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Timco, G. W.

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THICKNESS DEPENDENCE OF THE FAILURE MODES OF ICE FROM FIELD OBSERVATIONS ON WIDE STRUCTURES

G.W. Timco

(Canadian Hydraulics Centre, National Research Council of Canada, Ottawa, K1A 0R6 Canada)

ABSTRACT

This paper presents a discussion of the ice failure modes that have been observed on wide caisson structures in the Arctic. These failure modes include ice bending (flexure), buckling, mixed mode, crushing, splitting and creep. It was found that bending and buckling are observed only for thinner ice whereas mixed mode, crushing and splitting are observed for all thicknesses of first-year ice with moving ice sheets. Creep is observed only with low loading rates. Analysis shows that the line loads increase with the ice thickness in a linear manner for ice crushing. This behavior appears to continue for thicker, Old Ice. The scatter in data is large with mixed mode and there is no clear trend of line load with ice thickness. There is insufficient information to determine the thickness dependence of bending, buckling, splitting or creep.

INTRODUCTION

It is well known that the load generated by ice failing against on offshore structure is a function of the failure mode of the ice. Crushing causes the highest load and bending generally produces the lowest load. The question is: “Why does one failure mode occur instead of another one?” Factors such as interface geometry and ice properties come into play here. It is generally thought that sloping structures induce bending whereas vertical-sided structures result in ice crushing. However, observations on wide offshore structures do not support this view. For example, observations on the Molikpaq in the Canadian Beaufort Sea show that crushing

occurred only about 1% of the time in spite of the fact that the structure is essentialvertically-sided (Wright and Timco, 1994). Mixed mode failure, bending and thermal-induced creep were also observed depending upon the local ice regime. Timco and Johnson (2003, 2004) have examined the global ice loads on the caisson structures that were used for exploratory drilling in the Canadian Beaufort Sea. They found that the global load increased with ice thickness and that the loads were a function of the failure mode of the ice.

There are two questions that arise from this. The first one is: "What factors affect the failure mode of ice acting on a wide caisson structure?" That is, why does one failure mode occur instead of another one? The second question is "How does ice thickness affect the loads caused by each failure mode?". The answers to these questions are important for input into analytical and probabilistic models for predicting ice loads.

This paper examines the second question. It looks at the available information and data on ice interacting with wide, vertical-sided caisson structures. A particular emphasis is placed on the role of ice thickness in influencing the load for different failure modes of the ice.

ICE FAILURE MODES

When ice interacts with an offshore structure it can fail in several ways. Fig.s 1 to 4 show photos of different failure modes including large-scale bending (Fig. 1), ice buckling (Fig. 2), ice rubbling and splitting in a mixed mode failure (Fig. 3) and ice crushing (Fig. 4). The first three photos were taken at the SDC during the winter of 2005/06 at the Paktoa C-60 site. Fig. 4 was taken at the Molikpaq at the Amauligak I-65 site. Since creep occurs over long time periods, there is no photo for creep. These failure modes have been identified by Timco and Johnson (2004) in developing their predictive equations for global ice loads. They found that the global load (L_{gl}) on a wide caisson structure could be determined from:

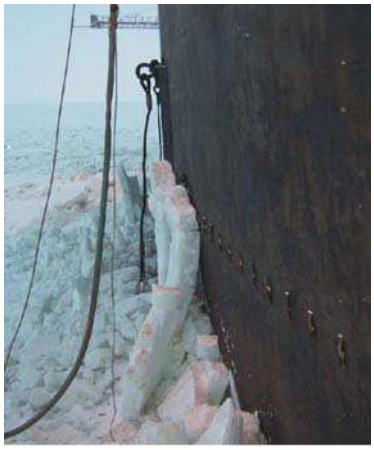

Figure 1: Large-scale ice bending on the SDC (Photo courtesy of S. McDermott)

$$L_{gl} = T_{fm}\, w\, h \tag{1}$$

where L_{gl} is the global load (in MN), w is the width (in m) of the structure, h is the ice thickness (in m). T_{fm} is a failure mode parameter with values of 1.09, 0.83, 0.63 and 0.18 MN/m^2 for crushing, creep, mixed-mode and bending failures respectively.

Fig. 2 Photograph showing ice buckling at the SDC in the Beaufort Sea (photo by the author)

Fig. 3 Photograph of mixed mode failure including rubbling and splitting at the SDC in November 2005 (photo by the author).

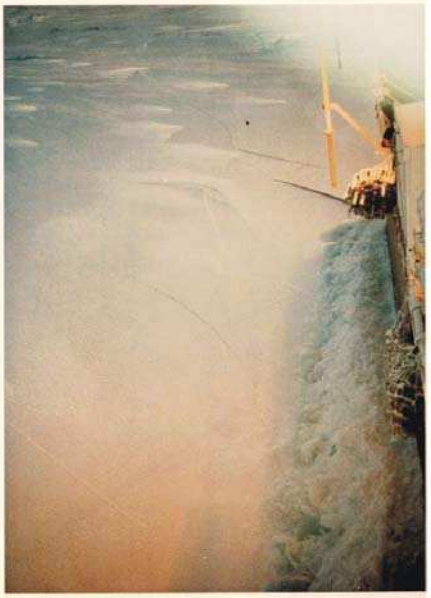

Figure 4: Ice crushing along the Molikpaq (Photo courtesy of Gulf Canada Resources).

It is possible to examine the full-scale data presented by Timco and Johnston (2004) on wide caisson structures (Molikpaq, SSDC, Tarsiut) to determine the conditions that cause different failure modes. Fig. 5 shows a plot of the Line Load (i.e. load per unit width of the structure) as a function of ice thickness for all data points. The plot has been subdivided to show the different failure modes of the ice. The data show that

for first-year ice, bending was only observed with thinner ice (0.6 m) whereas both mixed mode and crushing were observed over the full range of thickness of first-year ice (in this case from 0.6 m to 1.2 m). There is large scatter in the data with a best-fit ($R^2 = 0.23$) power law equation:

$$LL_{all} = 0.76\ h^{1.2} \tag{2}$$

where Line Load (LL) is in MN/m and the ice thickness (h) is in meters. A linear regression through all the data has a lower correlation coefficient of $R^2 = 0.16$ with a slope of 0.79. This is also shown on the plot. Fig. 5 includes the 95% Predictive Limits (indicated as dashed lines on the Fig.) for any new observations. The statistical analysis indicates that 95% of additional observations, similar to those in the sample, would fall within these bounds. The equations for these 95% upper ($LL^{u95\%}_{all}$) and lower ($LL^{l95\%}_{all}$) Predictive Limits are:

$$LL^{u95\%}_{all} = 0.67\ h + 0.59 \quad \text{.... for } 0.6\text{ m} < h < 1.2\text{ m} \tag{3}$$

$$LL^{l95\%}_{all} = 0.67\ h - 0.42 \quad \text{.... for } 0.6\text{ m} < h < 1.2\text{ m} \tag{4}$$

ICE BENDING

There are only a few data points for ice bending and they all occur with thinner ice. In general, it is not a common failure mode by itself on a wide caisson structure but it is observed in combination with other failure modes. The quantity of data available is not sufficient to examine the function dependence of the line load with ice thickness.

ICE BUCKLING

Ice can fail by buckling through thermally-induced or wind-driven loading. There is not enough information available to determine its functional dependence on ice thickness. The author has observed classic buckling occurring for moving ice of 0.2 m thickness, and as shown in Fig. 2, it can occur for ice up to about 0.4 m thickness. Buckling generally does not occur with thicker ice.

MIXED MODE (RUBBLING) FAILURE

Ice failing in a mixed failure mode can take many forms. Ice rubbling is generally the predominant mode but there can also be periodic fracture, splitting, local crushing, etc. The specifics of which local failure mode will occur are often a function of the interface geometry, and the thickness and speed of the ice. Mixed mode is a very

common failure mode for ice interacting with a wide structure.

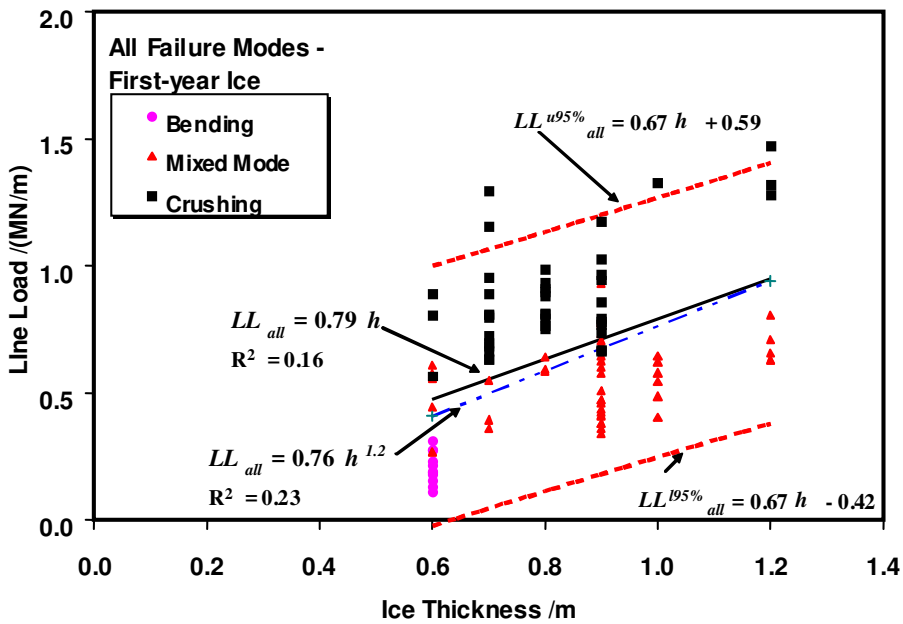

Fig. 5 Plot of the Line Load as a function of the ice thickness for various failure modes of the ice. The best-fit lines and 95% Predictive Limits are shown on the plot

Fig. 6 shows a plot of the Line Load (LL_{mm}) as a function of the ice thickness for first-year ice interacting with wide caisson structures and failing in a mixed-mode. There is considerable scatter in the data. This is understandable since mixed mode encompasses a variety of failure modes that would have different local pressures. Two lines are fit to the data. The first shows an average value which is independent of ice thickness (with a value of 0.55 MN/m width). The second solid line shows a linear regression line. In this case, the correlation is extremely low (R^2 = 0.04) indicating that there is little correlation of the Line Load with the ice thickness for mixed mode failure. The dashed lines show +2 and –2 standard deviations (0.15 MN/m) from the average. These represent Line Load values representative of the upper ($LL^{u95\%}_{mm}$) and lower ($LL^{l95\%}_{mm}$) 95% Predictive Levels. Thus, for mixed mode the Line Load (LL_{mm}) for first-year ice is:

$$LL_{mm} = 0.55 \text{ MN/m} \ldots\text{..for } 0.6 \text{ m} < h < 1.2 \text{ m} \quad (5)$$

$$LL^{u95\%}_{mm} = 0.85 \text{ MN/m} \ldots\text{..for } 0.6 \text{ m} < h < 1.2 \text{ m} \quad (6)$$

$$LL^{l95\%}_{mm} = 0.25 \text{ MN/m} \ldots\text{..for } 0.6 \text{ m} < h < 1.2 \text{ m} \quad (7)$$

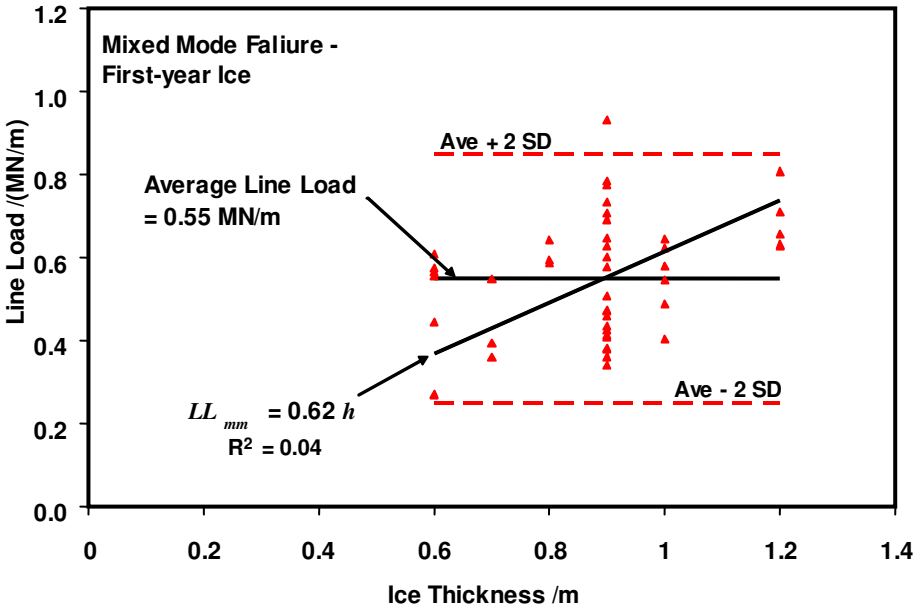

Fig. 6 Line Load as a function of ice thickness for mixed mode failure for first-year sea ice

ICE CRUSHING

Ice crushing is known to produce the highest loads on a structure and this results in the highest Line Loads (as shown in Fig. 5). Large-scale crushing on a wide structure is not a common occurrence since ice irregularities often induce a mixed mode failure pattern. However it does occur and information is available for both first-year and multi-year ice interactions. Fig. 7 shows a plot of the Line Load ($LL_{cr\text{-}fy}$) as a function of ice thickness for first-year ice failing by crushing. There is scatter in the data with values up to 1.4 MN/m width. A linear regression of the data (forced through the origin) gives a functional relationship between the Line Load and ice thickness as

$$LL_{cr\text{-}fy} = 1.08\ h \tag{8}$$

with $R^2 = 0.35$. Fig. 7 also shows the 95% Predictive Limits with functional form:

$$LL^{u95\%}_{cr\text{-}fy} = 0.92\ h + 0.50 \quad \text{.... for } 0.6\text{ m} < h < 1.2\text{ m} \tag{9}$$

$$LL^{l95\%}_{cr\text{-}fy} = 0.86\ h - 0.17 \quad \text{.... for } 0.6\text{ m} < h < 1.2\text{ m} \tag{10}$$

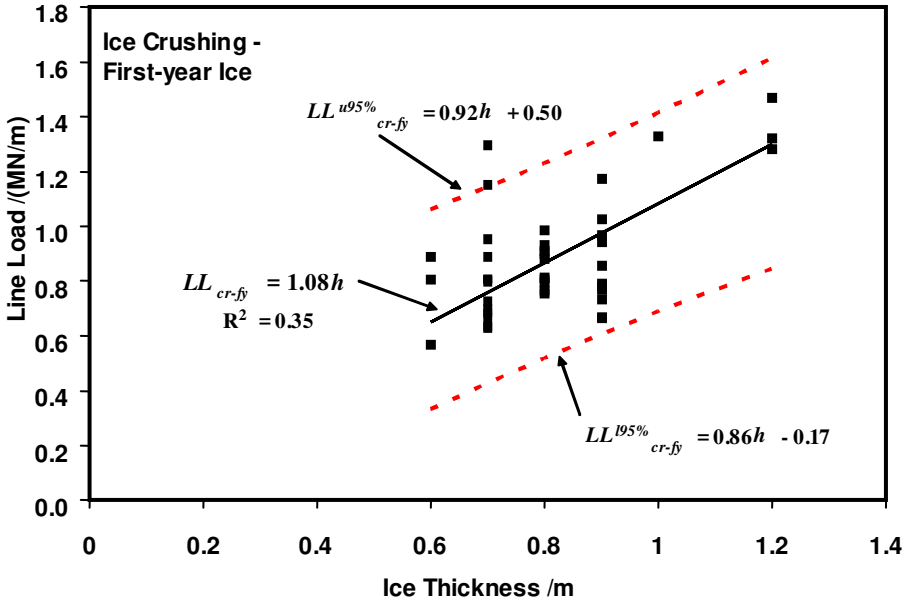

Fig.7 Plot of the Line Load as a function of ice thickness for first-year ice failing by crushing. The best-fit line and 95% Predictive Limits are shown on the plot

Ice crushing is also observed when multi-year (Old) ice interacts with a wide caisson structure. It is a predominant failure mode in this case. Fig. 8 shows a plot of the Line Load as a function of ice thickness for ice failing by crushing for both first-year ice and multi-year ice. A linear fit to the data (forced through the origin) is very similar to that for first-year ice only (Equation 8). It has a very high correlation ($R^2 = 0.96$) with the form:

$$LL_{cr\text{-}all} = 1.02\ h. \tag{11}$$

The Fig. also shows the 95% Predictive Limits with the form:

$$LL^{u95\%}_{cr\text{-}all} = 0.99\ h + 0.66 \ \ldots\ldots \text{for } 0.6 \text{ m} < h < 7 \text{ m} \tag{12}$$

$$LL^{l95\%}_{cr\text{-}all} = 0.97\ h - 0.47 \ \ldots\ldots \text{for } 0.6 \text{ m} < h < 7 \text{ m} \tag{13}$$

Thus it appears that a linear relationship works well for ice crushing for all ice types.

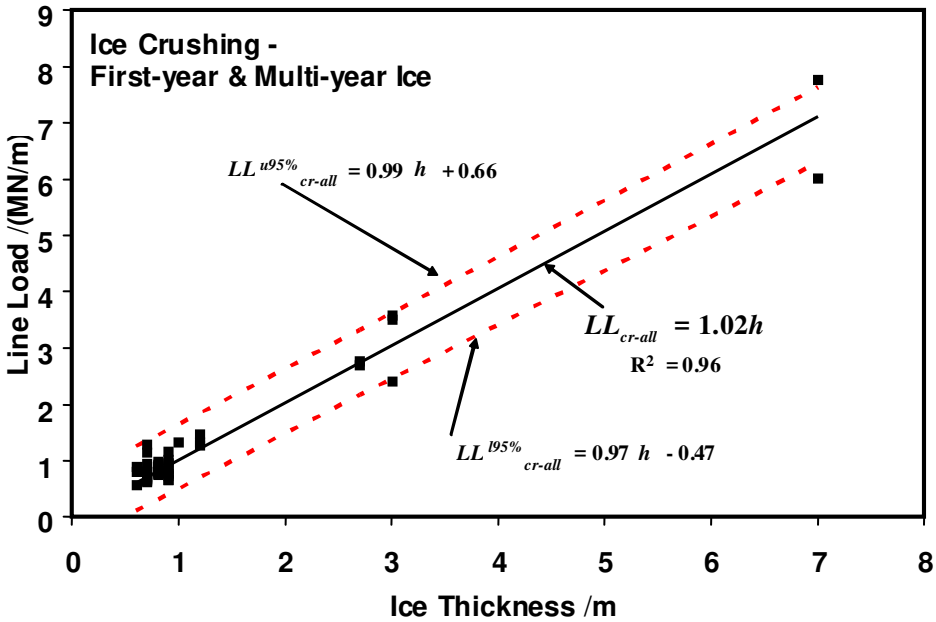

Fig.8 Plot of the Line Load as a function of ice thickness for both first-year ice and multi-year ice failing by ice crushing showing the linear relationship.

The best-fit line and 95% Predictive Limits are shown on the plot

SPLITTING

Large-scale splitting has been observed in ice interacting with wide caisson structures for both first-year ice and Old ice. It takes the form of a large crack that physically separates the ice floe or ice sheet. It is often a component of mixed mode failure. Measurements of ice loads on caisson structures do not give any information on the thickness dependence of this failure mode. It is known, however that a large-scale split can reduce the confinement in the ice and this can reduce the loads. Research has been performed to try to understand the scale effect of the fracture toughness of sea ice (see e.g. Dempsey et al., 1999).

CREEP

Creep failure of the ice can occur due to either thermal loading or wind shear on the ice sheet. The failure time for creep is very long compared to the other failure modes discussed in this paper. Creep failure occurred in first-year ice of up to 2 m thickness at the Tarsiut caisson structure. However, there is not enough reliable data of creep failure on wide structures to determine any relationship between the Line Load and the ice thickness.

SUMMARY

This simple analysis of full-scale data on wide caisson structures (Molikpaq, SSDC, Tarsiut) has shown that the relationship between the Line Load per unit width on a wide caisson structure has different functional relationships depending upon the failure mode of the ice. Fig. 9 summarizes the results. This Fig. is a schematic illustration showing the range over which various failure modes have been observed in sea ice (both for first-year and multi-year ice). It can be seen that bending, buckling, mixed mode and creep are observed only for first-year ice whereas crushing and splitting have been observed for both first-year ice and multi-year ice. Data are available to determine the functional relationship of the Line Load with ice thickness for only two failure modes. For mixed mode failure, there is no functional dependence observed and there is large scatter in the data. For ice crushing, there is a strong linear relationship with ice thickness.

Information presented in this paper can be used as input into numerical and analytical models of ice interacting with a wide caisson structure. It clearly shows that the failure mode is an important aspect of this situation. More field observations and measurements would greatly enhance this type of analysis.

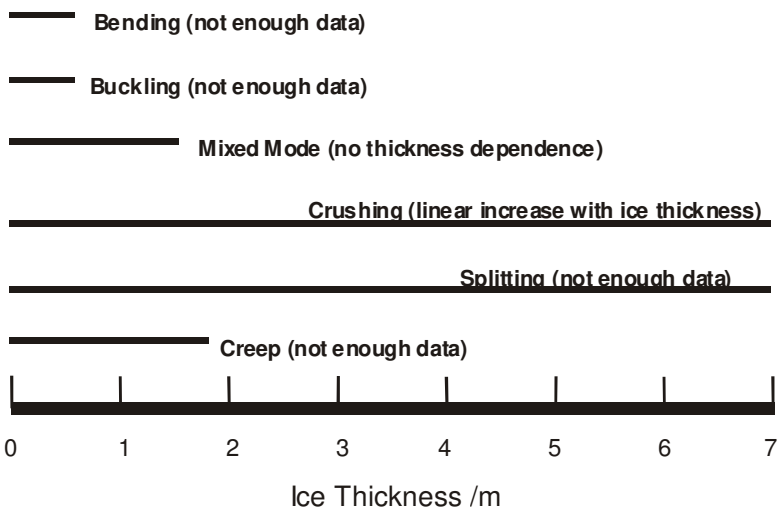

Fig.9 Illustration of the range of ice thickness over which various failure modes have been observed in ice interacting with wide caisson structures. The thickness dependence of the Line Load is indicated for each failure mode

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