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Proc., 18th Int. Conf. on Port and Ocean Eng. Under Arctic Conditions, Vol. I (2005) 387-398

ICE LOADS ON ELECTRIC POWER GENERATING STATIONS IN THE BELLE ISLE STRAIT

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ABSTRACT

Recently, the provincial government of Newfoundland and Labrador, Canada, issued a call for a pre-feasibility study for potential construction of a fixed link between Newfoundland and Labrador. Several concepts/ideas have been proposed. One old and popular concept is the construction of an immersed tunnel across the Belle Isle Strait (BIS). An alternative concept calls for the construction of a series of large concrete hydroelectric stations across the BIS and use these stations as piers for a bridge between Newfoundland Island and Labrador. Potentially, the "bridge" will pay for itself over time by generating electric energy from the natural tides in the strait.

The main objective of this research project is to conduct a study to evaluate the structural stability and the economic viability of the proposed power-generating stations across the BIS. The task of the structural stability deals with concerns related to whether or not the concrete hydroelectric stations are able to withstand the environmental loads (ice and hydrodynamic loads). The task of the economic viability, however, deals with estimating the electric power capacity that can be generated from the natural tidal waves and current in the strait.

In this paper, the work on the task for the structural stability of the concrete hydroelectric stations is summarized. More specifically, the results given in the paper are those dealing with the predictions of maximum ice loads on the concrete stations. The hydrodynamic load predictions and the calculations of the electric power capacity are beyond the scope of this paper.

INTRODUCTION

The call for the pre-feasibility study by the government of Newfoundland and Labrador (http://www.gov.nf.ca/releases/2004/exec/0119n01.htm2004l) led to many brainstorming sessions to develop a viable concept for a fixed link between Newfoundland and Labrador. Historically, the concept for an immersed tunnel across the Belle Isle Strait was proposed as a solution to avoid both ice impacts as well as to avoid potential water inflow in a bored tunnel. An immersed tunnel can be actualized at the cost of about $1.5 billion dollars (http://home.thezone.net/~deltaprt/fixlink/). An alternative deign concept is proposed by the Atlantic Energy Solutions, AES. The latter uses large concrete caissons (each is about 40 m wide, 40 m high, and 120 m long) as piers for a bridge across the Belle Isle Strait (Fig. 1). The caissons are, in fact, hydroelectric generating stations installed in series across the strait (about 14 to 18 km) to harness electric energy from the natural tidal waves and current in the strait.

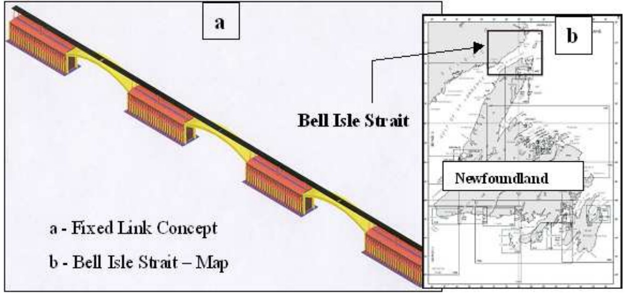

Figure 1: Concept design and location for the proposed fixed link.

The main objective of this project is to conduct a study to evaluate the structural stability as well as the economic viability of the proposed power-generating stations in the BIS. The task for the structural stability deals with concerns related to whether or not the concrete caissons can withstand the environmental loads (ice loads and hydrodynamic loads). The task for the economic viability, however, deals with estimating the electric power capacity that can be generated by each station, from natural tidal waves and current in the strait, and subsequently calculate the total electric power capacity that can be harnessed across the entire strait.

The larger objective of this research project is to investigate the potential for the development of ocean electric energy generating systems in the Arctic and sub-Arctic countries, such as Canada. Clearly, the development of renewable energy sources is a global concern, and harnessing electrical energy from ocean waves may help to elevate those concerns. Definitely, generating energy from ocean waves is technologically possible. However, in Canada, the complexity of harsh environment (presence of sea ice and icebergs) calls for designs of systems that can withstand the impacts of ice, in addition to withstanding hydrodynamic wave loading.

From the project management point of view, it was decided that for this feasibility study, numerical analyses will be used as the main tool to address the above two tasks. The use of numerical analyses will keep the cost of the feasibility study down, and it allows identifying critical design issues and potential construction problems for the proposed design concept.

This paper deals only with the predictions of maximum ice loads on the concrete caissons. The hydrodynamic loads predictions and the calculations of the electric power capacity are beyond the scope of this paper (that is a part of the larger project at the IOT, www.iot-ito.nrc-cnrc.gc.ca).

ANSYS and LS-DYNA commercial codes are used to perform the simulation. The scenario considered in this study deals with one concrete caisson being pushed by a relatively large ice floe (120 m X 60 m). The computer simulations and the predictions of maximum ice loads on the caisson are presented. Local and global ice loads are analyzed. Discussions and conclusions are provided.

Hydroelectric Station – The Design Concept

The concept design uses a series of large reinforced concrete caissons (geometry and dimensions for one caisson is shown in Figs. 2a and 2b). Each caisson is designed to sit on the seabed with its top deck positioned at sea level. Large rock berms (about 20 m high) surround the caissons to enhance its stability and resistance to both ice and hydrodynamic loads.

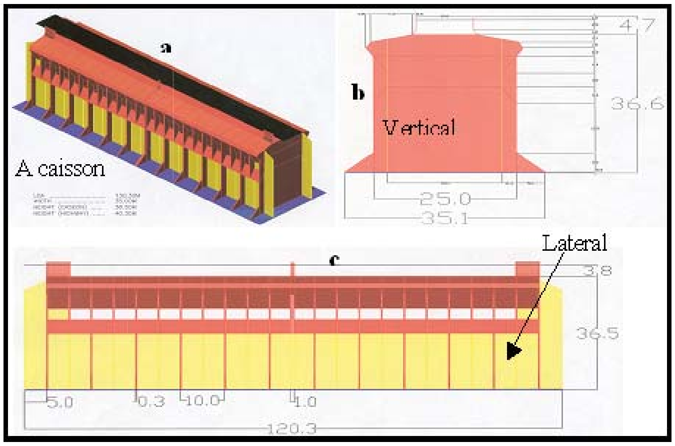

Figure 2a: Geometry and dimensions for one concrete caisson (in meters)

Structurally, each caisson is made up of a series of vertical compartments (chambers), and each chamber houses a large (12 m diameter) bi-directional paddle wheel (one chamber with its own paddle wheel is shown in Fig. 2b). Note that a caisson is made up of 10 to 12 chambers (and 10 to 12 paddle wheels are needed). A large shaft through the chambers connects all paddle wheels in the caisson. The vertical walls are strong enough to resist ice loads. The lateral walls are designed to guide the flow of water through the wheel chambers (for maximum tidal power).

To support a bridge, certain vertical walls of the caissons would have to be extended above the water level (see Fig. 2a). The architectural design of the compartment is modular; a caisson may include as many chambers as possible. Not all caissons have the same number of chambers. In this study, one caisson with ten (10) compartments is considered.

The vertical walls are the main ice impact resisting structural components. The tapered lateral edges at the top, however, allow ice to ride up, favouring its flexural failure (this tapered edge is called the ice fence, Fig. 2b). Tapered upper sections of the lateral walls are used for effective guidance of the flow of water through the chambers (called hydro wall in Fig. 2b).

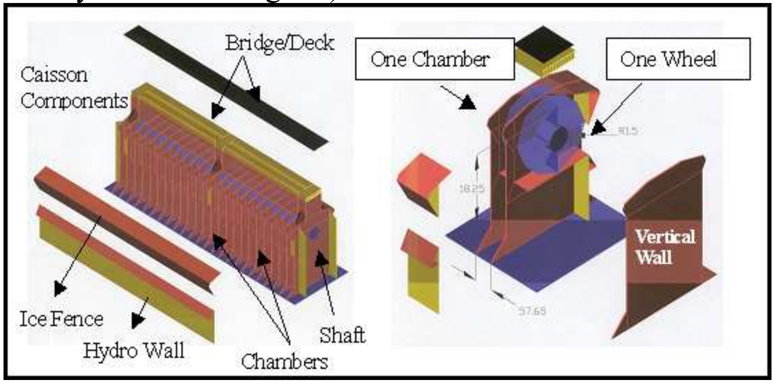

Figure 2b: Internal components for the concrete caisson and paddle wheel.

Ice Regimes and Ice Properties in the Strait of Belle Isle

Over the years, many research programs and expeditions have been carried out to survey and document ice regimes and its conditions in the Belle Isle Strait. The Canadian Ice Service (www.ice-glaces.ec.gc.ca/) published "The Sea Ice Climatic Atlas, East Coast of Canada 1971-2000". The Atlas shows charts for ice concentration throughout western Newfoundland and the Gulf of St. Lawrence. Each chart represents the 30-year median for the concentration (and the frequency of presence) of sea ice over the ice season (typically, from November to July). Several other field research programs gave the details for ice properties across the strait, ice type, ice thickness and density, ice floes sizes and shapes, and ice velocities (see reports by Sandwell, 1998, Johnston, 1999, and Croasdale et al., 2000). From these, one can estimate average values for ice properties (Table 1a and 1b).

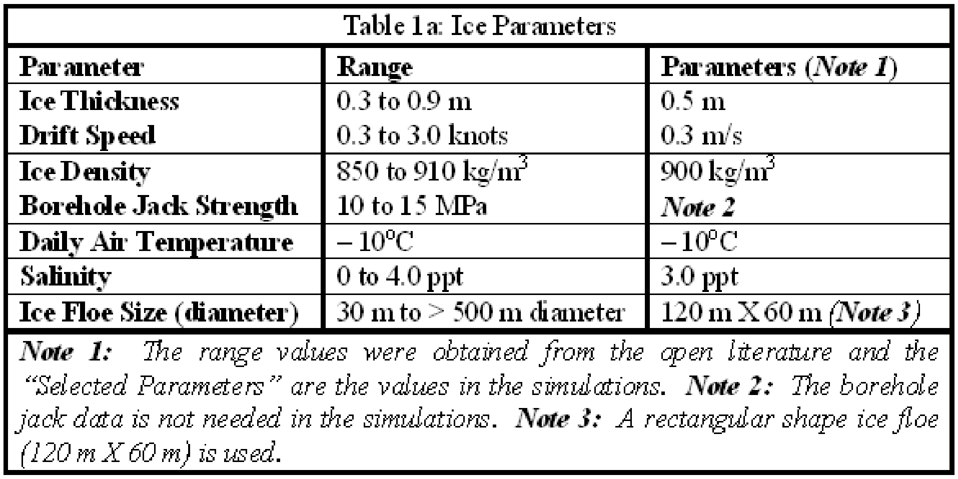

Table 1a: Ice Parameters

Parameter	**Range**	**Parameters (*Note 1*)**
Ice Thickness	0.3 to 0.9 m	0.5 m
Drift Speed	0.3 to 3.0 knots	0.3 m/s
Ice Density	850 to 910 kg/m^3	900 kg/m^3
Borehole Jack Strength	10 to 15 MPa	***Note 2***
Daily Air Temperature	– 10°C	– 10°C
Salinity	0 to 4.0 ppt	3.0 ppt
Ice Floe Size (diameter)	30 m to > 500 m diameter	120 m X 60 m *(Note 3)*

Note 1: *The range values were obtained from the open literature and the "Selected Parameters" are the values in the simulations.* ***Note 2:*** *The borehole jack data is not needed in the simulations.* ***Note 3:*** *A rectangular shape ice floe (120 m X 60 m) is used.*

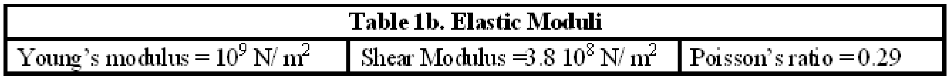

Table 1b. Elastic Moduli

Young's modulus = 10^9 N/m^2	Shear Modulus =3.8 10^8 N/m^2	Poisson's ratio =0.29

FINITE ELEMENTS MODEL

The Finite Element (FE) model was developed using ANSYS pre-processing (www.ansys.com) and the actual simulations of the ice impacts with the concrete caissons were performed using LS-DYNA (www.lstc.com). The combination of ANSYS pre-processor and LS-DYNA solver was proven to be a very powerful numerical technique to study the impacts of ice masses (level ice, pack ice, ice ridges and bergybits) onto offshore structures (either fixed or floating structures). Derradji-Aouat (2003a) showed how these two commercial FE programs could be combined to perform fully coupled analyses of marine accident scenarios involving fluids, ice, offshore structures and ships (multi-physics simulations).

One of the major assets of ANSYS is its pre-processing power. This includes its capability to import CAD models into FE platforms, Boolean Operations to create solid models, and control the meshing of complex model shapes. These capabilities allow users to develop complex FE models in a short time. The major asset of LS-DYNA, however, is in its ability to simulate impacts, collisions and accidents scenarios effectively using Explicit Finite Element Method (EFEM)). Historically, the EFEM was developed to solve violent impacts, explosions, collisions and accidents problems. The analyses of these types of problems are highly non-linear, dynamic, short term, and destructive (involving failure and loss of materials and components). Major automakers in North America use LS-DYNA to evaluate the crashworthiness of their vehicles. Derradji-Aouat and Earle (2003) used LS-DYNA to evaluate the crashworthiness of ships in ship-offshore structure accident scenarios.

For ice-engineering problems, one major deficiency in both ANSYS and LS-DYNA is the lack of an ice model in their material libraries, and therefore, there is a need for a constitutive model to represent the mechanical behaviour of ice and its failure in both software packages. Perhaps, for ice engineering, the market is not big enough to justify the development of ice material models in either package.

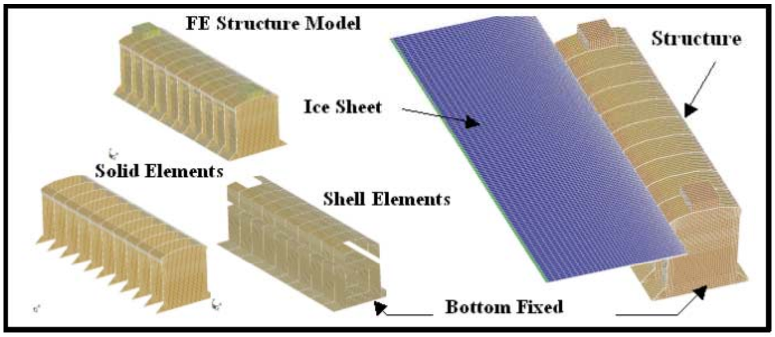

Figure 3: FE mesh and boundary conditions

Certainly, for a preliminary analysis, one can use a traditional continuum mechanics model such as the elastic stress-strain model with von Mises failure criterion to describe the behaviour of ice and its failure. However, over the years, it has been shown that most "classical material models" are not capable of describing the behaviour of ice and its failure. Simply, they do not reflect the real behaviour of ice, which is time, rate, and temperature dependent material. The so-called "classical yield criteria" (Hill, 1950) are time, rate and temperature independent models, and they are not formulated for the anisotropy of the material (such as sea ice) and the effects of the micro cracking activity (initiation and accumulation of micro-cracks) on the progressive structural deterioration (softening mechanism) of ice, which ultimately leads to its failure (Derradji-Aouat, and Evgin, 2001).

One constitutive model that was developed with FE commercial programs in mind was published by Derradji-Aouat (2003b). The model accommodates the effects of time, rate (loading or strain rates) and temperature on the behaviour and failure of ice. Also, the model includes the effects of anisotropy, salinity and porosity on the strength of the ice. The model is used as a routine in ANSYS and LS-DYNA to compute ice loads on the caissons of the proposed hydroelectric generating.

The FE model for one concrete caisson (10 paddle chambers) is shown in Fig. 3. The model includes two types of elements. They are solid (8 nodes brick) elements and surface elements (4 nodes shell elements). Each node of the solid elements has 3 degrees of freedom, DOF (3 displacements along the X, Y, and Z axes) while each node of the shell elements has 6 DOF (3 displacements and 3 rotations along/around the 3 axes). The solid elements are used to model the vertical walls and the ice fence and the shell elements are used for the lateral walls and the wheel housing walls.

An ice sheet (120 m X 60 m X 0.5 m) was modelled using solid elements (Fig. 3). The sheet was meshed using finer elements in the region near the structure with a gradual increase in element sizes away from the structure towards the end.

A total of 120,580 elements (17,160 shell elements, the rest are solid elements) were used to create the FE model (Fig. 3). All nodes at the bottom the structure (elevation Y = 0.0 m) are fixed in all three directions (X, Y, and Z) to simulate fixed foundations "potentially piles".

ICE CONSTITUTIVE MODEL AND PARAMETERS

One major factor that affects the mechanical behaviour of ice is the strain rate, $\dot{\varepsilon}$. At high strain rates ($\dot{\varepsilon} \geq 10^{-2}$ /s), the stress-strain behaviour of ice is mainly linear elastic with a brittle mode of failure. At low strain rates ($\dot{\varepsilon} \leq 10^{-3}$ /s), ice undergoes creep, grain-boundary sliding, micro-cracking activities, and ductile mode of failure.

To calculate the strain rate, $\dot{\varepsilon}$, in ice for an actual ice-structure indentation problem, several empirical equations have been proposed in the literature. Traditionally, $\dot{\varepsilon}$ is presented as function of the structure width (D), the velocity of ice (V) and the ice thickness (h). For wide structures, D/h>2, Bohon and Weingarten (1985) gave the strain rate as $\dot{\varepsilon} = 2V/h$. In the BIS, observed ice drift velocity range between 0.15 to 1.5 m/s (0.3 to 3 knots) and the average ice thickness is, h = 0.5 m. The width of the structure is, D = 120 m, and thus the ratio D/h is large (D/h = 240). It follows that the strain rates in ice are well above $\geq 10^{-3}$ /s. At these high strain rates, the behaviour of ice is linear elastic with a brittle mode of failure. In this paper, linear elastic behaviour for ice is assumed, and the brittle failure mathematical model (and its constants) used in these simulations were given previously by Derradji-Aouat (2003b).

CONTACT ALGORITHM AND INTERACTION MODEL

For the numerical simulations, ice comes into contact with the structure, and therefore a contact model is needed. Computationally, the first challenge in contact simulations is the detection of whether or not a "numerical contact" has been established (this part of the model is called the <u>contact algorithm</u>). Once the contact is established, contact formulation is used to transfer loads, pressures, displacements, and velocities between the two contacting entities (this part of the model is called the <u>interaction model</u>). The terminology "<u>contact model</u>" is used to refer to both contact algorithm and interaction model.

As LS-DYNA was developed for collisions and impacts analyses, many contact models are provided with the standard software license (see LS-DYNA user manual). The simplest contact algorithm is the "Nodes_to_Surface" model. In this model, contact is detected once the nodes for the ice sheet occupy the same "geometric space" as the surface of the structure.

Two contact models are of the up most importance to simulate ice structure interactions. These are: The "<u>eroding contact model</u>" and the "<u>single surface contact model</u>". During the indentation of ice with the concrete structure, ice blocks (elements) fail and break away (erode), and therefore, the contact surface is continuously changing. During each time step, the software updates the contact information. Nodes of failed elements are deleted and new sets of nodes are checked for the contact. The eroding contact algorithm allows to investigate instantaneous pressure distribution over the contact areas.

As ice elements break away, they may come into contact with other broken ice pieces, or they may pile up on top of the initial ice sheet. In this situation, ice is contacting itself (the two contacting entities are ice). Hence, the "single surface contact" is developed to take into account situations when a material contacts itself (imagine the crushing process of a PEPSI aluminium can). Thus, in this study, two types of contact models are needed. They are:

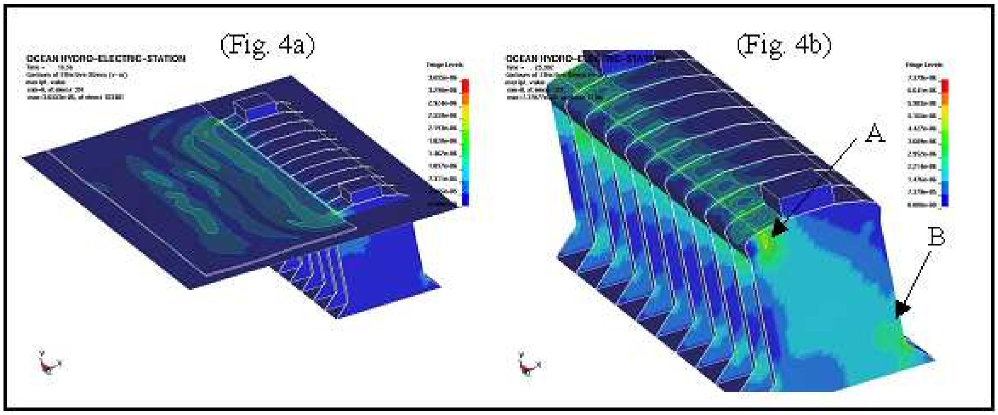

Figure 4: Contours of von Mises Stresses: a) stresses in the ice sheet (the horizontal plane under the ice sheet is the free surface), and b) stress contours in the structure.

- Eroding contact model between ice and structure (ice elements erode as they fail and brake away).
- Single surface contact model between the ice sheet and the broken ice pieces (or between broken pieces themselves).

The mathematical formulation for both eroding contact and single surface contact are given in LS-DYNA theoretical Manual. The challenge, however, is to develop a set of the appropriate commands for the contact algorithm to work properly. This is needed in order to avoid large penetration (interference) between the contacting entities. One common and major problem associated with large penetration is that two entities may go through each other before detecting each other; large interferences lead to non-accurate contact areas and forces. It should be cautioned that extreme attention should be paid to the contact command formulation to avoid generating high oscillatory loads and displacements during the initial stages of contact.

Numerically, in order to simulate two contacting entities, one entity is assumed to be the master (active) and the other entity is the target (passive). Once the contact is established, the loads, displacements, and velocities are transferred from the master nodes to the target ones. This transfer is achieved via nodal constraint equations, where the target nodes assume the loads, the displacements, the velocities and the accelerations of their master nodes.

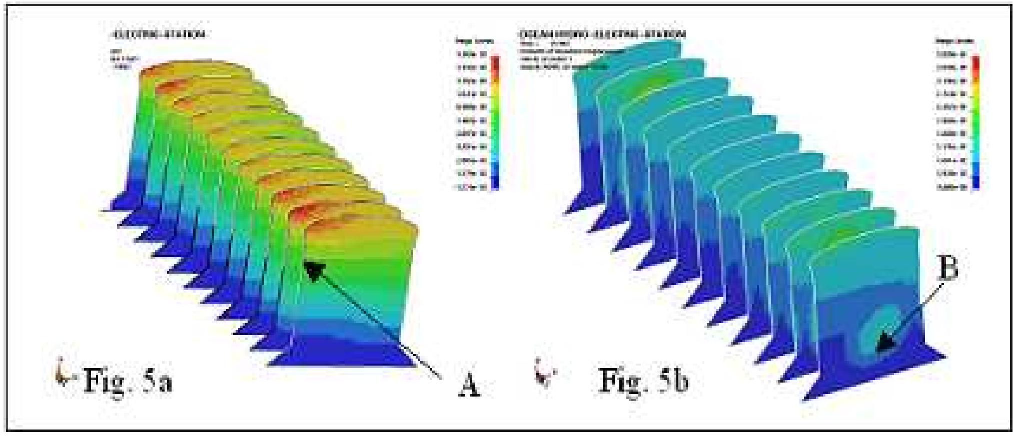

Figure 5: Displacements of the vertical walls: a) horizontal X-displacement, and b) resultant displacement (resultant of X, Y and Z displacements).

TIME STEP EFFECTS AND SIMULATIONS CONTROL

The entire time of the impact analysis is divided into small time steps. The time step is calculated as a function of the ratio of the element size to the material elastic modulus. A typical value for the time step is about 10^{-6} s to 10^{-4} s. This is very small, and therefore, the entire simulation may take longer time than desired. The computer power is the limiting factor. Therefore, in this analysis, the entire simulation time is limited to a maximum of 1 minute. It is hypothesized that maximum ice loads are obtained during the initial stages of the impact (considering a homogeneous ice sheet).

RESULTS AND ANALYSES

During the simulation, it was observed that at 25.9 seconds, the ice elements (elements interacting with the concrete structure) start to fail, and shear macro-cracks start to develop. Therefore, the following discussion will be focused on the analysis of the results and plots generated at 25.9 seconds of the simulations. Maximum horizontal ice loads are obtained at time just before the onset of the large cracks. Post macro-cracks behaviour is the subject of another study (Derradji-Aouat, 2005, in this conference. Session: Fracture and Damage Mechanics Applied to Ice).

Contours for von Mises (shear) stresses in both the ice sheet and the structure (at 25.9 seconds) are shown in Figs. 4a and 4b, respectively. The vertical walls are subjected to an overturning moment induced by the horizontal push of the ice sheet. On the walls, stresses concentrate in the vicinity of the ice-fence (area A, Fig. 4b) and at the bottom wall (area B, Fig. 4b). Area "A" is where the horizontal ice load is transferred to the vertical walls, while area "B" is where the load is transferred from the vertical walls to the flanged foundation base. The horizontal load induced by ice combined with the vertical load (dead weight from the piers for the deck) generated a diagonal stress path in the vertical walls (Fig. 4b).

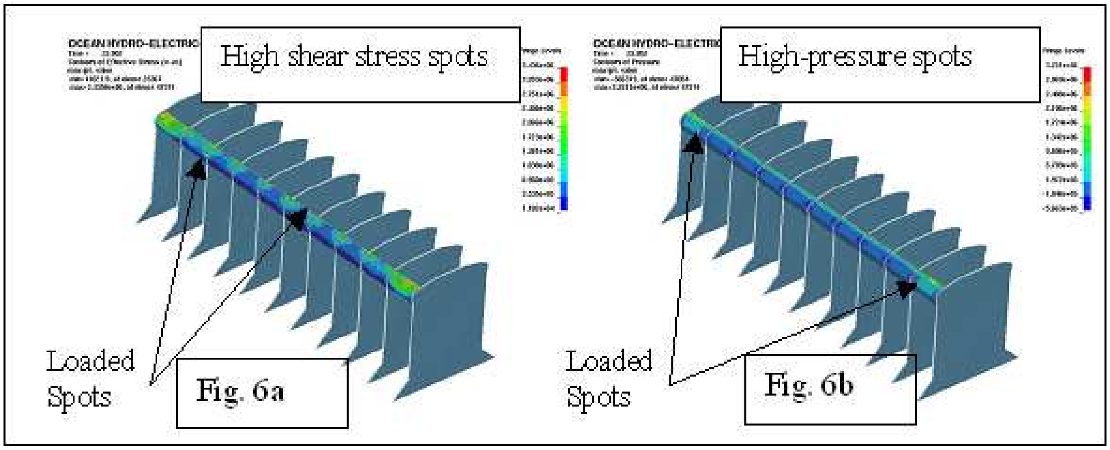

Figure 6: Local stresses and pressures in the ice fence: a) von Mises stress b) pressure.

The ice load tends to displace the vertical walls horizontally, and since the walls are fixed at the bottom, the entire concrete structure exhibits a cantilever type of deformation and behaviour. In the horizontal, X-direction, large displacements are observed at the top of the caissons wall with a gradual decrease towards the fixed foundation (Fig. 5a). Slightly larger displacements are observed in the locations where the ice fence joins the vertical walls (Area A, Fig. 5a). The resultant displacement (resultant of displacements in X, Y and Z directions, Fig. 5b) shows that the walls undergone torsion (circular area B, Fig. 5b) at about 1/3 high of the walls height, just above the bottom concrete flanges.

During the contact of ice with the structure, the magnitude of ice-loads increase monotonically until ice failure takes place, and then, non-simultaneous and non-uniform ice contact areas take place. Contours for "local shear" stresses and contours for "local pressures" are shown in Figs 6a and 6b, respectively. There are spots "areas" where stresses and pressures are higher than in the rest of the ice-fence (as shown in Fig. 6a), those are areas of temporary ice-structure contact. Low stresses and pressure areas are located at the locations where the local ice elements broke, and there is no contact between the structure and the ice at that time step. As the simulations continue, these high and low stress "local spots" change in time and space. For example, at 25.9 seconds, high-pressure areas took place at the ends of the ice fence (Fig. 6b) that is due to the fact that, in addition to pushing and longitudinal bending, the ice sheet is undergoing lateral bending as well. Thus, ice is exerting loads on the ice fence ends in both horizontal and vertical directions. This results in higher stress and pressure areas at both ends of the ice fence. Numerically, with time and as ice breaks, new contact zones are created during each time step, resulting in the continuous change of the location of these high-pressure zones.

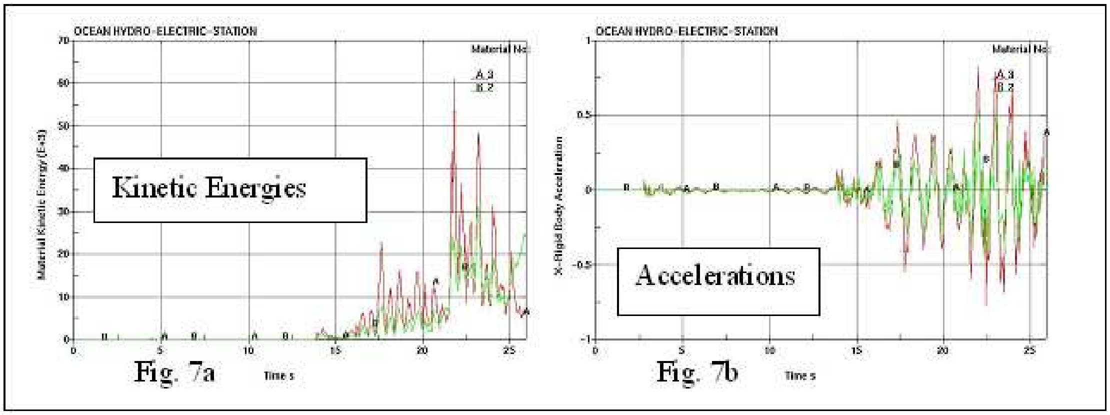

Fig. 7a

Fig. 7b

Figure 7: Kinetic energy and accelerations in the concrete structure

The time histories for both kinetic energy and accelerations in the vertical walls and the ice fence are given in Figs. 7a, and 7b, respectively. Those for the ice sheet are given in Figs. 8a and 8b. From the acceleration time histories of the structure, global ice loads are usually computed. Alternatively, global ice loads are the resultant reaction at the bottom fixed nodes.

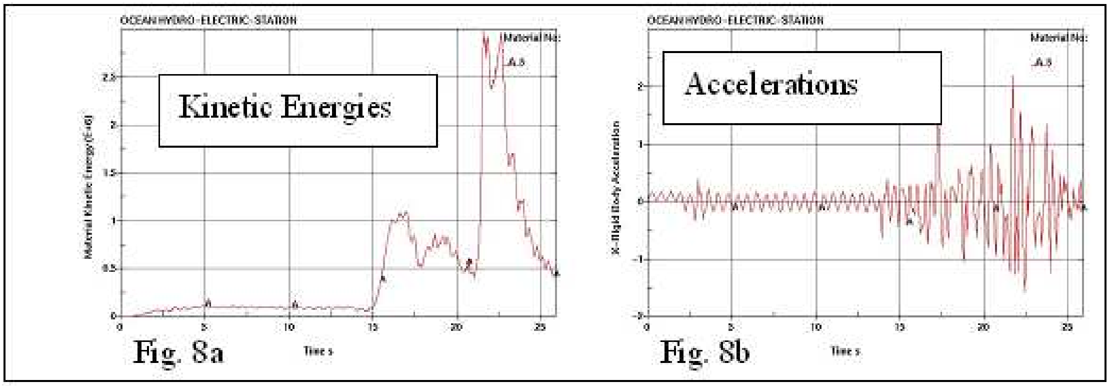

Fig. 8a

Fig. 8b

Figure 8: Kinetic energy and accelerations in the ice sheet.

Figures 9b and 9c show the maximum "local" stresses and "local" pressure in the concrete structure. The most loaded structural elements are found to be in the middle vertical wall just behind the ice fence (Fig. 10a). Maximum shear (von Mises) stresses of up to 7.0 MPa and maximum pressure of up to ± 2.5 MPa were obtained. The negative pressure (extension) and the positive pressure (compression) are generated due to the overturning moment in the structure (note that mathematically, pressure is calculated as the sum of the 3 principal stresses, it can be negative or positive while von Mises shear stress is the 2nd deviatoric stress tensor, which is always positive, see Derradji-Aouat 2003b for the nomenclature). These maximum local loads took place just before a major shear crack took place at 25.9 seconds. Figure 10b shows the location of the first shear macro-crack. As indicated above, the dynamic behaviour of the structure in post macro-crack time frame is the subject of another study.

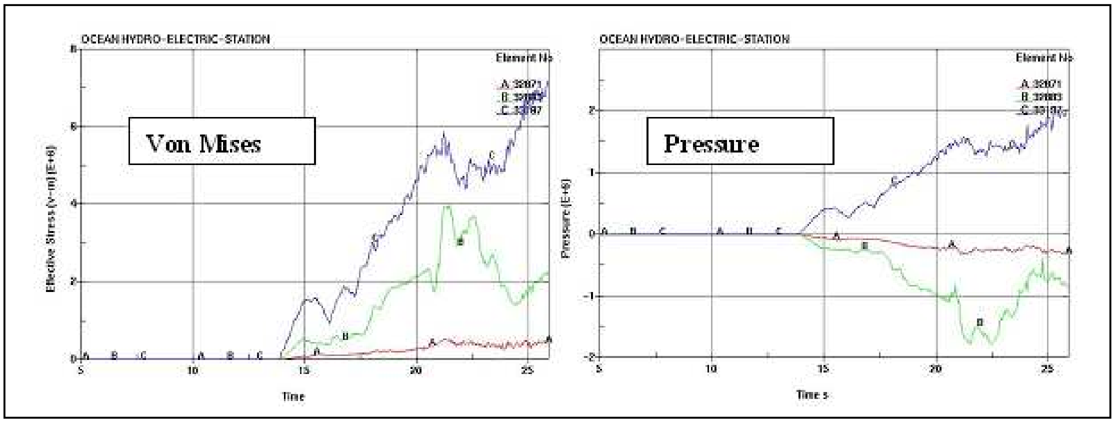

Figure 9: Local shear stresses and "local" pressures in the concrete structure.

CONCLUSIONS

1. Naturally, if different parameter values (different than those in Table 1a and 1b) are used, different maximum shear and pressure loads will be obtained. However, the overall behaviour, the general trends of the computed time histories and the overall structural behaviour will be more or less the same. An uncertainty analysis and a verification and validation study is yet to be performed.
2. For the caisson and ice conditions studied in this paper, ice induced shear stresses of 7.0 MPa on the structure. And pressures of up to 2.5 MPa were obtained. A larger scope parametric study is needed to identify ice parameters for worst-case scenario and confirm the design ice loads for about 7 MPa.
3. If needed, and required by the client - AES, the joints between the vertical walls and ice fence can be redesigned to reduce the 7.0 MPa shear ice force (trade off, less ice loads means a flanging or a bracing system is needed).
4. The development objective of this paper is to show how explicit FEA is coupled with a realistic ice constitutive and an eroding ice contact model to analyze actual ice engineering problems. Algorithms (macros) for the universal ice failure model

were already presented (Martonen et al., 2003). This paper presents the use of the eroding ice contact model. These publications/macros (Martonen et al., 2003, and this paper) allow users to develop their own models and perform their own simulations for ice-structure interactions and calculate ice loads.

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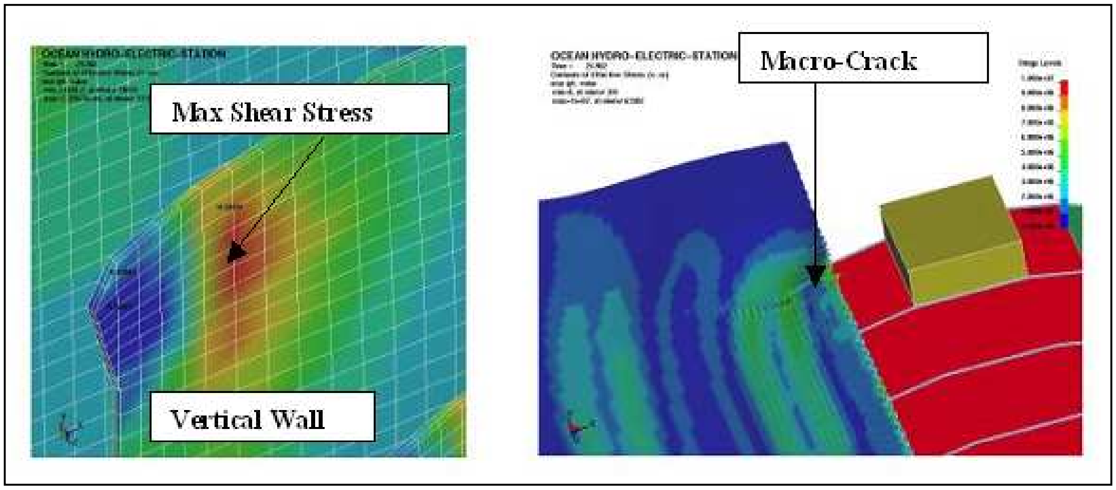

Figure 10: Maximum local shear stresses and shear macro-crack generation.