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Experimental verification of dynamic ice load identification method

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ABSTRACT

Ice load is a prominent form of random dynamic load, which cannot be overlooked due to its impact on the structural response. This study proposes a new approach for identifying dynamic ice loads using Green's function, taking into consideration the convolution relationship between the load and response. A comparison between the Green's function method and influence coefficient matrix method in the identification of dynamic ice loads was conducted during an ice-stiffened panel test. Findings illustrate that the influence coefficient matrix method results in a larger outcome, while Green's function method is more accurate.

KEY WORDS dynamic ice loads, Green's function, ice-stiffened plate, influence coefficient matrix method

INTRODUCTION

Global warming has caused the melting of the Arctic sea ice, which leading to the gradual development of the Arctic shipping route and making it possible for ships to navigate through the Arctic region. Compared to traditional shipping routes, the Arctic route substantially shortens the distance for maritime transportation between East Asia and Northern Europe, making its commercial value undeniable (Ebinger and Zambetakis , 2010). Sea ice is one of the primary threats that ships face when navigating through ice-covered areas, as ship-ice interactions may lead to local damage to the vessel or even capsizing. Therefore, accurately and effectively assessing the impact of sea ice on ship structures is an important prerequisite for ensuring navigation safety.

The most reliable characteristics of hull ice load can be obtained by full scale test. The current practice is to indirectly obtain local ice loads on the hull structure based on measuring shear strain of the frames (Ritch et al., 2008). Therefore, how to calculate the ice load based on the ice-induced response of the ship structures has become a difficult issue in ice load measurement research. Leira et al. (2009) calculated the shear stress of ice load by analyzing the shear strain of the ribs and the relationship between strain and stress. Then, they integrated the shear stress along the ribs to obtain the ice load. Suominen et al. (2017) proposed an impact coefficient matrix method based on static equilibrium, taking into account the transmission of ice load between adjacent ribs, and conducted theoretical derivations and numerical analyses. Yong-Hyeon et al. (2015) used direct calculation and impact coefficient matrix method to identify local ice pressure based on the shear strain of the IBRV Araon ship, and verified the engineering feasibility of the impact coefficient matrix method. However, both direct calculation and the impact coefficient matrix method only recognize and calculate under static equilibrium conditions. As a typical random dynamic load, the dynamic response of ice load should not be ignored.

This article considers the dynamic response of ice loads and establishes an ice load identification model using the Green's function method. By designing a stiffened plate model experiment, the effectiveness of the influence coefficient matrix method and the Green's function method in identifying ice loads was compared and analyzed, validating the feasibility of the Green's function method in identifying ice loads.

1 Dynamic ice load identification method

According to the superposition principle of linear time-invariant systems, the strain response caused by an arbitrary dynamic load can be obtained through the superposition of responses to a series of unit impulse loads (Liu et al., 2011) (Figure. 1). Therefore, the relationship between ice loads on hulls and ice-induced strain can be expressed in the form of convolution integrals:

$$\varepsilon(t)=\int_0^t g(t-\tau)f(\tau)d\tau \tag{1}$$

where $\varepsilon(t)$is the time history of strain responce under iceloads; $g(t)$is the Green's function between the load on an action point and the response at the corresponding measuring point, which is used to represent structural dynamic characteristics; $f(\mathrm{t})$is the time history of ice loads.

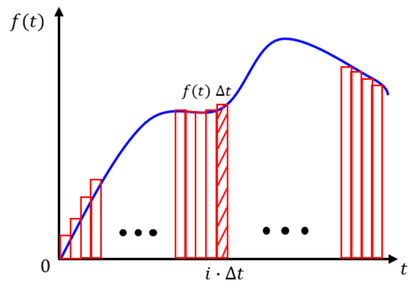


Fig.1 Load history represented by the impulse function

In the time domain, Δt is set to be a time interval of sampling and m the number of sampling points. Then, the convolution relationship of structural dynamic responses shown in Eq.(1) can be discretized as follows:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_m \end{bmatrix} = \begin{bmatrix} g_1 & 0 & \cdots & 0 \\ g_2 & g_1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ g_m & g_{m-1} & \cdots & g_1 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_m \end{bmatrix} \Delta t \tag{2}$$

where $\varepsilon_i$is structural response at $t=i\cdot\Delta t$; $g_i$is the Green's function value at $t=i\cdot\Delta t$; $f_i$is a load to be identified at $t=i\cdot\Delta t$.

Ice-ship impact is usually characterized by multiload action. The response induced by an individual load can still be expressed by Eq.(2), and the overall response of a structure is a linear superposition of responses induced by all individual loads. Therefore, the relationship between response and excitation undermulti-load action can be expressed as:

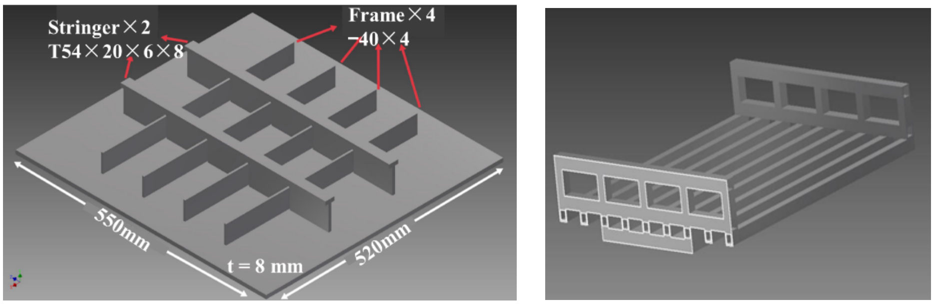
$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_N \end{bmatrix} = \begin{bmatrix} \boldsymbol{G}_{11} & \boldsymbol{G}_{12} & \cdots & \boldsymbol{G}_{1M} \\ \boldsymbol{G}_{21} & \boldsymbol{G}_{22} & \cdots & \boldsymbol{G}_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{G}_{N1} & \boldsymbol{G}_{N2} & \cdots & \boldsymbol{G}_{NM} \end{bmatrix} \begin{bmatrix} \boldsymbol{F}_1 \\ \boldsymbol{F}_2 \\ \vdots \\ \boldsymbol{F}_M \end{bmatrix} \Delta t \tag{3}$$

where M is the number of sub-panels of loads to be identified; N is the number of measuring points for load identification, satisfying $N \geq M$; $\boldsymbol{G}_{ij}$ is the Green's function matrix of the sub-panel j corresponding to the measuring point i; ε_j is the time history of structural response at the measuring point j; $\boldsymbol{F}_i$ is the time history of the load in the sub-panel i.

2 Dynamic ice loading model test

2.1 Dynamic ice loading test scheme

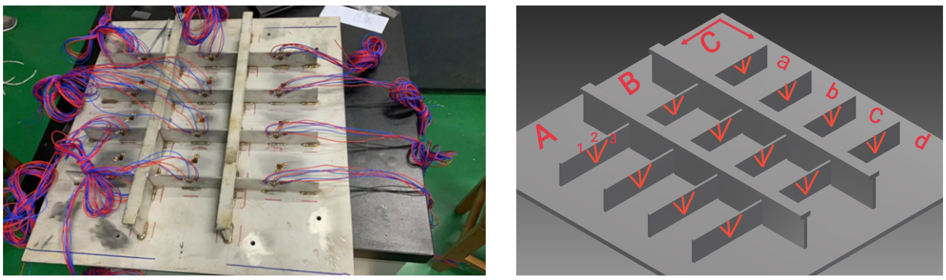
The stiffened plate structure is the main structural form used in ship structural design, and is primarily used to increase the overall rigidity and ice resistance of the structure through reinforcement in key icebreaking areas such as the bow and waterline of polar vessels. The test model is made up of an outer plate, two stringers, and four frames, and is manufactured by welding stainless steel materials. The main compressive surface dimension of the outer plate is 550mm×520mm×8mm. During loading, the short sides are fixedly supported by brackets made of Q235 steel, which are painted to prevent rust. The structural diagram of the test model and support is shown in Figure 2.



(a) test model (b) support

Figure 2. The structural diagram of the test model and support

The arrangement of gauge map in the test is shown in Figure 3. The shear strain, the positive strain perpendicular to the outer plate and the stress state can be measured at the same time by placing a three-direction rectangular rosette sensor on the frame structure. Three gauge points were arranged on each frame, and totaling 12 gauge points.



(a) gauging points on the frames (b) gauge map

Figure 3. The arrangement of gauge map

In order to accurately analyze the strain response of the structure under ice load, the artificial frozen ice samples were placed on the surface of the typical structure and compressed until the sea ice samples were completely destroyed. During the compression of the ice sample, the pressure on the indenter and the stress of the structure are recorded. Figure 4 shows the ice sample in the test.

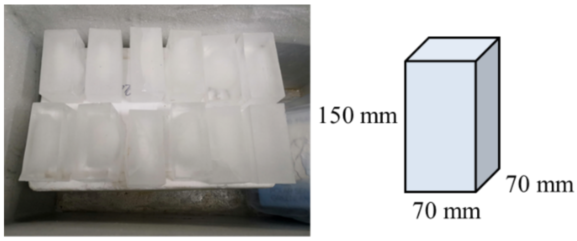
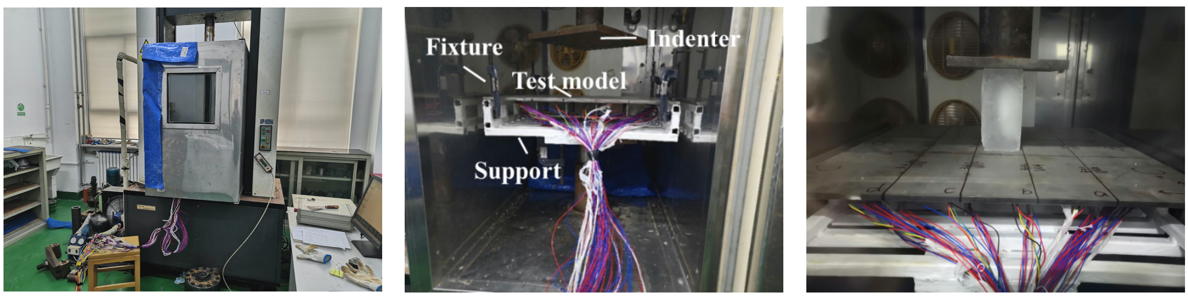


Figure 4. Ice sample for loading

The instrument required for this test includes two parts: applied load and structural strain test. The test instruments for applying ice load to the stiffened plate structure include a low temperature test environment chamber and a servo testing machine for applying load. Among them, the low temperature environment chamber can control the loading area at the required ambient temperature, and ensure that the temperature field of the ice sample is stable during the loading process. The testing machine can make the beam for uniform motion, so as to provide a stable compression load. The test scheme is shown in Figure 5.

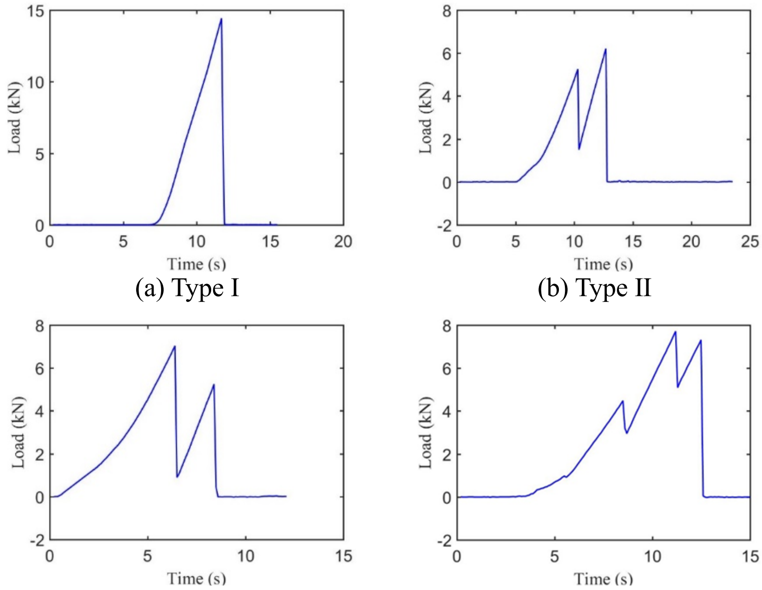


(a) low temperature environment chamber (b) test scheme (c) ice loading

Figure 5. Ice loading test scheme

2.2 Time history curve of loading force under ice compression

In the full-scale measurement of hull structure ice load, a complete ice load event includes the loading and unloading phases of the ice load, and the ice load period is defined as the time between the start of loading and complete unloading. In the research, the ice load events during the ice-breaking process are classified into four categories based on whether there is an intermediate peak in the loading or unloading stage (Lee et al., 2016). Type I is that there is only one ice load peak in the ice load event, and the shape is similar to a triangle. Type II is that the intermediate peak value appears in the loading stage of the ice loading event. Type III is that the intermediate peak occurs during the unloading stage of the ice load event. Type IV is that intermediate peaks appear in loading and unloading phases. In the compression loading test of the ice sample, ice loads also take four patterns due to changes in temperature and loading rate, as shown in the Figure 6, which reflects the similarity between the model test and the full-scale test. However, it is inconsistent that the duration of the unloading phase is similar to that of the loading phase in the full scale measurement, but the duration of the unloading phase is much lower than that of the loading phase in the model test.



(a) Type I (b) Type II

(c) Type III (d) Type IV

Figure 6. Four types of ice loads in dynamic ice loading model test

3 Analysis of ice load identification results

3.1 Finite element model calibration of stiffened plates

In the ice load identification problem on actual ships, accurate coefficients of the matrix in the ice load identification equation are often approximated using the finite element method because it is impossible to directly apply a fixed load at the certain area where the ice load acts (Fenz et al., 2018). Therefore the accuracy of finite element model is an important prerequisite for ice load identification. The finite element model of the structure was established in ANSYS, as shown in the Figure 7. The mesh size of the finite element model was set as 4mm×4mm, and the boundary condition was set as two short edges along the direction of the frame with fixed constraints. The gauging points were arranged in the central positions of the four frames. The finite element calculation parameters are listed in Table 1.

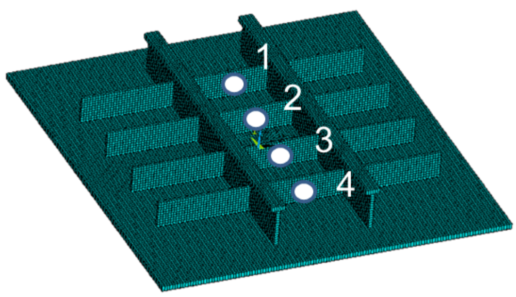


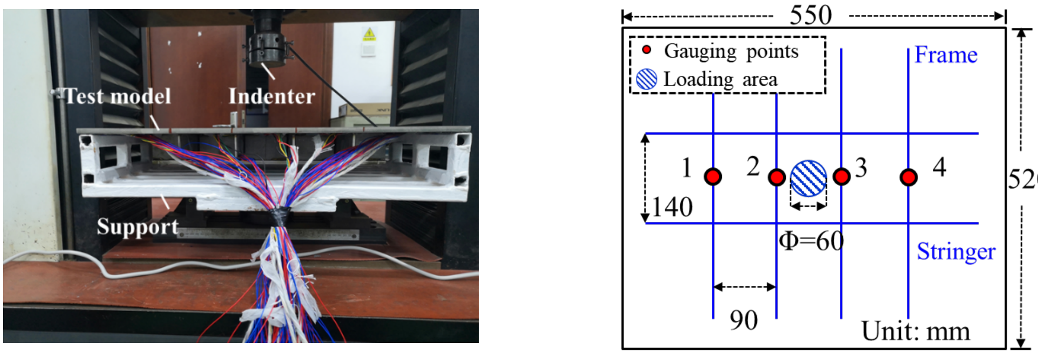
Figure 7. Finite element model of stiffened plate

Table 1. The finite element calculation parameters

Parameters	Symbols	Unit	Value
Elasticity modulus	*E*	GPa	193

Poisson ratio	v	-	0.3
Density	ρ	kg/m³	7930
Damping coefficient	ζ	-	0.02

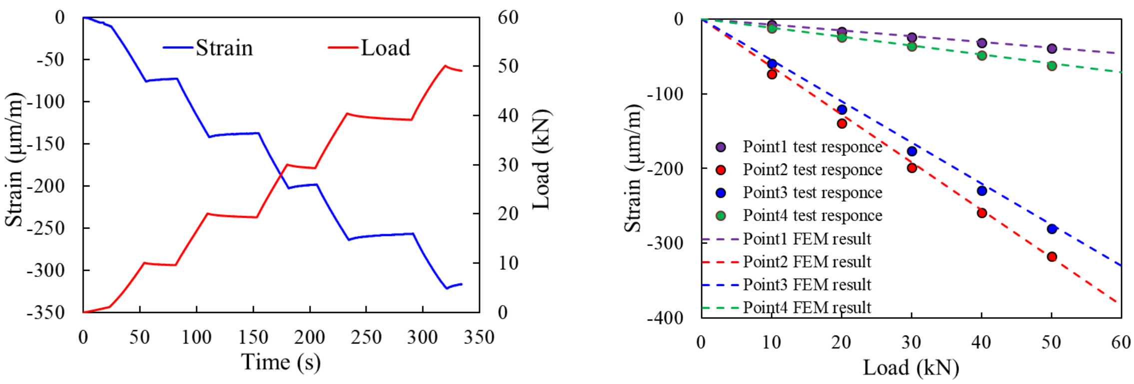
The calibration experiment for the finite element model was conducted using a compression test machine at room temperature, as shown in the figure. The loading range of the test machine is 0-100 t, and the shape of the test machine's indenter is a cylinder with a diameter of 60 mm. Figure 8 shows a schematic diagram of the loading area and measuring point positions. The loading machine is loaded in the central area of the model, and the accuracy of the finite element model is verified by comparing the measured strain response data under different load sizes with the finite element calculation results.



(a) Static loading test diagram (b) Loading area diagram

Figure 8. Finite element model calibration test

Controlled loading was applied to the testing machine to impose a step-wise surface load on the plate, while recording the strain responses of gauging points. Figure 9(a) shows the time-history curves of loading force and strain at gauging point 2. Frame bones exhibited synchronous strain responses under the action of loading force, and the signal noise in both loading force and strain signals was low. A static analysis was conducted in ANSYS to compare the actual strain responses of gauging points and the finite element strain responses under the same loading force, as shown in Figure 9(b). The finite element results corresponded well with actual measurement data, and the accuracy of the finite element model was evaluated using the slope as a indicator (Suominen et al., 2017). The calibration results of each gauging point are summarized in the table 2. The relative error between the finite element results and test data was less than 5%, and the error of the finite element model was completely within an acceptable range.



(a) Loading force and strain response time history curve

(b) Comparison between test strain response data and FEM results

Figure 9. Strain response in static loading test

Table 2. Gauging points calibration results

NO.	The slope of the FEM results μm·m^{-1}/kN	The slope of the test data μm·m^{-1}/kN	relative error
1	-0.78	-0.79	1.78%
2	-6.38	-6.28	1.45%
3	-5.50	-5.61	2.00%
4	-1.19	-1.24	4.24%

3.2 Comparison of identification results of dynamic and static ice loads

Based on a finite element model, static and dynamic simulations of the structure were conducted. The loading area and measurement point positions for the finite element analysis are shown in the figure 10, with a rectangular loading area of 70mm×70mm. The influence coefficient matrix was formed by applying a surface load of 1MPa to the rectangular area at the center of the structure, based on the strain response at four measurement points. The Green's function matrix was formed by applying a unit impulse load function to the rectangular area at the center of the structure, based on the convolution relationship between the load and strain response at the gauging points.

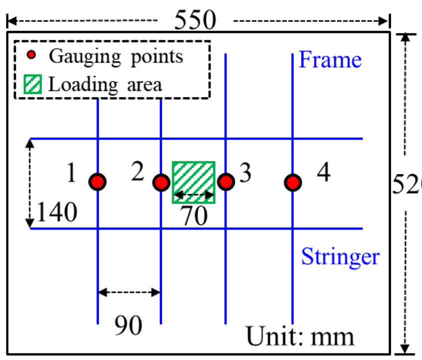
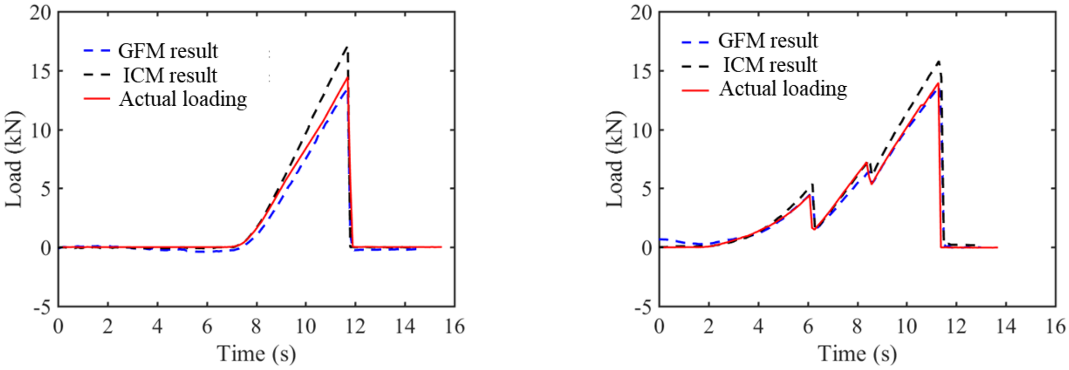


Figure 10. Schematic diagram of dynamic ice loading

The coefficient matrix method (ICM) and Green's function method (GFM) were used to identify the ice load time history in the experiment. Figure 11 shows the ice load identification results for two experimental conditions, which are the single peak ice load condition and the multi-peak ice load condition. Obviously, the ice loads identified by both methods exhibit similar curve characteristics to the actual load, but the ICM method produces higher identification results with an error of more than 10%. In contrast, the GFM method achieves higher identification precision with an error below 5%, indicating its advantage in identifying dynamic ice loads. The specific identification values are listed in Table 3. This suggests that the use of the impact coefficient matrix method to identify dynamic ice loads will result in overestimation due to the fact that ice loads in ice-going conditions typically exhibit dynamic load characteristics, which can lead to significant measurement errors. Therefore, the dynamic response of ice loads should be considered in structural design, which is significant for defining extreme ice load conditions in ice navigation. It is worth noting that the identification result of the GFM method may be lower than the actual load value, which may be due to the increase in the elastic modulus of steel structures at low temperatures. This requires further analysis in conjunction with the low-temperature mechanical properties of steel materials.



(a) case1 iceload identification result (b) case2 iceload identification result

Figure 11. Comparison of identification results of dynamic and static ice loads

Table 3. The finite element calculation parameters

Case	Methods	Identified pattern	Identified peak load	True peak load	Relative error
Case1	ICM	Static ice load	17.09	14.44	18.35%
	GFM	Dynamic ice load	13.49		4.85%
Case2	ICM	Static ice load	15.79	13.94	13.27%
	GFM	Dynamic ice load	13.67		3.32%

CONCLUSIONS

Based on the dynamic response of ice loads, this article proposes a Green's function method for identifying ice loads, and designs a model experiment of dynamic ice load loading to evaluate the accuracy of the method. Artificially frozen ice is used to compress the reinforced plate model during the experiment, and the ice loads exhibit a similar loading pattern as in full-scale measurements. By comparing the identification results of the Green's function method and the influence coefficient matrix method for dynamic ice loads, the results show that the latter tends to overestimate the ice loads, while the Green's function method has higher accuracy and can be used for identifying ice loads.

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