Simultaneous ice crushing failure on narrow and compliant structures

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Abstract
Simultaneous crushing failure of ice sheet was observed in the field test of Bohai Sea. The ice force time histories from load panels on the jacket platform indicates that during quasi static loading and ice induced self excitation, local crushing ice forces increase and decrease concurrently. Subsequent study shows that the local crushing ice forces correlated with each other very well, which concludes that the contact between ice edge and vertical structure was full, in other words, ice sheet tends to fail in ductile manner. Since previous study has proved that quasi static loading and ice induced self excitation correspond with ductile and ductile-brittle transition failure of ice respectively, which means that simultaneous failure exists on narrow and compliant vertical structures, and the peak ice pressure on this type of structure must be higher than that of traditional calculations based on non-simultaneous failure.

Key word:
Ice crushing; Simultaneous failure; Narrow structure; Compliant structure; Peak ice pressure

1. Introduction
Cylindrical leg structure is the most popular option for fixed offshore drilling or production platforms. However in ice infested waters, ice sheet’s crushing on cylinder leg causes remarkable forces, which involve a great many open questions so far. Fig.1 includes a snapshot of ice sheet crushing on a cylinder leg and a sketch of the phenomenon. From the structure designers’ point of view, the primary question is how to calculate the peak crushing ice force which should not exceed resistance of the structure. In order to answer this question lots of attempts have been made, including theoretical model, numerical simulation and field or model tests (Sanderson, 1988, Sodhi, 2003, Timco, 2004, et al.).
Unfortunately, because of the extremely scattered and unexpected mechanical properties of natural ice, it is impossible to develop a universal formulation which is able to predict peak crushing ice force under every condition. Timco (2006) made a survey to ask 19 predictors to calculate ice force for one scenario, and the result indicated that after decades of study, there is still obvious disagreement among different formulas.

Usually the peak ice crushing force is expressed as global ice force divided by the nominal contact area:

\[ p = \frac{F}{Dh} \]  

where \( F \) is global crushing ice force, \( D \) and \( h \) is structure width and ice thickness respectively, and their product yields the “nominal” contact area. The nomenclature nominal contact area results from the fact that ice edge does not always fully contact structure’s surface, thus the real contact area is often smaller than nominal area. \( p \) is defined as ice pressure or effective pressure, which represents crushing ice force per area.

In general, the magnitude of peak crushing ice pressure depends on a great number of aspects (Sanderson, 1988), such as compressive strength of ice sheet, nominal contact area which is called “size effect”, and the ratio between structure width and ice thickness \((D/h)\), which is often called “aspect ratio”. It has been proved by many research work that peak ice pressure decreases as nominal contact area and aspect ratio increase.

The size effect attributes to two reasons: firstly the grain size of natural ice is big and comparable with macroscopical size, resulting in the fact that ice’s compressive strength is quite sensitive to the size of ice specimen, in other words, bigger ice specimen normally has lower strength; secondly, natural ice is a kind of material that shows brittle property in most cases, accordingly, wider structure and thicker ice sheet will increase the probability of crack formation and propagation, which leads to local failure and decrease of global strength of ice sheet.

The effect of aspect ratio can be explained using solid mechanics: as shown by the sketch in Fig.1, increase of aspect ratio means to increase structure width or to decrease ice thickness, which will change the stress state in ice sheet from triaxial compression to nearly plane stress state. According to solid mechanics, biaxial compressive strength is normally lower than that of triaxial compression, which leads to the aspect ratio effect.
Fig.2 Sketch of non-simultaneous and simultaneous failure

In spite of the effects discussed above, crushing ice pressure can be considered in another point of view, and scientists summarized the effects on ice crushing and describe it in a simple phenomenal way. Ashby et al. (1986) proposed a theoretical model as illustrated by Fig.2, in which it is the contact condition on the interface that determines the global ice force: left hand side figure denotes irregular contact on the interface, which leads to lower global force, thus this phenomenon is called “non-simultaneous failure”. In contrast, the right hand side figure denotes the full contact and consequent higher global ice force, which is called simultaneous failure.

In fact, the essential difference between simultaneous and non-simultaneous failure results from the failure mode of ice. Natural ice is a kind of material that can behave as different failure modes under compressive loading: under low stress or strain rates, ice fails in ductile manner, which means plastic deformation is dominant and few crack forms; otherwise under high stress or strain rates, ice fails in brittle manner which means fracture and cracks prevail. Non-simultaneous failure takes place when ice sheet crushes in brittle manner, resulting in irregular ice edge as shown in Fig.2. It is evident that during non-simultaneous failure, real contact area is smaller than nominal area remarkably, and on the other hand, brittle compressive strength is lower than maximal ductile compressive strength, resulting in lower global ice force than that of simultaneous mode.

Because modern continuum and fracture mechanics are not able to predict ice crushing process, applicability of crushing ice force formula has to be tested using data from field or model tests. So far, lots of field and model tests have been conducted, and many of them indicated that non-simultaneous failure hypothesis is valid. Therefore, “low level ice force” becomes popular and it has been accepted by some offshore codes (Schwarz, 2001).

Non-simultaneous failure and low level ice force looks natural because of the brittle properties of ice in most cases. However, some researchers found that in the case of narrow structure under slowly static loading, simultaneous failure might arise (Sodhi, 2001, 2003, Bjerkås, 2004). Existence of simultaneous failure implies that sometimes ice crushing tends to be ductile, and peak ice pressure calculation on these occasions should be reconsidered.

2. Field test in Bohai Sea

In order to study crushing ice force in the prototype condition, field tests were performed on a couple of jacket platforms in Bohai Sea, during which ice force, ice induced structural response, ice thickness and velocity were recorded concurrently (Yue et al., 2001, 2003). In the
two winters of 1999 and 2000, the two platforms named JZ9-3 MDP-1 and MDP-2 were instrumented as prototype structures, and the test set-up is shown by Fig.3.

![Fig.3 Field set-up on the platform JZ9-3 MDP-1](image1)

![Fig.4 Side view of the load panel](image2)

MDP-1 and MDP-2 have the same configuration except for the different location, and they are single leg platforms for oil tanker’s mooring. The basic parameters of the platform are listed in Table.1, and it can be seen that the structure is significantly narrower and more compliant than the lighthouse Norströmsgrund in Gulf of Bothnia and Canadian caisson structures (Engelbrektson, 1989, Timco, 2004).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure diameter (m)</td>
<td>1.5</td>
</tr>
<tr>
<td>Stiffness at ice level (kN/m)</td>
<td>48600</td>
</tr>
<tr>
<td>Top mass (kg)</td>
<td>34000</td>
</tr>
<tr>
<td>Lowest natural frequency (Hz)</td>
<td>2.32</td>
</tr>
</tbody>
</table>

In Fig.3, accelerometers were installed on the platform’s deck to detect structure’s vibration, and video cameras were applied to calibrate ice thickness and drifting velocity. At water level, a series of ice load panels were mounted on the cylindrical surface of the structure, and the detailed side view of the load panels is shown by Fig.4. It can be seen that the ice load panel consists of 12 independent segments forming two rows, hence the load panel covers the whole tidal range and local forces could be recorded independently during the ice season.

3. Analysis of the field test data

According to analysis of the field ice force data from JZ9-3 MDP-1 and MDP-2, crushing ice forces could be classified into three modes, which cause quasi static loading, self excited vibration of structure and stochastic structural response respectively (Yue et al. 2009). In the present paper only the first two modes quasi static loading and self excitation mode under relatively slow ice speeds will be discussed.
Quasi static mode takes place when ice drifting velocity is very low and it is actually static loading process without remarkable dynamic effect. Fig. 5 shows ice force time histories from the event took place at 17:00 pm on 10th Feb, 2001, in which the three local forces obtained by load panel segments number 9, 10 and 11 are plotted versus the same discrete time points. It is obvious that the three local ice forces increase concurrently and promptly decrease at the same time, which means that ice crushing might be simultaneous on the contact surface in this case.

![Fig.5 Three local ice forces time histories under quasi static process](image1)

Correlation analysis was performed to the quasi static ice forces data above, and the histogram in Fig. 6 plots correlation coefficients among local ice forces obtained by load panel segments number 9, 10 and 11 during quasi static process. The diagonal values in Fig. 6 are 1.0 precisely because they represent the correlation coefficients between local forces themselves respectively. It can be seen that correlation coefficients between different local forces are 0.6~0.9 approximately, which means that local ice forces correlate to each other very well.

When the ice velocity is a little bit higher than that of quasi static loading, a special phenomenon called locked-in may occur and crushing ice force fluctuates at the lowest natural frequency of structure, resulting in amplification of structure’s vibration. Subsequent analysis shows that this process is self excitation (Yue et.al, 2009). During analysis of the ice forces in ice induced self excitation, it was found that simultaneous failure arise as well. Fig. 7 shows the time histories of ice forces and structure’s displacement from the event 13rd, Feb, 2001, in which the upper two saw tooth curves are local forces and the lowest smooth curve is structure’s displacement.

![Fig.6 Correlation coefficient of local ice forces in quasi static mode](image2)
According to the two upper time histories in Fig.7 that local ice forces fluctuate concurrently, and the frequency of ice force is very close to structure’s response, which is called “locked-in” phenomenon. Therefore, simultaneous local ice forces indicate simultaneous failure of ice sheet under self excitation process. Fig.8 plots correlation coefficients among local ice forces obtained by load panel segments number 7, 8, 9 and 10 during ice induced self excitation. The histogram values in this figure are also close to 1.0, which means fairly well correlated.

Therefore, it is discovered that simultaneous crushing failure is available when quasi static loading and self excitation takes place. As discussed earlier, the simultaneous local crushing of ice sheet is very likely to imply the full contact between ice edge and structure, and it also means that ice tends to fail in regular ductile manner, instead of irregular brittle cracking. However, we need to understand that in what kinds of conditions simultaneous crushing failure probably take place, which will be analyzed as follows.

4. Conditions of simultaneous failure occurring

According to analysis of the field test data from Bohai Sea, it was found that crushing ice forces on vertical structures can be classified into three distinct modes: quasi static mode, locked in or self excitation mode and random vibration mode (Yue et al., 2009). It was also found that the three ice force modes can be explained using three failure mechanism of ice under different strain rates respectively, and the characteristics of the three failure mechanism is ductile, ductile-brittle transition and brittle.

It has been proved that quasi static loading takes place when ice sheet fails in ductile manner, ductile-brittle transition failure of ice results in frequency lock in of ice force and ice induced self excitation, and finally, random dynamic crushing ice force arises when ice fails in brittle manner under fast ice velocities. Accordingly, during quasi static and self excitation process, ice sheet’s failure mechanism is much closer to ductile rather than brittle, and this is why the crushing ice force time histories discussed in Fig.5 to Fig.8 show the characteristics of simultaneous failure. From the viewpoint of ice material’s failure, because loading speed is quite slow during quasi static and self excitation mode, low strain rates in ice sheet lead to dislocation of ice grain and fully compressive deformation inside ice, hence ice sheet fully contacts
structure’s surface and cause simultaneous failure. Anyhow it is the low strain rate that leads to ductile and simultaneous failure of ice.

![Configuration of relative velocity between structure and ice sheet](image)

It is well understood that under crushing process, strain rate in ice is a spatial field function of x, y and z coordinates, or it can be simplified to 2D situation as shown by Fig.9, in which the aspect ratio $D/h$ is so high that variation of strain rate in ice thickness direction can be neglected.

Strain rate in ice sheet depends on relative velocity between structure and ice sheet. As shown in Fig.9, if the deformed or so called damaged zone $L_d$ between the dashed line and structure is simplified to one dimensional compressive specimen, the average or nominal strain rate in the deformed zone can be expressed as:

$$\varepsilon_n = \frac{V_r}{L_d} = -\frac{V_{ice} - V_{str}}{L_d}$$ (1)

where $V_r$ is relative velocity, $L_d$ is length of the deformed zone in ice sheet, $V_{ice}$ is ice velocity and $V_{str}$ is structure’s velocity at ice level. The minus sign in the equation is because ice sheet is under compressive loading.

According to equation (1), the nominal strain rate in ice depends on three parameters: $L_d$ denotes the length of the deformed zone and it is a function of structure’s width and ice thickness; $V_{str}$ stands for structure’s velocity at ice level, and if we assume the simplest harmonic motion, structure’s velocity depends on amplitude and frequency of vibration; $V_{ice}$ is ice drifting velocity and it can change with wind, current etc. It can be seen that the values for $L_d$ and $V_{str}$ depend on parameters of structure and ice, thus they are in limited ranges, whereas $V_{ice}$ is able to change in a wide range, e.g. 0–1.2m/s in Bohai Sea. Therefore, ice velocity must be very low to restrict the strain rate in equation (1) to a low level, and then ice might crush in ductile and simultaneous manner.

Based on field tests on jacket platforms in Bohai Sea, in most cases ice velocity is quite high and create brittle failure of ice and non-simultaneous crushing, which produce random ice forces and vibration. On the other hand, only the very low ice velocities are able to induce
ductile and simultaneous failure, which cause quasi static loading and self excitation discussed earlier. Accordingly, the low ice velocity is the primary condition of simultaneous crushing occurring.

Besides, only the low ice velocity does not necessarily yield simultaneous failure. The experience on Canadian caissons and lighthouses in Gulf of Bothnia have told us simultaneous failure is not prevail on wide structure, this is because ice failure is not uniform on the contact surface if the structure is wide, and even though simultaneous crushing takes place in some local areas, it is difficult to make them fluctuate concurrently, as a result, the local forces are always non-simultaneous.

Compared with the structures at higher latitudes, e.g. the lighthouse Norströmsgrund is 7.5m wide and the caisson Molikpaq is 100m wide at water level, jacket platforms in Bohai Sea are much narrower, only 1.2~1.5m. Therefore, local ductile crushing is much easier to be synchronous on narrow structures, and this is another condition of simultaneous crushing occurring. Although the exact criterion of narrow structure on which simultaneous failure dominates can not be presented in this paper, at least it has been proved that simultaneous failure does occur on prototype structure.

Finally, the jacket platforms in Bohai Sea relatively compliant, which makes simultaneous failure easy to take place. Table.2 lists some dynamic parameters of four platforms. Other researchers have discovered that static crushing ice force will increase with structure’s compliance increasing (Kamesaki, 1996, Kärnä, 2008), which means that structures with lower stiffness are easier to cause ductile and simultaneous crushing failure of ice sheet. This might be explained as follows, considering the slowly loading process when ice sheet contact vertical structure. Relations among the main parameters can be expressed as following simple equations:

\[
\begin{align*}
F_p &= K_{str}X \\
X &= V_{ice}T
\end{align*}
\]

where \( F_p \) is peak ice force, \( K_{str} \) is structure’s stiffness at ice level, and \( X \) is maximal displacement of ice moving from initial loading until peak ice force is reached, which is also structure’s deformation at ice level. \( V_{ice} \) is ice moving velocity and \( T \) is the time interval for peak ice force is reached.

Assuming that peak ice force \( F_p \) is independent on structure’s stiffness \( K_{str} \), according to equation (2), structures with lower stiffness undergo bigger \( X \) than that of stiffer structure. If ice velocity \( V_{ice} \) is the same for both compliant and stiffer structure, the time interval \( T \) is longer for compliant structure. Accordingly, compliant structures provide longer time for ice loading, which indicates that strain rates in ice sheet must be lower and tend to make simultaneous failure and higher peak ice force \( F_p \). Therefore, it has been proved that increasing structure’s
compliance will make peak ice force go up. In addition, based on equation (2) higher value for $F_p$ and lower value for $K_{str}$ will increase $X$ and $T$, which enhance the effect of simultaneous failure and higher peak ice force.

According to the analysis above, it is concluded that simultaneous crushing of ice sheet on vertical structure might arise when the following conditions are satisfied:

1) Ice drifting velocity is adequately low, i.e. low ice velocity;
2) Structure’s width is small, i.e. narrow structure;
3) Structure’s stiffness at water level is low, i.e. compliant structure.

5. Conclusion and discussion

Simultaneous crushing failure of ice sheet is obtained from field tests on jacket platforms in Bohai Sea. It is realized that the essential difference between simultaneous and non-simultaneous failure is ductile damage or brittle fracture in ice sheet, besides, the dominant element of determining ductile or brittle failure mode is strain rate in ice, which depends on relative velocity between structure and ice sheet.

According to subsequent analysis, it is pointed out that simultaneous failure tends to take place on narrow and compliant vertical structures, under adequately low ice velocities.

Now that simultaneous crushing failure does exist on prototype condition, peak crushing ice force for narrow compliant structure should be carefully estimated, since popularly used low level ice force is not valid in this case.

Reference