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A non-simultaneous dynamic ice-structure interaction model

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ABSTRACT

To simulate non-simultaneous ice failure effects on ice-structure interaction, an extended dynamic Van der Pol based numerical model is developed. The concept of multiple ice failure zones is proposed to fulfil non-simultaneous crushing characteristics. Numerical results show that there is more simultaneous force acting on all segments at lower ice velocity and there is more non-simultaneous ice failure at higher velocity. Variations of force records show a decreasing trend with increasing ice velocity and structural width. These effects can be attributed to the assumption that the size of ice failure zone becomes smaller with increasing ice velocity, which increases the occurrence of non-simultaneous ice failures. Similarly, the decreasing size of ice failure zone as velocity increases is explained as the reason of different ice failure modes shifting from large-area ductile bending to small-area brittle crushing. The simulation results from a series of 134 demonstration cases show that the model is capable of predicting results at different ice velocities, structural widths and ice thicknesses. In addition, analysis of the ice indentation experiments indicates that the mean and minimum effective pressure have an approximately linear relationship with ice velocity, which testified the assumption on variations of ice failure zone in the model.

1. Introduction

As the study of ice failure has advanced, non-simultaneous failure has gained increasing attention. It can be utilized to explain several well-recognized issues, such as higher localized pressure zone than global pressure (Johnston et al., 1998) and different failure modes at different indentation speeds (Sodhi and Haehnel, 2003). Kry (1978) proposed an estimation of statistical influence on non-simultaneous failure across a wide structure and divided the ice interaction surface into multiple equivalent zones that are statistically independent of each other. Then Kry (1980) found that ice generally had a more uniform contact with a structure at low velocity and more irregular contact at higher velocity. Ashby et al. (1986) explained the non-simultaneous failure as a size effect resulting from cracks of different lengths having been distributed statistically in ice. Bhat (1990) proposed that ice fails at many self-similar zones like many other fractals in nature and proposed an equation to control the size effect depending on the scale to estimate the irregular ice contact geometry.

Sodhi (1998) used segmented indentors to conduct a series of ice indentation tests and found simultaneous failure at low velocity and non-simultaneous at high velocity, and proposed an equation to estimate the decreasing size of ice failure length with increasing indentation velocity. Yue et al. (2009) installed ice load panel on a full-scale monopod platform and found simultaneous ice failure on different panels during lock-in condition.

At the same time, many ice-structure interaction numerical models have been developed. Matlock et al. (1971) proposed the very first ice-structure interaction model and many Matlock based numerical models have been developed since then (Huang and Liu, 2009; Karr et al., 1993; Withalm and Hoffmann, 2010). Non-simultaneous ice-structure interaction models have been developed based on Matlock model (Hendrikse et al., 2011; Yu and Karr, 2014) by extending the single ice strip into multiple strips moving towards the structure. Another method of modelling the interaction process is through utilizing Van der Pol ice force oscillator to control ice force fluctuations (Wang and Xu, 1991). Three distinctive structural response modes and ice-induced vibration

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Nomenclature

L_i	Ice failure length of each ice strip (m)
c	Constant distributed normally with mean μ and variance σ_s^2
H	Ice thickness (m)
v_0	Reference velocity (m s^{-1})
v	Ice velocity (m s^{-1})
K_0	Reference stiffness (kN m^{-1})
K	Structural stiffness (kN m^{-1})
N_{strip}	Number of ice strips
W_i	Width of an ice failure zone (m)
M	Mass of the structure (kg)
C	Damping coefficient (kg s^{-1})
ξ	Damping ratio
$\ddot{X}$	Structural acceleration (m s^{-2})
$\dot{X}$	Structural velocity (m s^{-1})
X	Structural displacement (m)
T	Time (s)
A	Magnification factor
σ	Ice stress (kPa)
D	Structural width (m)
q_i	Dimensionless fluctuation variable of each ice strip
a, ε	Scalar parameters that control the q_i profile
ω_i	Angular frequency of ice force (rad s^{-1})
f_i	Ice failure frequency (Hz)
B	Coefficient depending on ice properties
$\dot{Y}_i$	Velocity of each ice strip (m s^{-1})
Y_i	Displacement of each ice strip (m)
$\ddot{Y}_i$	Acceleration of each ice strip (m s^{-2})
σ_{max}	Maximum stress at ductile-brittle range (kPa)
σ_d, σ_b	Minimum stress at ductile and brittle range (kPa)
v_r	Relative velocity between ice and structure (m s^{-1})
v_t	Transition ice velocity approximately in the middle of transition range (m s^{-1})
α, β	Positive and negative indices to control the envelope profile
μ_P	Mean effective pressure (kPa)
σ_P	Standard deviation of effective pressure (kPa)
F_μ	Mean value of ice force (kN)
F_σ	Standard deviation of ice force (kN)
$\Delta\mu_p$, $\Delta\sigma_p$	The difference between the results from model and experiment for μ_p and σ_p

phenomenon were captured in Ji and Oterkus (2016). Physical mechanism of ice-structure interaction at each stage were discussed based on feedback mechanism and energy mechanism in Ji and Oterkus (2018).

In this study, following the concept of Matlock-based non-simultaneous modelling, an extension of Ji and Oterkus (2018) Van der Pol based model is introduced. Apart from the ice velocity and structural stiffness effect on the ice failure, a normally distributed variable is added in the ice failure length equation instead of a constant in the previous model. In addition, the previous one-dimensional single strip ice model is extended to a two-dimensional multiple strips ice model in this study.

2. Experimental data from Sodhi (1998)

Sodhi (1998) listed 159 test results including structural width D, ice thickness H, ice velocity v, mean μ_p and standard deviation σ_p of the effective pressure across the interaction surface. In Test 582 and 576 as well as Test 764 and 763, they are sharing similar ice thickness and structural width but different ice velocities. In Test 582 and 764 as well as Test 576 and 763, they share similar velocities but different ice thicknesses and structural widths. Therefore, different tests, Test. 582, 576, 764 and 763, are simulated by the numerical model. The time history of ice force and structural displacement are plotted and compared with the time history of experimental results.

To use the data more efficiently for blind test later, they are relisted in the Table 1. There are four main sections in total with different D ranging from 50 mm, 150 mm, 250 mm–350 mm. Each section has several groups of data from (A) to (K). Each group has the ice thickness with 1 mm difference, or rarely with 1.5 mm difference. Then each group is sorted from the lowest to the highest ice velocity. There are 25 tests that are not grouped together because of limited similar ice thickness, as shown in grey color in the Table 1. Therefore, 134 different tests are simulated by only changing the D, H and v. Then, μ_p and σ_p are compared between the numerical simulations and experimental results.

To show the ice velocity effect on the ice force level, four groups of data, (C), (E), (F) and (J) at different structural widths with similar ice thickness are selected from Table 1, as shown in Fig. 1. Fig. 1 (a) and (b) show the mean μ_p and standard deviation σ_p of the effective pressure from the Table 1, respectively. Fig. 1 (c) and (d) are the maximum and minimum effective pressure calculated from $\mu_p \pm 2\sigma_p$, respectively. In Fig. 1 (a) and (c), the pressure decreases from higher value to the lowest value first before ice velocity reaches the transition ice velocity. Reason of this pressure difference can be the difference between static frictional force at low velocity and kinetic frictional force at high velocity (Ji and Oterkus, 2018). After the transition ice velocity, the mean value increases approximately linearly with increasing ice velocity. It is due to the fact that there is more momentum energy transferred to the structure from ice, i.e. higher acceleration of the structure in the form of $F = M(\partial v/\partial T)$. Apart from ice speed effect, it shows that thicker ice has higher effective pressure and wider structure has lower effective pressure. In other words, the higher the aspect ratio of structural width D over ice thickness H, the lower the effective pressure is.

Fig. 1 (b) shows the standard deviation of pressure decreases with increasing velocity. The decreasing trend indicates smaller ice failure size and the occurrence of more non-simultaneous failure. Provided that the minimum effective pressure to be $\mu_p - 2\sigma_p$, Fig. 1 (d) also indicates that it has more dependency on ice velocity and less dependency on structural width or ice thickness. Slope at lower velocity is higher since simultaneous failure has large standard deviation caused by the maximum force value. For the same reason, the data points at lower velocity calculated in this method has less accuracy. Because there should not be any of negative pressure. Then the minimum value increases approximately linearly with ice velocity, which means that the lower bound of ice force follows the similar pattern. Considering that most part of the ice maintains constant contact with structure at high ice speed after failure, ice force will not reduce back to zero as that at lower ice speed.