced by random ice loading is determined to be the amplitude root mean square stress intensity factor K_{arm}. The test results are presented on the crack propagation diagram where the crack growth rate da/dN is described as the function of K_{arm}. It is evident that the ice failure modes have great influence on the fatigue crack propagation behavior of the steel in ice-induced vibration. However, some of the experimental phenomena and test results are hard to be physically explained at present. The work in this paper is an initial attempt to investigate the cause of collapse of offshore structures due to ice loading.

Key words: *low temperature*; *fatigue crack propagation*; *offshore structure*; *steel A131*; *ice load*; *random vibration*

1. Introduction

The exploitation and exploration of offshore oil have been developing since the late 1960s in China, and more and more offshore fixed platforms have been set up and put into operation in the Bohai Gulf, South China Sea and East China Sea. Bohai Oil Field is the earliest and one of the largest offshore oil fields in China. It is located in the high latitude area which is covered with sea ice in the whole winter. The offshore platforms in the Bohai Gulf experience both ice loading and low temperature, leading to the collapse of the structures (Duan *et al.*, 1994; Duan and Liu, 1995a). Ice is a very complex material, and its loading on offshore structures is then very different from other environmental loads such as wave load, for example, ice load on strcutures has much more random characteristics and the loaded structures are under two different temperatures, the parts in the air under low temperature and the parts emerged in water under sea water temperature (Liu and Duan, 1996; Chung, 1987). Therefore, the vibration of offshore platforms in sea ice is a random process (Fang and Duan, 1994b; Duan and Liu, 1995d), causing a random stress state in the structure, and the fatigue damage as well as the crack propagation caused by the random stresses in the structures is either at low temperature or at water temperature (Liu and Duan, 1996). In order to ensure a sufficient ability of the platform in sea ice to resist not only random ice loading but also low temperature fatigue damage and crack propagation, many researches on ice-related problems have been carried out in China (Liu and Duan, 1995). Most of the research projects are financially supported by the National Natural Science Foundation of China and China National Offshore Oil Corporation. The researches cover the following areas: physical and mechanical properties of ice (Li, 1985;

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Chen and Lin, 1988), ice action on structures (Liu and Duan, 1995; Fang and Duan, 1995a), ice-induced vibration (Xu, 1983; Fang and Duan, 1994b; Duan and Liu, 1995b~d), low-temperature fatigue and damage of structures under ice loading (Duan *et al.*, 1995; Liu and Duan, 1996; Fang and Duan, 1992, 1994a, 1995b), structural design of offshore structures against ice loading (Duan *et al.*, 1994; Duan and Liu, 1995a, 1995c; Liu and Duan, 1995; Fang and Duan, 1994b, 1995a), etc. Much more widely conducted on ice problems in other countries are such projects as: ice properties studied as a material (Chung, 1987; Nixon and Smith, 1984), ice loads on structures (Derradji-Aouat, 1994; Frederking *et al.*, 1992) and ice-induced vibration of structures (Karna and Turunen, 1989; Sodhi and Morris, 1986; Jones, 1991). And low temperature fatigue of kinds of materials was studied in the last decade (Stephen, 1985). However, researches on low temperature fatigue and crack propagation of offshore structural steels were seldom reported except the above reviewed, and the ice-induced fatigue crack propagation (FCP) at low temperatures has not been published except the only paper by Liu and Duan (1996). This paper is the extension of that work (Liu and Duan, 1996).

2. Testing Procedure of Random Ice-induced FCP at Low Temperatures

2.1 The Purpose of the Test

Many tests and researches on the FCP behavior of offshore strctural steels under constant amplitude loads have been conducted by the authors as reviewed above. However, fatigue crack propagation under constant amplitude loads represents only the physical and mechanical features of the material itself, which can not stand for the feature of FCP under loads of variable amplitude or random loads that are the real environmental load conditions. To reflect the real FCP behavior under field ice loading, we conduct this test that is to: (1) study the fatigue crack propagation behavior of offshore structural steels under random ice loading; (2) investigate the effect of ice breaking modes on the FCP behavior; (3) find out the degree of temperature effect on ice-induced fatigue crack propagation.

This study is on the FCP behaviors of offshore structural steel A131 under different field ice loadings at the lowest environmental temperature in the Bohai Gulf.

2.2 Material and Test Specimen

ASTM A131 is an offshore structural steel that has not only high strength limit but high toughness, and has good weldability as well. However, it is developed not for use at low temperatures, so we choose it for this test. The mechanical properties and the chemical compositions are described in a previous paper of Liu and Duan (1996).

The test specimen is chosen to be the compact tension specimen, cut out from A131 steel plates in the L-T direction, the dimensions and configuration of which are shown in Fig. 1. All specimens are precracked to a desired initial length of 2 mm under constant-amplitude loading at room temperature.

2.3 Loading Conditions

For the reason that the stress history of a CT specimen is in agreement with its loading history, the stress response of the hot spot in the platform is taken as the loading history of the test

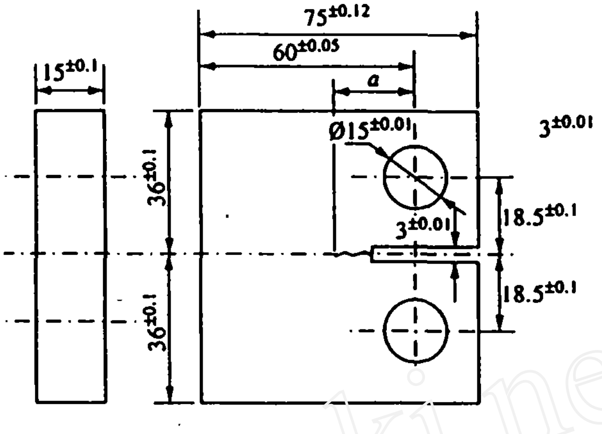

Fig. 1. Dimensions and configuration of the tested specimen.

of FCP in the specimen. From field investigation, the main ice modes in the Bohai Gulf can be divided as crushing, bending and buckling respectively according to the ice breaking conditions when it meets the structures. Different ice modes induce different stress states in the structrue, and such induced fatigue and crack propagation behaviors are therefore very different. For determination of the loading conditions of the test, ice-induced vibrations of fixed platforms are analyzed (Duan and Liu, 1995b; 1995d), and the corresponding stress responses are calculated (Duan *et al.*, 1996). The calculated hot spot stress responses of the platform are employed for the fatigue loading spectra of ice as required by the principle that the stress near the crack tip of the tested specimen is equal to or commensurate with the ice-induced hot spot stress of the platform. Such simulated loading histories in this test are presented in Fig. 2 respectively for crushing ice loading, bending and buckling ice loading, the data on the vertical axis omitted as required by China National Offshore Oil Corporation.

2.4 Test Procedures and Data Processing Software

The authors developed a testing system for low temperature FCP under random loading, having solved two key technical problems in the test (Duan *et al.*, 1995; Liu and Duan, 1996), one being the accurate low temperature control, and the other the measurement of crack length in the hermetically-sealed chamber. The testing system is described respectively by Duan *et al.* (1995) and Liu and Duan (1996). Here the schematic diagram of the system is given, as shown in Fig. 3. The test temperature is set to be 248 K, as indicated above, for each ice loading history. The test data are processed as described by Liu and Duan (1996) by a special-purpose software named FCPUSL developed according to the FCP theory and the theory of statistics. The software has the following functions:

(1) Searching for the maximum and minimum values of the random loads;

(2) Finding and storing the peak and valley values of the random load history, forming the data file of the peak and valley values including the corresponding time;

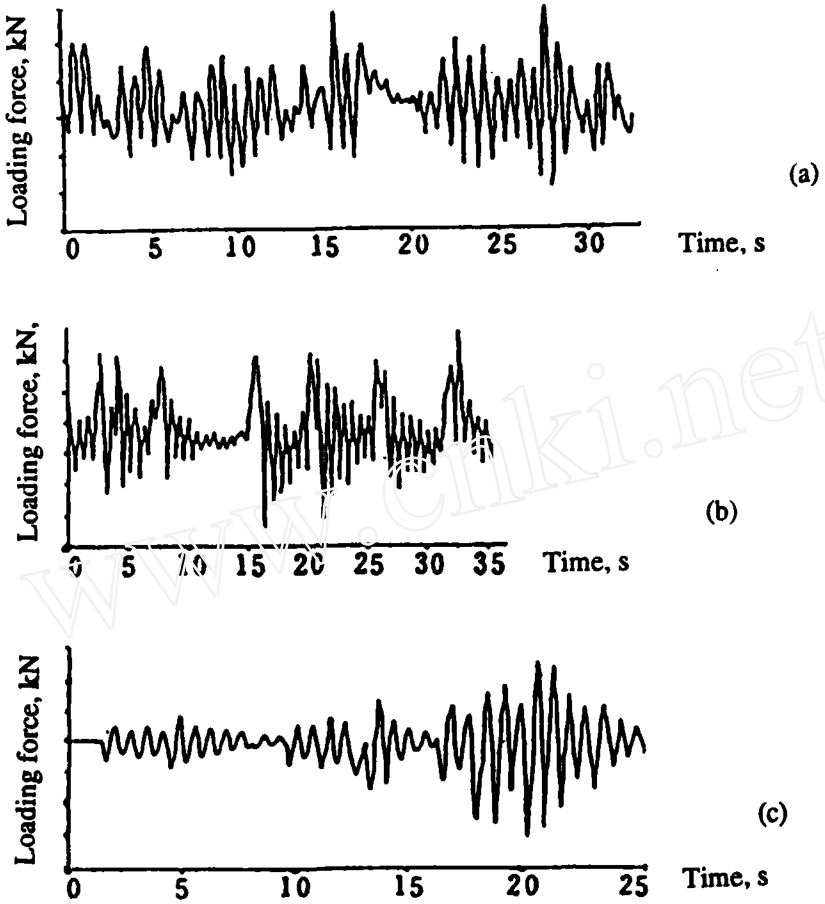

Fig. 2. Ice loading histories for FCP test at 248 K.
(a) crushing ice (b) bending ice (c) buckling ice

(3) Calculating the mean value, mean square value, root mean square value, variance and standard deviation of the random load history, all these parameters being called the statistical characteristic values or functions of the random loads;

(4) Calculating the statistical characteristic values of the peak values and the valley values, and the differences of the characteristic values of the peak values and those of the valley values;

(5) Calculating the characteristic values of the amplitudes (the differences between the nearest peak and valley values) of the random loads;

(6) Calculating the stress intensity factors (SIF) for any given characteristic value of the random load history as defined by the above items, such calculated SIF are called characteristic stress intensity factors;

(7) Calculating, by regression analysis, the coefficients of the polynomial relationship between the crack length and the number of blocks of the load history:

$$N = f(a) = \sum_{i=0}^{m} C_i a^i \tag{1}$$

where, N is the number of blocks, a is the crack length, and C_i the polynomial coefficient;

(8) Calculating the crack growth rate $da / dN = [dN / da]^{-1}$, dN / da is given from Eq. (1);

(9) Calculating the experimental constants in the Paris Equation for a given characteristic stress intensity factor, and the corresponding FCP life;

(10) Determining the optimum controlling parameter for FCP called the fundamental parameter controlling FCP under random loads.

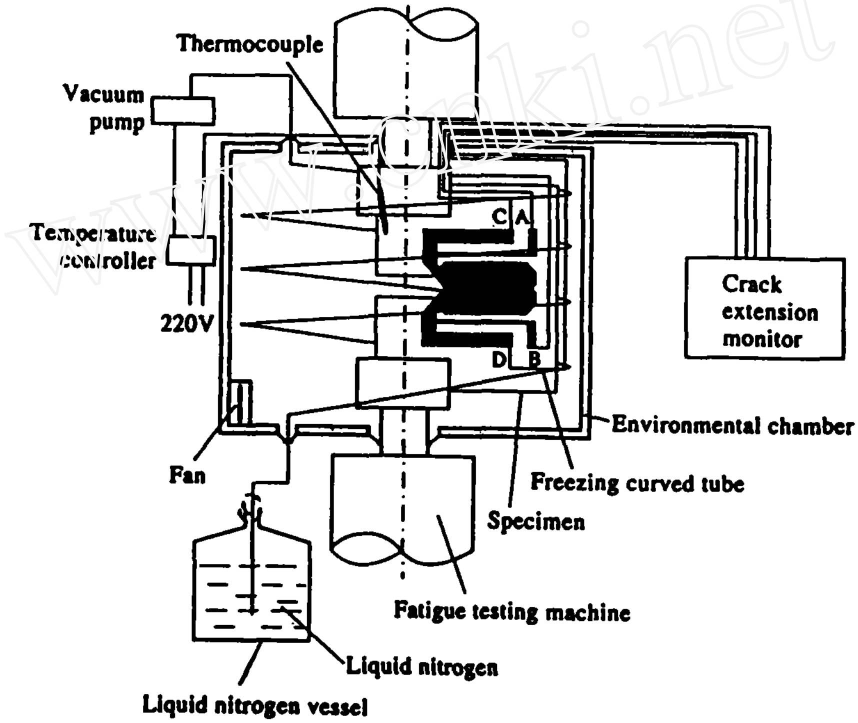

Fig. 3. The low temperature FCP testing system.

3. Optimization Results of the Controlling Parameter for FCP under Random Ice Loading

The optimization of the controlling parameter for FCP requires a great amount of calculation. To reduce the length of this paper, we omit the procedure of optimization. By comparing the crack growth rates calculated by every characteristic SIF through the Paris Equation, marked by R_c, with the tested da/ dN values, marked by R_t, the amplitude root mean square SIF, K_{arm}, is determined to be the fundamental parameter for all types of ice loading histories. Table 1 is the comparison for crushing ice loading, in which σ_k is the standard deviation of R_c and R_t:

$$\sigma_k = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(R_c - R_t)^2} \tag{2}$$

where the units of R_c and R_t are *m/ cycle*, n is the selected number of corresponding R_c or R_t for every characteristic SIF, the unit of which is $MPa\sqrt{m}$. Evidently, the standard deviation calculated from the amplitude root mean square SIF, K_{arm}, is the smallest. For the other two ice loads, i.e., bending and buckling, the same conclusion is obtained.

Table 1 Assessment result of the fundamental controlling parameter of FCP for crushing ice loading

Parameter	K_{m}	K_{rm}	K_{am}	K_{arm}	ΔK_{m}	ΔK_{rm}
$\sigma_k \times 10^{-5}$	0.963594	0.642718	0.643299	0.616969	0.640736	0.642351

K_{m} — mean stress intensity factor, K_{rm} — root mean square stress intensity factor, K_{am} — amplitude mean stress intensity factor, K_{arm} — amplitude root mean square SIF, ΔK_{m} — peak mean stress intensity factor range, ΔK_{m} — peak root mean square stress intensity factor range.

4. Results and Discussion

In the theory of fatigue crack propagation, the fatigue crack growth rate *da/ dN* is generally expressed as a function of stress intensity factor K or its range ΔK. It is well confirmed that *da/ dN* and K or ΔK take the form of the Pairs Equation for almost all materials and loading conditions, not only for constant amplitude loading but also for variable amplitude or random loading, that is, on the FCP diagram, ln (*da/ dN*) is linearly related with ln (K) or ln (ΔK) in most of the propagation stage, as shown in Fig. 4.

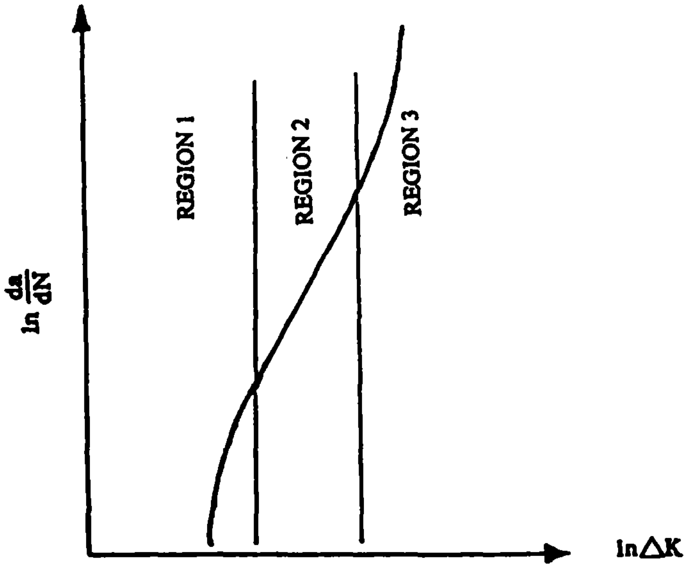

Fig. 4. Schematic show of the typical FCP under constant amplitude loading.

In this study, the test data of ln (da/dN) and $\ln(\Delta K)$ are processed by regression analysis and presented on the FCP diagram. For a better view of the difference of the FCP behaviors expressed by different ice breaking modes, the three FCP curves corresponding to the three ice breaking modes are presented in the same diagram as shown in Fig. 5. Evidently, the difference is large, and the following FCP behaviors can be concluded from the diagram.

For constant amplitude fatigue crack propagation, there are the evident propagation stages, i. e., threshold stage (crack initiating stage), stable propagation stage (Paris linear region) and unstable propagation stage (fast fracture). The schematic representation of the typical FCP behavior under constant amplitude loading is shown in Fig. 4. Comparing Fig. 5 and Fig. 4, we can see that there is no crack initiating stage, i.e., crack threshold stage, in the ice–induced FCP for any ice breaking mode, and except for buckling ice, there is no fast fracture stage on the FCP curves for both crushing ice and bending ice. For these two ice modes, cracks propagate in the form of the Paris law once they are initiated, and stable propagation lasts very long. The fracture takes place not during the time of the last and high acceleration of crack propagation as shown in Fig. 4, but happens at the time of gradual increase of the growth rate after the curve deviates from the linear stage. The fracture does not have any evident sign as expected in Fig. 4 where the fracture occurs soon after fast accelerated propagation takes place. However, for crushing ice, there seems to be an indication of fracture on the FCP curve that the crack growth rate remains almost unchanged for some time before the fracture occurs. The comparison of the

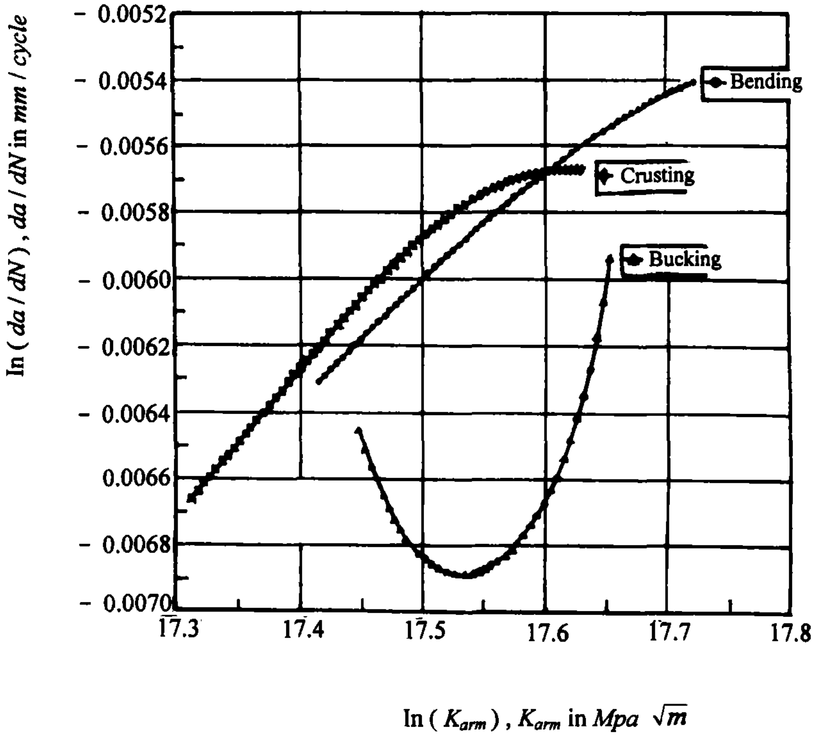

Fig. 5. FCP diagram of steel A131 under random ice loading at 248 K.

shapes of the curves for crushing ice and bending ice with the one in Fig. 4 leads to another conclusion that during non-linear propagation, the slopes of the curves for ice loading in Fig. 5 are inclined to decrease with the increase of K_{arm}, while the slope of the late fast unstable propagation in Fig. 4 tends to increase with the increase of ΔK. This is also an evident difference between the ice-induced FCP and the typical FCP by other kinds of loads. For buckling ice, besides the absence of the threshold stage, there is no stable linear propagation region. The curve takes the form of ″$\bigcup$″, and has the unstable propagation stage after some time of slow crack growth. The unstable propagation has the same form as in Fig. 4, but it seems that the crack growth rate is much smaller compared with that shown in Fig. 4. It is very strange that the crack should propagate in the case of deceleration after it is initiated. It is slowed down straight to a minimum growth rate, then begins to accelerate to an unstable fast propagation, to fracture. There must exist some inner cause for this unusual phenomenon. Unfortunately, we have not conducted the macroscopic to microscopic studies of the FCP behavior under such a loading condition, leaving the physical nature of such phenomenon undisclosed.

For the initiation of cracks, it is also very clear that the critical K^{i}_{arm} at which the crack is initiated is much smaller for crushing ice than that for bending ice or buckling ice as well, the one for buckling being the largest. However, the corresponding crack growth rate for buckling ice is not the largest; it is smaller than that for bending ice which induces the highest rate. That is to say, the crack can be initiated much more easily by crushing ice loading than by the other two ice loadings, and the crack initiating rate for bending ice is the highest. For the same characteristic SIF, in most of the crack propagation stage, the crushing ice induces the fastest crack propagation compared to the other two ice sheets, with the buckling ice inducing mush slower crack growth. On the other hand, for crushing ice, the critical K^{fc}_{arm} at which the fracture takes place is the smallest in comparison with that for the other two ice loads. In this paper, we simply call this critical value fracture SIF.

If the crack growth rate is described by means of the Paris Equation, the da/dN expressions for crushing and bending ice modes can be written as follows, which are the result of linear regression of the test data:

$$da/dN = 0.923064(K_{\mathrm{arm}})^{4.23991\times 10^{-3}}, \text{ for crushing ice loading} \tag{3}$$

$$da/dN = 0.936866(K_{\mathrm{arm}})^{3.38295\times 10^{-3}}, \text{ for bending ice loading} \tag{4}$$

where the units of da/dN and K_{arm} are $m/cycle$and $MPa\sqrt{m}$ respectively. From the exponents of the above expressions, it can be seen that crushing ice results in much faster acceleration of crack propagation due to the higher value of the exponent, usually called the Paris exponent, compared to bending ice.

According to the above discussions on the FCP behaviors for the three ice loadings at Bohai lowest temperature, the following cognition can be obtained: the crack in steel A131 can be most easily initiated under crushing ice loading, and it propagates at the highest acceleration and at the highest growth rate for a given characteristic SIF, and moreover, it has the smallest fracture SIF, therefore, we can conclude that crushing ice results in the worst fatigue crack propagation in steel A131 at low temperatures. Unfortunately, crushing ice is the most common ice type in the Bohai Gulf (Duan and Liu, 1995a). However, although buckling ice induces a much better low-temperature FCP behavior, it excites the worst vibration responses of the structures (Fang and Duan, 1994b). Therefore, joint investigation of ice-induced FCP behavior and dynamic ice-induced vibration has to be conducted for the safety of offshore structures in ice environments.

5. Concluding Remarks

Low-temperature fatigue crack propagation under constant amplitude loads has been widely studied, and the FCP behavior under variable amplitude loads at low temperatures has also been studied (Stephen, 1985), but most of the investigations are focused on the materials used in ground vehicles, civil structures, pipelines, aircraft and aerospace structures. Studies on ice-induced fatigue crack propagation have not been reported except the work conducted by the authors (Liu and Duan, 1996). The work reported here as well as that by Liu and Duan (1996) is just an initial attempt, however, the results are meaningful. Ice-induced FCP is not only an academic area but also a practical engineering problem. There are many challenging problems to be solved. Duan and his group are conducting studies of temperature related FCP behaviors under various kinds of random ice loading for different offshore structural steels, hoping that more and more scientists and engineers get interested in this area and resolve the problems.

As a conclusion, the main points can be drawn as follows from the present work:

(1) The amplitude root mean square SIF is optimized to be the fundamental parameter of fatigue crack propagation in Steel A131 under all selected ice conditions at low temperatures;

(2) Generally, there are two stages of crack propagation in ice-induced fatigue, one is the linear propagation stage in which the Paris Equation can be applied to the description of crack growth rate, and the other the non-linear propagation stage in which unstable fast propagation as occurs in most environmental conditions for almost all materials does not take place;

(3) To a large extent, the ice breaking modes affect the crack initiation, the FCP behavior and the Paris constants as well, some specific features of which are presented;

(4) The FCP diagram for buckling ice takes the form of "$\bigcup$", which represents very different FCP behavior from either the other two ice loads of crushing and bending or constant amplitude load or other random loads. The physical nature of such phenomenon remains unknown;

(5) The ice that excites much greater dynamic response of structures may induce much better low temperature FCP behavior, then joint investigation of ice-induced FCP and dynamic ice-induced vibration is strongly recommended to be conducted for the evaluation of the safety of the structures in ice conditions.

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References

Chen, W. and Lin, S. Z., 1988. Fracture Toughness of Bohai Bay Sea Ice, *J. of OMAE*, **110**, 409~413.

Chung, J. S., 1987. Ice Mechanics, *Applied Mechanics of Reviews*, **40**(9), 1191~1244.

Derradji-Aouat, A., 1994. Ice Loads on Conical Piers: A Finite Element Investigation, *Int. J. of Offshore and Polar Engineering*, **4**(1), 53~61.

Duan, M. L., Fang, H. C., and Chen, R. H., 1994. Field Investigation on Collapse of Bohai Former Platform No. 2 due to Sea Ice Loading, *Oil Field Equipment*, **23**(3), 1~4. (in Chinese)

Duan, M. L., Wen, H. W., Zhang, X. J., Jiao, X. M. and Fang, H. C., 1995. On the Test of Low-temperature Fatigue of Offshore Structural Steels", *Oil Field Equipment*, **24**(1), 14~17. (in Chinese)

Duan, M. L. and Liu, C. T., 1995a. Investigation on Failure of Offshore Steel Structure under Sea Ice Conditions, *Proceeding of the Int. Conference on Technologies for Marine Environment Preservation* (MARIENV'95), Tokyo, Japan, **1**, 71~74.

Duan, M. L. and Liu, C. T., 1995b. Dynamic Interaction between Ice and Offshore Structures: Self-excited Vibration, invited paper on the 4th China National Structural Engineering Conference, Fujian, also printed in *Journal of Engineering Mechanics*, a supplementary issue in 1995, 1070~1074.

Duan, M. L. and Liu, C. T., 1995c. Analysis of Ice-induced Displacement Responses of Offshore Fixed Platforms in Time and Frequency Domains", *Proceedings of the Int. Conference on Technologies for Marine Environment Preservation* (MARIENV'95), Tokyo, Japan, **1**, 255~258.

Duan, M. L. and Liu, C. T., 1995d. Random Dynamic Analysis of Offshore Structures under Ice Conditions, *Proceedings of International Conference on Strctural Dynaimics, Vibration, Noise and Control* (SDVNC'95), Hongkong, **1**, 679~684.

Duan, M. L., Liu, C. T. and Wang W. M., 1996. Dynamic Ice-induced Responses of Offshore Fixed Platforms, *China Ocean Engineering*, **10**(1), 55~63.

Duan, M. L., 1997. Low Temperature Fatigue Crack Propagation Behavior of Offshore Structural Steel A131 under Random Ice Loading, *Proceedings, 1997 OMAE*, **4**, Arctic / Polar Technology, ASME, 321~328.

Fang, H. C. and Duan, M. L., 1992. Temperature Dependent Crack Propagation of Steel A537 at Room and Lower Temperatures. *Proceedings of the Second (1992) Int. Offshore and Polar Conference*, ISOPE'92, **4**, San Francisco, USA, 130~136.

Fang, H. C. and Duan, M. L., 1994a. A Simplified Model of the Paris Law and a Low-temperature Critical Value of Danger about Fatigue Crack Propagation in Steel A537, *Oil Field Equipment*, **23**(1), 1~5. (in Chinese)

Fang, H. C. and Duan, M. L., 1994b. Ice-induced Displacement Responses of Fixed Platforms in the Bohai Gulf, *Proceeding of the Special Offshore Symp.*, China (SOSC-94 / PACOM-94), Beijing, China, 731~743.

Fang, H. C. and Duan, M. L., 1995a. A Study of Production Platform Design in the Bohai Sea under Low Temperature and Ice Loading, *Oil Field Equipment*, **24**(1), 1~8. (in Chinese)

Fang, H. C. and Duan, M. L., 1995b. Optimization of Fundametal Parameters of Fatigue Crack Propagation Control for Steel A537 at Room and Lower Temperatures, *Journal of the University of Petroleum*, China, **19**(1), 61~65. (in Chinese)

Krana, T. and Turunen, R., 1989. Dynamic Response of Narrow Structures to Ice Crushing, *Cold Regions Science and Technology*, **17**, 173~187.

Li, F. C., 1985. Probability Analysis of Design Ice Thickness in the Bohai Gulf, *Proc. POAC'85*, **1**, 241~248.

Liu, C. T. and Duan, M. L., 1995. *Problems on Structural Mechanics in Sea Ice Engineering*, invited paper by Journal of Mechanical Strengt on its 20th Anniversary of the first issue in 1975, **17**(3), 7~20. (in Chinese)

Liu, C. T. and Duan, M. L., 1996. Experimental Investigation on Low Temperature Fatigue Crack Propagation in Offshore Structural Steel A131 under Random Sea Ice Loading, *International Journal of Engineering Fracture Mechanics*, **53**(2), 231~237.

Nixon, W. A. and Smith, R. A., 1984. Preliminary Results on the Fatigue Behavior of Polycrystalline Freshwater Ice, *Cold Regions Science and Technology*, **9**, 267~269.

Sodhi, D. S. and Morris, C, E., 1986. Characteristic Frequency of Forced Vibrations in Polycrystalline Freshwater Ice, *Cold Regions Science and Technology*, **12**, 1~12.

Jones, S., 1991. Ice-structure Interation, Canada.

Stephen, R. I., 1985. Fatigue at Low Temperatures, ASTM STP 857, 293~312.

Xu, J. Z., 1983. Features of Frequency and Amplitude in Ice-induced Vibration of a Jacket Platform, *Proc. POAC'83*.