Research Article

Feasibility of using continuous, stiff materials for reinforcing freshwater ice covers

Wenrui Chen[1] · Ning Liu[2] · Karl-Erich Lindenschmidt[3] · Chris Swallow[4]

Abstract

Winter roads are economical and effective means of providing reliable transportation links to remote regions. Operators establishing ice crossings over rivers and lakes have been facing increased pressure to deliver higher volumes of goods, larger loads, in challenging climatic conditions. A question arose from industry: “is there a way to safely provide additional bearing capacity in ice covers and assist with extending operating seasons, possibly through reinforcing the ice?” This study investigated this operational challenge by developing a model to simulate ice reinforcement theories using ANSYS computer modeling techniques. ANSYS 18.0 was utilized to successfully model reinforced ice covers and estimate the ice deflection under a centrally concentrated load. ANSYS computer models allow us to learn complex behaviours of materials and provide a more accurate estimation of deflection compared to the analytical method, which provides a closed-form solution to a given problem. The results show that the reinforcing material is able to stiffen the ice cover which enables a larger surface area to carry the load; a higher percentage of the reinforcement by volume further reduces ice deflection. The test results also indicate that the reinforcing material must be considerably stiffer than the ice so that the load can be more efficiently transferred from the ice to the reinforcing material. The results highlight a successful modelling of reinforced ice covers and discuss the feasibility of installing the reinforcing material, through an example using wood as a possible reinforcing material because it is readily available on site and meets a number of pre-determined criteria. While the creation of an ice reinforcement modeling tool was a success, further research is needed to verify the feasibility of using a variety of materials as reinforcement to increase the safe bearing capacity of ice covers as well as evaluate different applications and orientations of the reinforcement to achieve the best outcome. All of this bearing in mind that the reinforcement must be able to be safely installed in situ within the ice cover. Moreover, a collection of actual ice deflections in the field is recommended to further assist in calibrating the ANSYS model. The simulations serve as an initial step in evaluating different reinforcement materials and methodologies. Subsequent research will need to evaluate the modelling in controlled, full-scale field applications prior to providing a tested solution for commercial use.

Keywords Ice cover · ANSYS model · Finite element analysis · Reinforcing material · Elasticity

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1 Introduction

1.1 Background

There are remote communities and vast resource exploration regions in Canada that lack basic all-weather road access. The transportation lifelines to these regions are connected sections of ice infrastructure within winter road networks that are rebuilt each year. Winter roads rely upon viable crossings on lakes and rivers to complete the road network between land portages. The minimum ice thickness on these lakes and rivers determine the safe bearing capacity of the entire winter road network. Although ice covers are an economical and effective means of supporting loads, resource extraction, and moving people and goods every winter, they are highly dependent on adequate weather conditions. Research indicates that, in the next 25 years, Canada will see a 13% reduction in winter road accessible land area. This translates to almost 400,000 square kilometres of Canadian real estate losing winter road accessibility in some of the most remote regions in the country [1]. Members of Canada's Federal Government recognize the loss of winter road access and the long-term impact on remote Northern communities [2].

There are trends of increasingly warmer winters occurring more frequently. For instance in the winter of 2005/2006, Environment Canada reports show the winter temperatures were significantly above normal in northern Canada, and they directly impacted numerous winter roads causing most of them to fall dramatically short of transportation goals [3]. These operational pressures on ice operators continue as they are being challenged to deliver heavier goods and higher traffic volumes in frequently shorter winter ice seasons. The ice construction industry seeks solutions to these operational challenges and ponders the introduction of a reinforcing material into ice covers to increase the safe bearing capacity of ice crossings.

The purpose of this study is to implement ANSYS computer models to determine whether ice reinforcement is a viable concept and whether it is worthwhile to implement the result in full-scale field tests. This study includes an ice reinforcement literature review and suggests screening criteria for reinforcing materials. Next, an ice plate model was built and analyzed using the finite element analysis (FEA) in ANSYS with a viable reinforcing material. The results of the analyses are presented for discussion. This report also includes recommendations for further modelling to evaluate additional reinforcing materials and suggestions for further investigations to compare ANSYS results with field tests.

2 Literature review and proposed reinforcement material screening criteria

2.1 Historic reinforcing materials

Based on the literature review and results from experimental research, a wide variety of materials have been frozen into the ice to reinforce the ice over the years. In general, it appears that most research determined that the bearing capacity of ice can be improved primarily by changing the thermal and/or the mechanical properties of the ice cover.

In 1942, Geoffrey Pyke proposed a project that was known as Project Habakkuk which was to add wood pulp to ice as a floating platform for aircraft (ice aircraft carrier) during World War II [4]. The reinforced ice was tested to be stronger and more durable compared to solid ice due to the low thermal conductivity of wood pulp, which greatly slows down the melting process. In addition, it was discovered that wood pulp can increase the tensile strength of the ice covers. Another test was conducted by Kingery [5] by adding both sawdust and fiberglass to the ice. It was shown that with 15% fiberglass by volume added to ice, the strength was increased about 10 times. Ohstrom and DenHartog [6] reported laboratory tests performed using branches, wooden dowels and steel cables as ice reinforcement. The ice reinforcement improved the flexural strength, but it could not reach the highest tensile strength of reinforcing materials due to limited bonding with ice.

In 1980, Jarrett and Biggar [7] discovered that the application of geotechnical fabrics can increase the flexural strength by up to 31%. Fransson and Elfgren [8] conducted a field test on freshwater ice reinforced with either sand, birch branches or sawn timber. The test results indicate that the reinforcement materials should be considerably stiffer than the ice so the load can be transferred from the ice to reinforcing materials. In 1989, Haynes and Martinson [9] found that Geogrid bonded well with ice and it was able to increase the bearing capacity of ice by up to 300%. In the same year, Nixon and Weber [10] reported that alluvium-reinforced ice could also increase the bearing capacity of ice. Later, a variety of lab studies on soil-reinforced ice were conducted and reported by [11–13]. It was proven from lab results that there was a clear increase in values of bending strength, flexural strength, as the percentage of reinforcement increases. Alluvium includes silts, sands or gravels, and all the materials are readily available in the remote Arctic locations and environmentally-friendly during the melting stage.

In summary, historical research has demonstrated that ice could be reinforced by fibers such as wood pulp, sawdust, branches and wooden dowels, structural materials such as steel cables, geosynthetic materials such as Geogrid and alluvium, including sand, gravels and more. Each material can reinforce ice covers to varying degrees, depending on the percentage of reinforcing material by volume, the bonding between reinforcing material and ice, and inherent properties of the reinforcing material itself. However, each material also has its own vulnerabilities, which are important to take into consideration during the selection process. For instance, Geogrid has a higher susceptibility to shear failure, concluded from extensive field tests performed by manufacturers [14]. Also, the addition of alluvium in the ice has negative effects on ice thickness, particularly in late season applications, due to the Albedo effect increasing the rate of ice melt. According to Light et al. [15]; see his Fig. 13 on page 27,749), the Albedo value for sediments is always larger than for clean ice, which indicates that solar radiation absorption by the sediments remains higher than ice throughout the whole late-winter season.

It appears that previous researchers focused more on incorporating reinforcing materials to either reduce the thermal conductivity of ice covers, or to increase the bending strength or tensile strength of ice covers. The idea of stiffening ice covers to enlarge the surface area for ice bearing the load has not been tested and implemented yet. This is the idea that was chosen as the focus of this study, which is to create a computer model that would assist in determining the feasibility of using continuous, stiff materials for reinforcement while increasing the safe bearing capacity of an ice cover.

2.2 Proposed screening criteria for reinforcement material

To evaluate materials for suitability in ice reinforcement, the following criteria were used for this study:

- Environmentally friendly and bio-degradable
- Ability to stiffen an ice cover to bring a larger ice surface area into bearing a given load, at low temperatures
- The raw reinforcing materials are readily available and easy to process on site
- Ability to be safely and easily installed and maintained.

3 Building the model

3.1 Field methods for measuring ice deflection

Ice deflection monitoring plays an important role in investigating ice behaviors and understanding the characteristics of ice covers. To begin to construct a computer model and calibrate it, the measured ice deflection under a given load in field conditions is used to compare with the modeled ice deflection. For the purposes of this study, NOR-EX's field study provided the field data to be used to build and calibrate our model.

3.1.1 NOR-EX field testing site description

A 100 m long and 30 m wide section of the ice crossing on Dome Lake of the Tibbitt to Contwoyto Winter Road was chosen to perform the ice deflection test. Dome Lake is located about 2.5 h drive northeast from Yellowknife and is in proximity to the TCWR JV Dome Lake winter road construction camp. Figure 1 shows the location of Dome Lake.

3.1.2 Static vehicle load ice deflection measurement in the field

Ground-penetrating radar (GPR) ice profiling, laser scanner, land survey equipment, and processing software were used to collect ice deflection data and produce data maps. The ice profiling of the test area was conducting by running transverse and longitudinal profiling lines, shown in Fig. 2. Survey level and rod system were set on the ice surface to measure a series of station elevations. Ice elevations are measured before vehicle loading, (with a vehicle as a test load on the ice) as well as after vehicle unloading. Each set of elevation measurements was repeated four times for a total of 80 measurements. Different test vehicles were deployed on the ice in the field test to allow a better investigation of the ice behaviors and ice deflections under static loads.

The deflection experiments were carried out on 13 December 2013. Maximum air temperatures recorded at Yellowknife (≈ 67 km southeast of the study site) on 12, 13 and 14 December 2013 were − 34.5, − 38.1 and − 23.7 °C, respectively. Air temperatures recorded at Pensive Lake (≈ 5 km south-southeast of the study site) correlate well with Yellowknife recordings ($r^2 = 0.95$).

3.2 Modeling calibration

Elastic modulus, E, is a key variable closely related to ice deflections and stresses in an ice cover. It is used to calibrate computer modelling of ice cover behaviour. Sinha and Cai [16] pointed out that the value of E can vary from 0.1 to 6.9 GPa. There are many factors which can result in this high variation in E, such as ice type, temperature and rate of loading. Gold [17] suggested an elasticity of 6.9 GPa is common for freshwater ice, and Masterson [18] suggested 5 GPa for a continuous ice sheet. The effect of the modulus of elasticity is noticeable on the deflection,

Fig. 1 Plan view of Dome Lake test site

which will be discussed further in the next section. Hence, selecting an appropriate effective elastic modulus is pivotal in predicting ice deflections accurately.

Our industry partner provided recent field ice deflection data for the purposes of calibrating the study's computer model. ANSYS simulations were compared to the 2014 Winter Program results collected by NOR-EX Ice Engineering Inc, demonstrated in Figs. 1 and 2. A two-axle, 12,000 kg water truck was used as a test vehicle providing a stationary load, which produced the deflection bowl of ice covers shown in Figs. 3 and 4. Our ANSYS model was deployed to generate deflection curves using different E value of 0.1 GPa, 1 GPa, 4 GPa and 7 GPa. The results provided in Figs. 3 and 4 show that an effective elastic modulus around 0.7 GPa was adopted to produce the best fit for the field deflection data collected in December 2013. Similarly, the same modeling calibration was conducted using field deflection data from the 2015 Winter Program. An effective modulus of elasticity between 5 and 6 GPa was more appropriate to predict actual field deflections for the 2015 field data. NOR-EX's data is a good example showing that the effective elastic modulus changes each year. Additionally, the effective elastic modulus is dependent upon temperature, ice cover type (in our case, lake ice

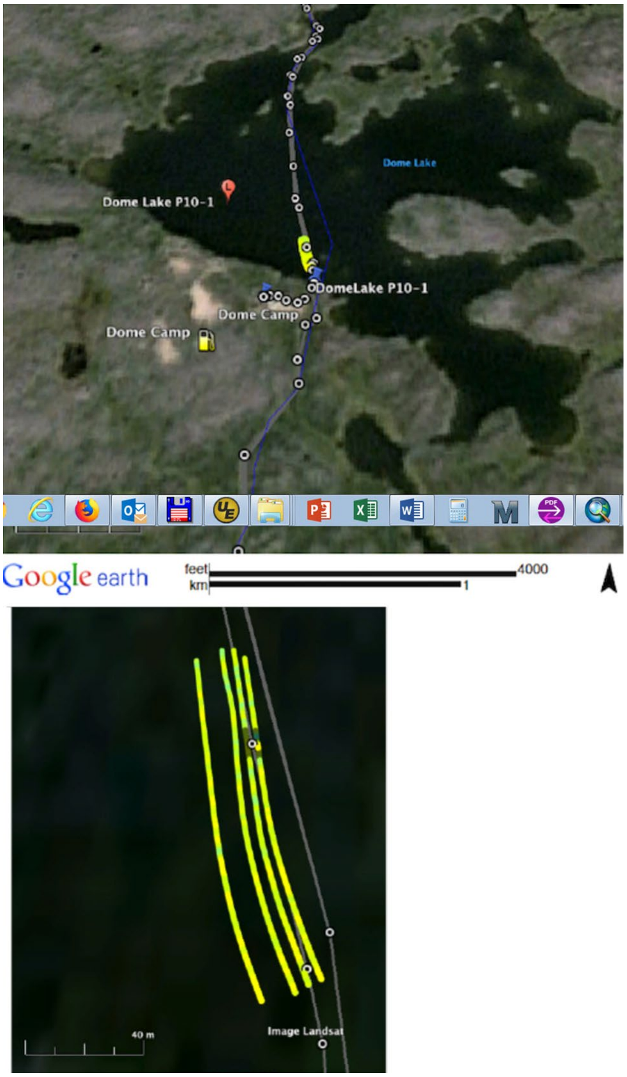


Fig. 2 Dome Lake test site and GPS profiling tracks

or river ice), water body and several other factors. Different water bodies such as sea water and fresh water provide different elastic support which is directly proportional to the density of water, which will be explained in the next section.

Therefore, increasing the accuracy of ice reinforcement models requires in situ measured ice deflections to provide the data for calculation of an effective elastic modulus. For the purposes of this study, an effective modulus of elasticity value of 1 GPa was chosen. Further explanation is provided in Sect. 3.

3.3 ANSYS modeling

ANSYS is a feasible and versatile tool for solving this complicated case study because it not only is able to provide a valid 3D model to demonstrate how ice covers respond under loads, but also achieve computational efficiency. FEA has been widely adopted in various engineering applications such as structural, fluid, and thermal analysis. The theory behind FEA includes a discretization strategy, a series of algorithms and data post-processing. This analysis can create a desirable number of mesh points of the object so that each specific point can be studied depending on our needs. FEA allows the visualization of the subtle details of the structures and the accurate calculation of stress and strain distributions of bodies, which can be utilized to analyze deflection of ice covers. With the advancement of computer hardware and software technology, it is an application to make more complex case studies computationally efficient.

3.3.1 Model set up

A continuous, non-reinforced ice cover with a point load was created to compare with a reinforced ice cover. The non-reinforced cover is shown in Fig. 5, with a width of 60 m, length of 100 m and 0.4 m thickness. The ice cover is assumed to be constrained by surrounding ice. By testing different sizes of ice covers, this model is deemed large enough to capture the entire deflection bowl under a static load, which ensures that there are no edge effects exerted by simulated land edges of the water body.

The ice cover is considered to be a homogeneous and isotropic elastic material. The point load is assumed to be static (to match the field measured conditions and normally the maximum measured deflection). Ice properties are listed as follow:

- Ice density: 918 kg/m^3
- Elastic modulus: 1 GPa
- Poisson's ratio: $\nu = 0.35$
- Boundary condition: fixed supported at both ends along the width of the ice cover
- Elastic support (lakes or rivers) = $\rho_w g = 9800$ N/m^3
- Centrally applied point load: 100,000 N = 100 kN

As discussed previously, the E values commonly range from 0.7 to 7 GPa. For the purposes of this study, E is assumed to be 1 GPa and Poisson's ratio equals 0.35. Note that selecting a small value for E can better evaluate how the reinforcing material will affect relatively stiffer ice covers, and it is more conservative to predict ice deflections of reinforced ice covers.

Due to transverse and longitudinal symmetry, a quarter of the ice cover was discretized. Figure 6 shows the geometry of the ice cover with reinforcing material. The analysis of the reinforced ice cover model focuses on wood as the reinforcing material, because of its light weight and high workability. Timber is also readily available, cheap

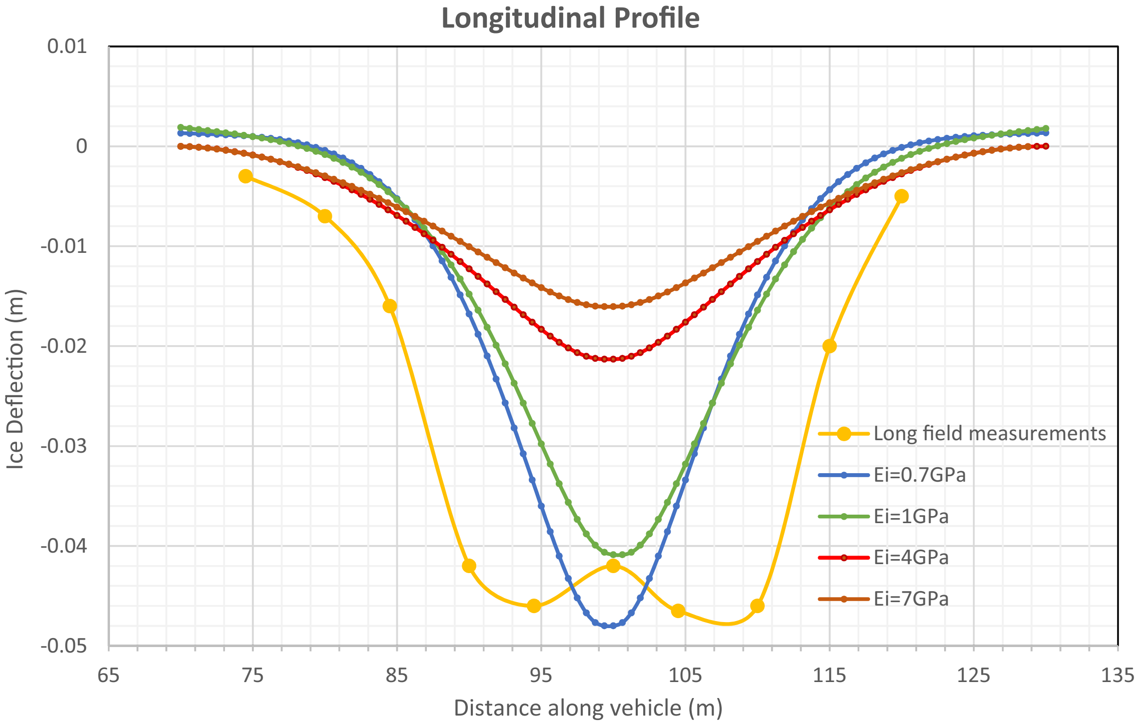


Fig. 3 Ice deflection ANSYS modeling compared to field longitudinal profile, December 2013

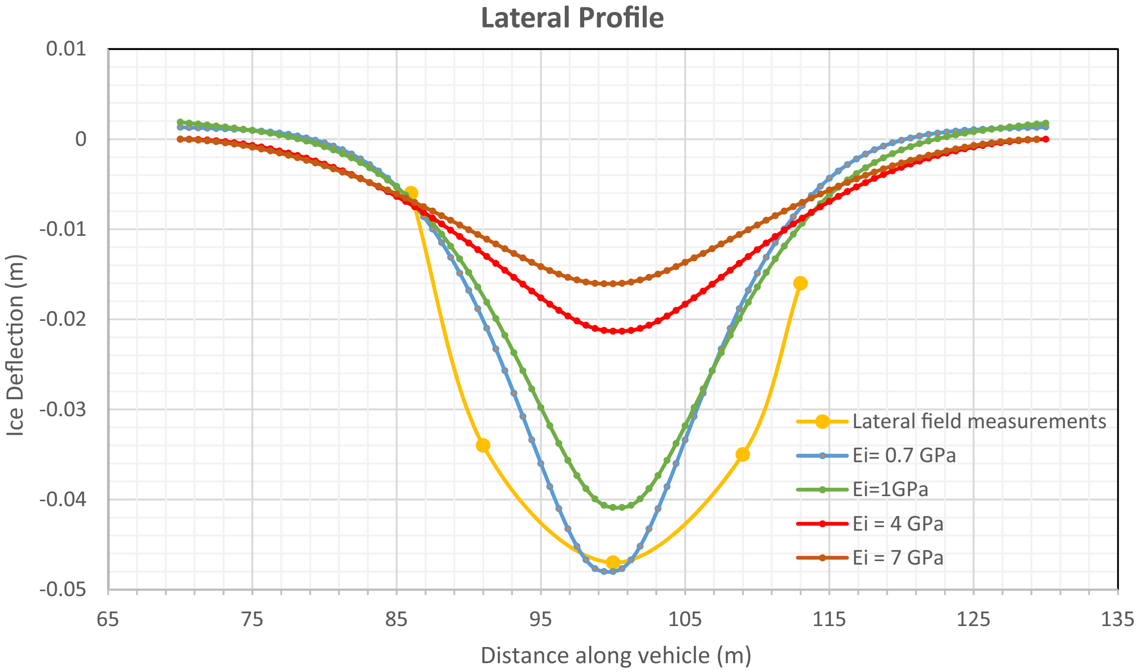


Fig. 4 Ice deflection ANSYS modeling compared to field lateral profile, December 2013

and accessible. This research gives a preliminary look at whether or not reinforcement could be modelled and, as a first step, we selected timber as being a reasonable material which meets the environmental impact criteria. Pulp would have been difficult to start with as a first model, however, in the future we wish to model a selectin

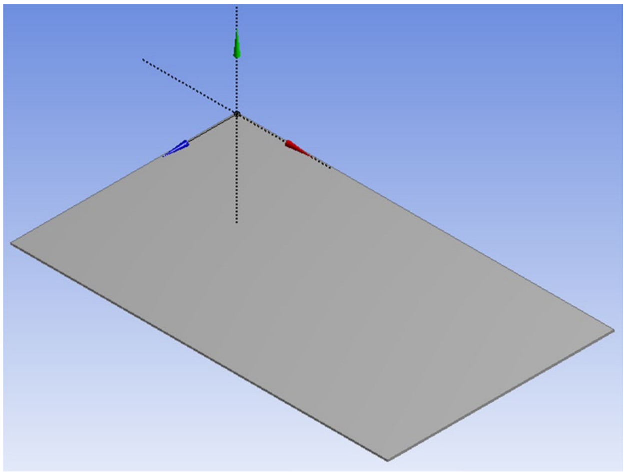


Fig. 5 Continuous ice cover without reinforcing material

of viable options and pulp could be an option that merits investigation in the future.

Deflections of the ice with and without wood are compared in order to determine the ability of wood to stiffen ice covers under given boundary conditions. The thickness of the wood boards is assumed to be 0.04 m. The spacing between wood boards varies from 0.25 to 2.0 m, which allows to determine the optimal spacing of reinforcement from a practical standpoint. The volume fractions of wood to ice are provided in Fig. 7. Models with different spacing will be described later in detail. Since the reinforcing material remains frozen within the ice covers, the connection between reinforcing material and the ice was considered completely bonded, which ensures there is no gap between the ice and reinforcing materials throughout the domain. Boundary conditions will be the same as in the ice-only cover model.

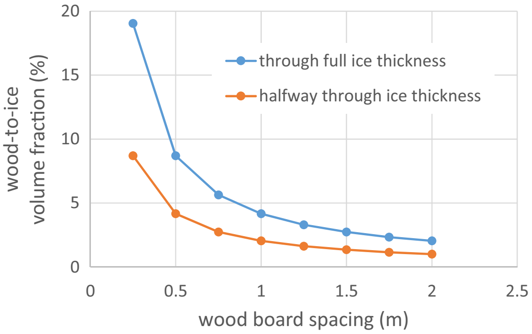


Fig. 7 Volume fractions (%) of wood to ice for different spacings between wood boards

The reinforcing material should be considerably stiffer than the ice so the load can be transferred from the ice to the reinforcing material. Wood generally has an elastic modulus between 8 and 12 GPa [19]. The average elasticity of wood is approximately 10 GPa, which is 10 times stronger than ice, and Poisson's ratio is generally around 0.42.

The extent of the reinforcement was seen as critical to improve bearing capacity, captured by two models. Wood is installed halfway through the ice thickness, shown in Fig. 8, and the wood inserted through the full thickness of the covers, shown in Fig. 9. However, it is worth noting that installation through the full thickness is not feasible from an operational point of view. The model is only used for comparison and demonstrates a range of the effect that reinforcement has on deflection reduction.

Fig. 6 Reinforced ice cover model

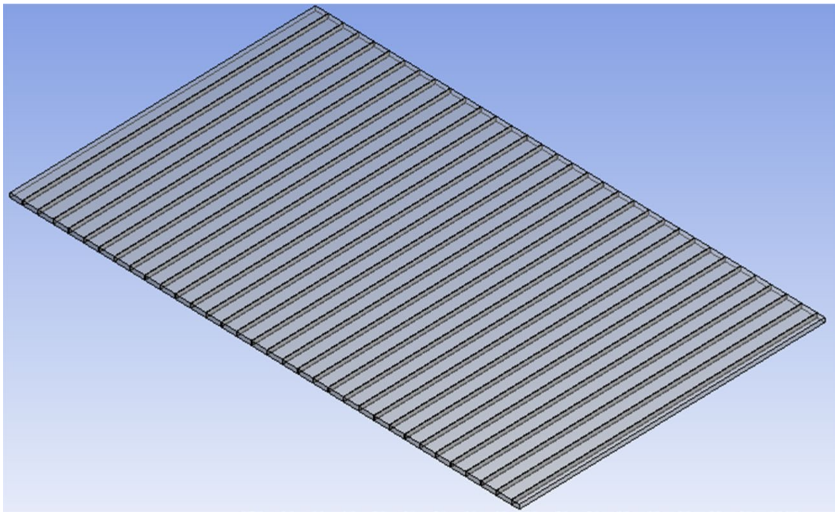


Fig. 8 Side view of the ice cover with reinforcing material half through thickness

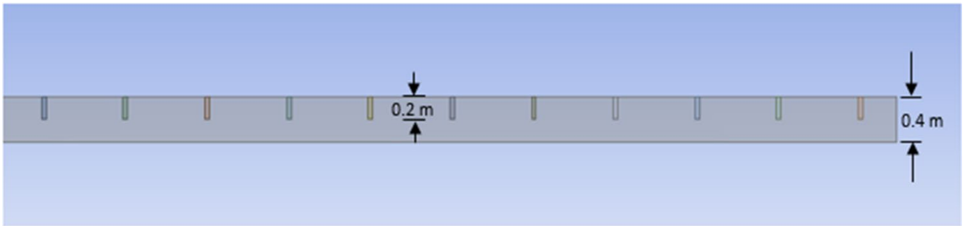
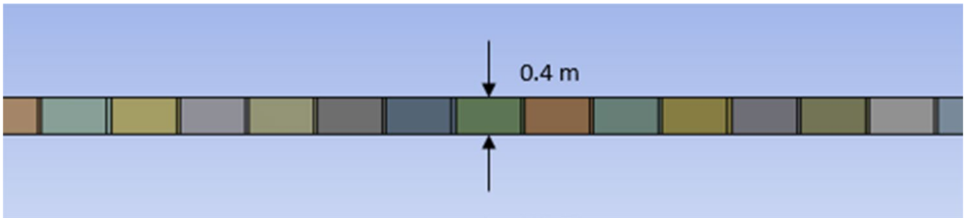


Fig. 9 Side view of the ice cover with reinforcing material through full thickness



3.4 Analytic methods

3.4.1 Ice cover model

Elastic theory is used to assess and verify the results obtained from ANSYS. Deflections of ice with and without wood boards are compared, together, in order to determine the ability of wood to reinforce the ice cover in order to investigate to what extent wood can reinforce the ice cover and determine the optimal percentage reinforcement. Wyman [20] developed a linear elastic plate model of ice floating on water. The response of an infinite, homogenous and isotropic elastic plate resting on a liquid and subjected to a static vertical load q can be described by in the following equation

$$D\nabla^4 w + \rho_w g = q.$$

where $D = \frac{Eh^3}{12(1-v^2)}$, flexural rigidity of the plate, *E,* Young's modulus; *h,* ice thickness; *v,* Poisson's ratio; w, deflection; ρ_w, density of water; q, a static vertical load.

3.4.2 Mechanical properties of composite materials

To verify the results obtained from ANSYS, it is important to know the properties of the composite or reinforced ice, such as elastic modulus, Poisson's ratio and thermal conductivity. The ice composite consists of the reinforcement and matrix materials. In general, the upper-bound for elastic modulus, E, in the direction parallel to the reinforcement can be as high as $E_c = E_f f + E_m(1-f)$. Once the results are obtained from ANSYS, the composite elastic modulus can be used to evaluate the validity of ANSYS results. $f = \frac{V_f}{V_f + V_m}$ is the volume fraction of the reinforcement, E_f is the elastic modulus of the reinforcement, and E_m is the elastic modulus of the matrix.

The Poisson's ratio of ice composites can be calculated using $v = v_f V_f + v_m(1 - V_f)$.

3.5 Simulation scenarios

The first scenario was set to insert wood boards from the surface of the ice cover into half its thickness, which equals 0.2 m. The second scenario is with wood boards through the full thickness of the ice. A point load of 100 kN acts on the center of the ice cover. Four side faces of ice covers are assumed to be fixed to resist vertical and horizontal forces as well as moments. Different spacings were studied, including 0.25 m, 0.3 m, 0.4, 0.5, 1, 1.25, 1.5, 1.75 and 2 m. Different types of wood, represented by using different elastic moduli, were also tested for each scenario.

Wood can be categorized into two groups, softwood (coniferous) and hardwood (deciduous). However, hardwood is not necessarily stronger or stiffer than softwood. Therefore, in the current stage of this study, instead of specifying which type of wood is being used, the elastic moduli of 8 GPa, 10 GPa and 12 GPa were used to estimate relative reductions in deflection. A range of values can better allow the client to make a decision about which type of wood to use based on the desired deflection characteristics informing ice bearing capacity design.

4 ANSYS model results

In any FEA model, the accuracy of results is directly related to the finite element mesh that has been used. In general, with the finer mesh, the computed solution will approach higher levels of accuracy. However, the higher accuracy means more computational resources such as longer solve times and more usage of CPU and memory are required. Therefore, a mesh sensitivity test is a necessary step to make sure to obtain the desirable accuracy of the results while achieving computational efficiency.

A mesh sensitivity study was carried out on a model that has the most complex geometry, which is an ice cover reinforced by wood planks with a spacing of 0.25 m through half the thickness of the ice cover. The results of eight runs were used to plot a curve demonstrated in Fig. 10, which indicates when the mesh number approximately falls between 125,000 and 225,000 and convergence can be achieved. In this range, it can be observed that by increasing and decreasing the mesh number, roughly by 20%, the difference in the results is less than 1%. Moreover, all 8 runs of the model have good quality of each mesh and overall mesh distribution by evaluating the mesh metric. All meshes are in a regular hexahedra shape, and the standard deviation of the mesh distribution remains from 0.1 to 0. A low standard deviation indicates that the majority of meshes have similar size and good element quality. This independency study eliminates the influence of the mesh on the computational results. Therefore, we can ensure that our results will not depend on neither the mesh size, nor the mesh number when we selected the case with the mesh number of 193,284 to conduct FEA in order to avoid inefficient computations. Our numerical result is indicated with a red point in Fig. 10.

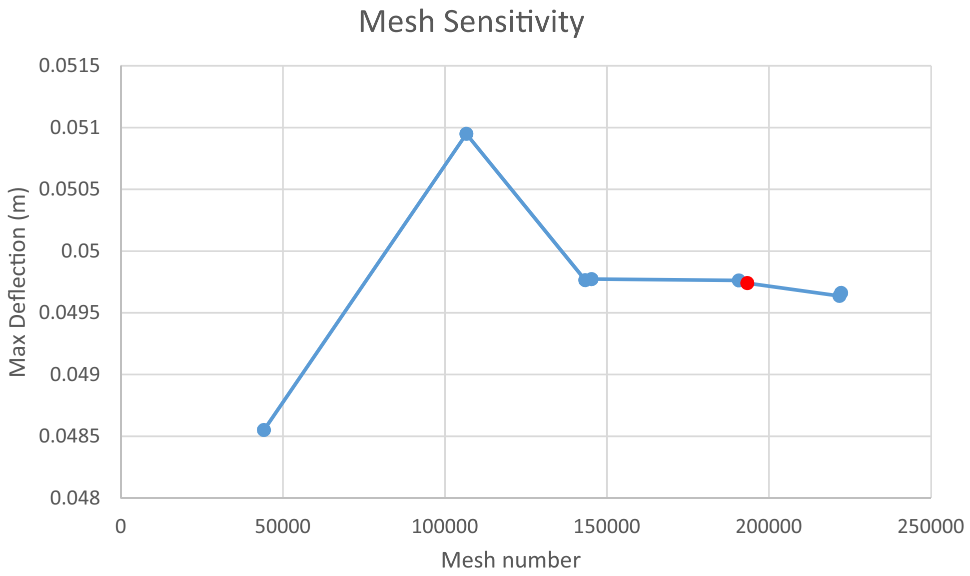
As mentioned above, the distribution of the wood boards is important when evaluating the reinforcing effects. The results for wood boards inserted halfway through ice thickness are compared with the full thickness application ice in Fig. 11. It is noted that Fig. 11 only shows the result for the reinforcing material with an elasticity equal to 8 GPa. Tests for elasticity equal to 10 GPa and 12 GPa were also conducted, and both of them exhibit the same pattern as the curve for 8 GPa.

The deflections of ice covers with reinforcement through the ice cover's full thickness are about half that of reinforcement only halfway through. There are two main reasons for this. First, when wood boards are installed through its full thickness, the reinforcement in the tension zone can withstand more tensile stress and contribute to resisting bending stress. The second reason is that the reinforcing effect depends on the percentage of wood reinforcement by volume. The greater percentage by volume of reinforcement results in stiffer reinforced ice covers and less deflection.

The curves in Fig. 12 demonstrate the deflection reduction for reinforcing material with elasticity of 8, 10 and 12 GPa. Wood boards are installed halfway through the ice thickness. Similarly, Fig. 12 shows the deflection reduction when wood boards are installed through the full ice thickness with elasticities of 8, 10 and 12 GPa for the reinforcing material. According to both Figs. 12 and 13, there is an exponential relationship between deflection reduction and spacing. Using the curves, the deflection reduction under certain spacing can be easily determined. The exponential curves show that the closer the spacing is between wood boards, the less ice covers deflect. This confirms that the stiffer reinforcing material performs better to reduce deflection in the ice cover under load. The exponential curves also help to demonstrate the optimal spacing of wood boards. Designers can determine the usage of reinforcing materials based on the curves to their desirable level.

To determine if the ANSYS model predictions comply with the analytical solution, the same set of numbers in

Fig. 10 Mesh sensitivity analysis



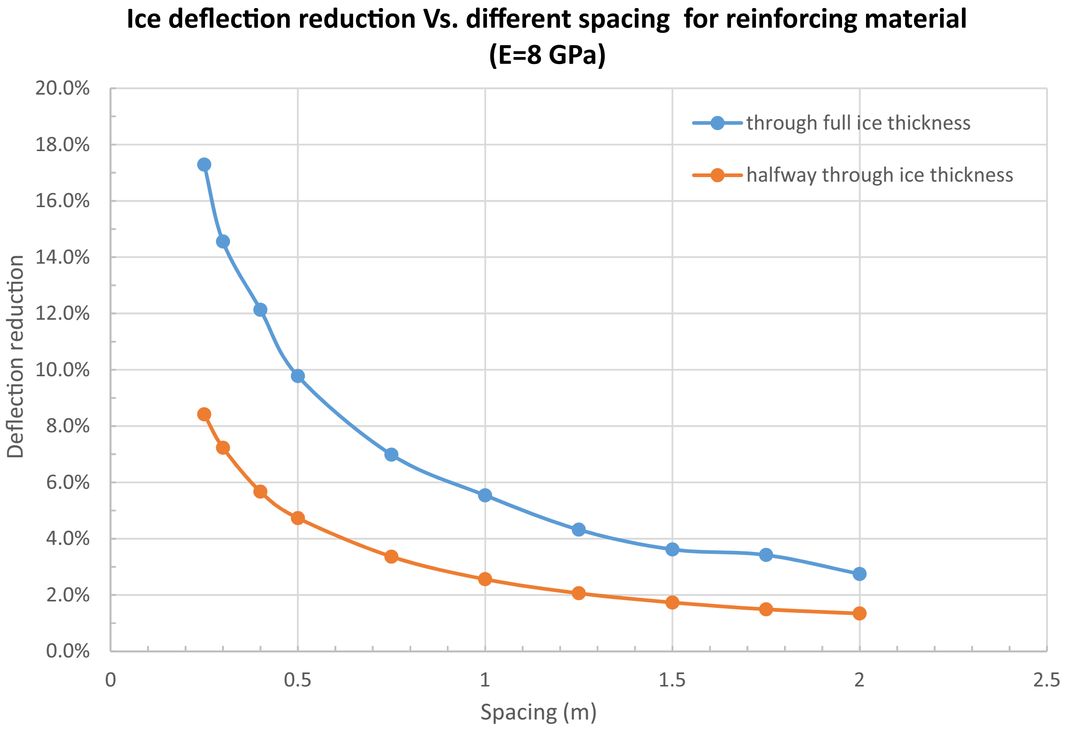


Fig. 11 Ice deflection reduction versus different spacing for the reinforcing material with E = 8 GPa with wood boards halfway through the thickness and through the ice cover's full thickness

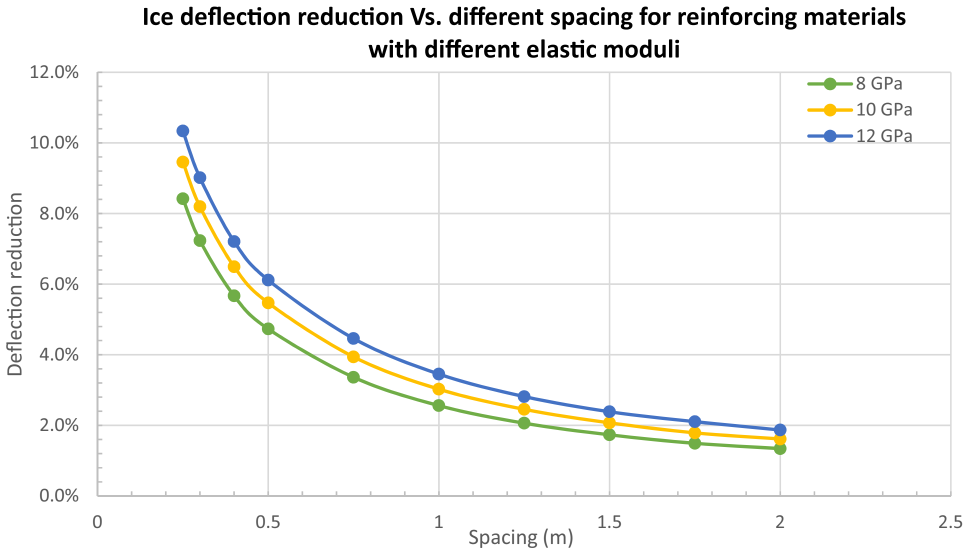


Fig. 12 Ice deflection reduction vs different spacing for reinforcing materials with different elastic modulus with wood boards halfway through the thickness

the ANSYS simulation were used for the analytical solution. Analytical solutions were derived by using elastic plate theory and the composite materials mentioned in the Analytical Methods Section. A good agreement was found between the finite element solution produced by ANSYS and exact elasticity solution derived by the analytical method in terms of the same order of magnitude. Moreover, both analytical and ANSYS curves exhibit an exponential relationship between deflection reduction and spacing. The difference between analytical results and ANSYS results varies from 0.04 to 3.73%, which is deemed acceptable.

Based on the theory behind the two methods, the results obtained from FEA using ANSYS are deemed to

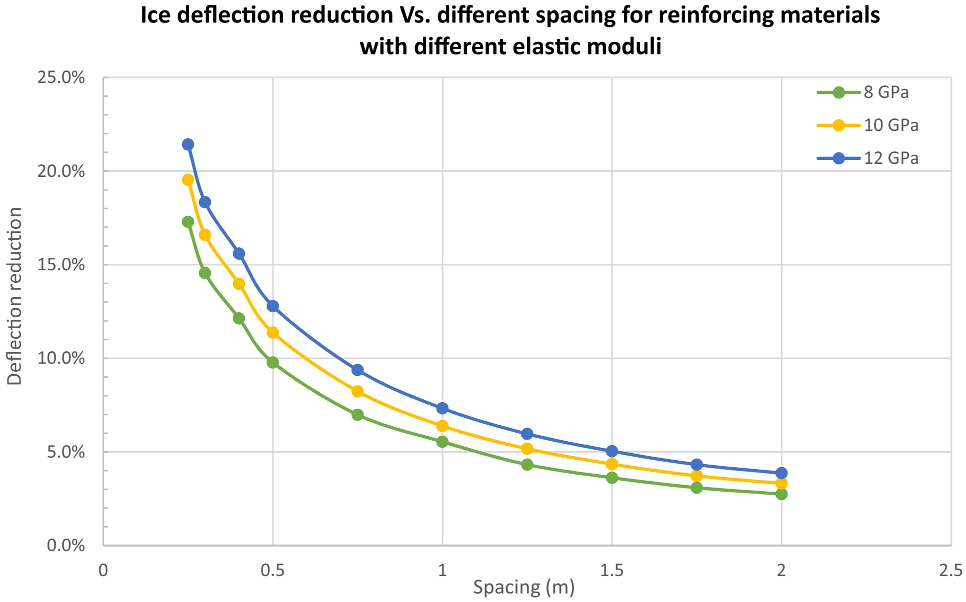


Fig. 13 Ice deflection reduction versus different spacing for reinforcing materials with different elastic modulus with wood boards through full thickness of the ice

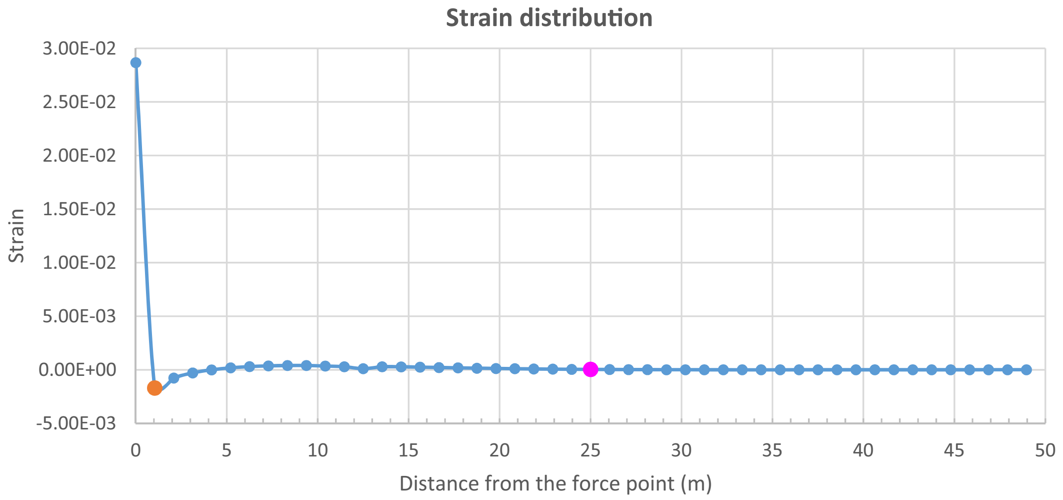
be more reliable. There are many factors that can lead to the difference between analytical and ANSYS results. The main one is non-linear strain and stress distribution within reinforced ice covers, either in the reinforcing materials or in the ice covers. However, in the analytical model, the reinforced ice cover is considered to be a homogenous and linearly elastic material. In reality, each material has a unique material structure, Poisson's ratio and elastic modulus. The strain and stress distributions cannot be perfectly linear as is assumed in the analytical model. In ANSYS, a non-linear strain distribution is reflected in Fig. 14 showing that using ANSYS models to estimate ice deflection will provide a more realistic representation of actual field conditions. A mesh sensitivity analysis was carried out to make sure that large errors do not arise from the meshing process when applying Finite Element Analysis. Overall, the analytical method verifies the results and increases our confidence in the ANSYS computer model simulations.

The beginning and end of the ice road season can be crucial due to potentially warmer air temperatures at the beginning and increasing air temperatures and solar radiation at the end of the season. Design requirements prescribe a minimum thickness of good integrity ice which governs the opening of the road. The length of the season is then limited by the ability to maintain high confidence in the ice integrity and thickness. As air temperatures warm, industry best practice generally accepts that if air temperatures rise above freezing and remain so continuously for 48 h then the bearing capacity needs to be reduced by half until the ice re-freezes with cold temperatures. That said, it is noteworthy to mention that ambient air temperature is the primary driver. At the beginning of the season snow cover, as an insulator retarding growth, impacts the ice cover, there are minimal if any sun effects in December when the days are shortest of the year. At the end of the season sun may play a factor but sunny and − 30 °C is a lot different than sunny and − 2 °C. Ambient air temperature plays the most significance and as the ice cover warms it becomes more flexible. Reinforcement stiffens the ice cover and counters that temperature effect. We are not saying the sun does not have effects but in most cases it does not become a significant factor as compared to ambient air temperature.

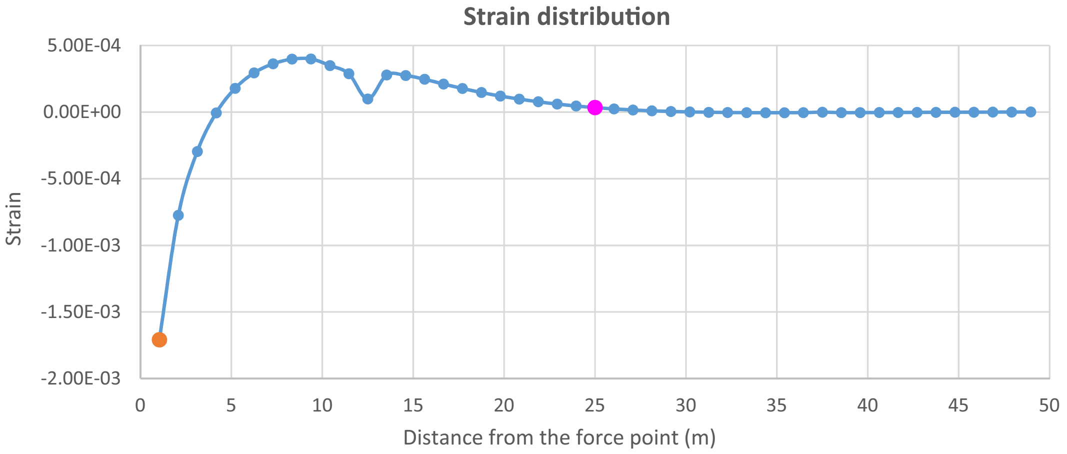
5 Discussion and conclusion

There appears to be two main methods available to improve the bearing capacity of ice covers by using ice reinforcement. One method is to focus on lowering its thermal conductivity by adding other materials into the ice such as sawdust and alluvium. The second method is to increase the elastic modulus of the ice cover by inserting reinforcing materials into the ice cover as was conducted in this study.

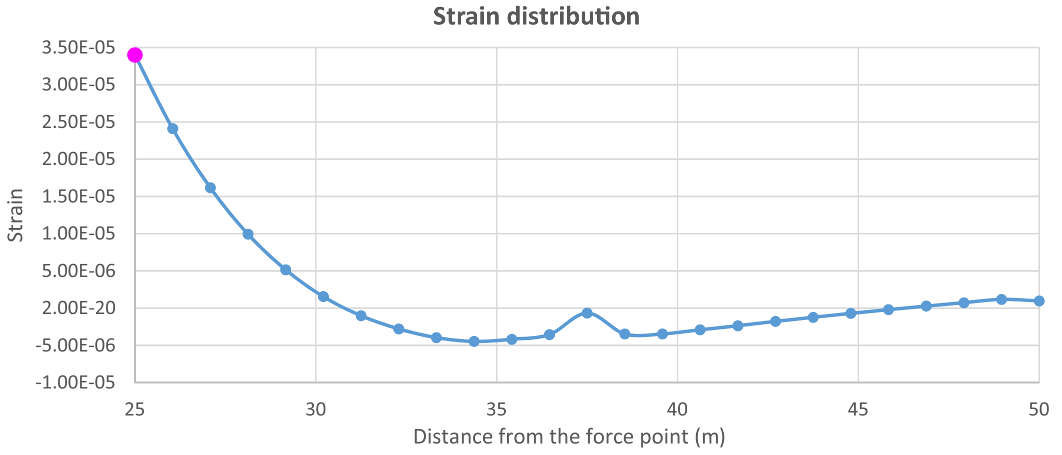
In terms of specific results from this study, an exponential relationship was found between the deflection reduction of an ice cover and the spacing of the wood board reinforcement. The reduced ice deflection can be explained by the stiffening effect of the reinforcement, which draws into effect a larger surface area to support the load. In other words, the deflection bowl has a larger surface area and will have a lower maximum deflection under the same load in a reinforced ice scenario. It is also shown that an ice cover with a higher percentage of wood reinforcement by volume will deflect less.



(a) *strain distribution for the ice cover in ANSYS*



(b) *strain distribution for the ice cover in ANSYS from 1 m to 50 m*



(c) *strain distribution for the ice cover in ANSYS from 25 m to 50 m*

Fig. 14 **a** Strain distribution for the ice cover in ANSYS. **b** Strain distribution for the ice cover in ANSYS from 1 m to 50 m. **c** Strain distribution for the ice cover in ANSYS from 25 m to 50 m

The ANSYS 18.0 Program was successfully utilized to simulate a small variety of scenarios. Some conclusions can be drawn from the analysis, as follows:

(1) Model calibration is critical to accurately predict ice cover deflection because of the significant influence of an effective elastic modulus.
(2) Properly calibrated ANSYS models have the ability to accurately estimate ice cover deflections.
(3) The ANSYS results show that reinforced ice behaviour is stiffer than plain ice. The reinforcing material is able to stiffen the ice cover and allows a larger surface area to carry the load, which helps to reduce the ice deflection.
(4) The test scenarios indicate that the reinforcement materials must be considerably stiffer than the ice so the load can be better transferred from the ice to the reinforcing materials. A higher percentage of reinforcement by volume was more effective in reducing ice deflections.
(5) In this preliminary study stage, we assumed a perfect bonded relationship between wood planks and ice covers. If other materials were to be investigated, such as those that are less adhesive to ice (e.g. fiberglass composite), we would suggest using a partial bonding setup between materials in the ANSYS settings.
(6) ANSYS simulations can provide more realistic estimations of ice deflections compared to simple analytical methods due to their ability to realistically calculate non-linear stresses and strains.
(7) Wood appears to be a feasible reinforcement material. However, further study and field experiments are required to determine the feasibility, effectiveness and safety of other potential materials for reinforcement.
(8) From a theoretical point of view, more wood by volume makes ice covers stronger, but it is very important to understand the threshold limitations of implementing such a modeling result. The actions required to install a large amount of wood beams will reduce the ice cover integrity making it unsafe during the application of reinforcing material. There must be a balance between volume of reinforcement and ice integrity associated with installation. Note that at this preliminary study stage, it is assumed that the integrity of ice covers will be reduced only under the circumstance that the spacing between reinforcement is too small.

In the past, deflection experiments have cost between $125,000 and $160,000 (Canadian dollars) depending on the scope and number of experiments being conducted (days in the field). This does not include accommodation expenses since facilities at clients' camps are often made available. With material, equipment and construction labour costs, we expect a field experiment with a season of trips to monitor the test site and review two reinforcement methods to cost a minimum of $250,000 (Canadian dollars).

Table 1 shows some rough estimates of costs of the reinforcing material, for both full and half ice cover thicknesses, and the approximate minimum total cost for the deflection experiment ($250,000), as stated in the previous paragraph. The cost for the lumber was assumed to be approximately $1/m. The total costs for the material is for each km of road with the width of the road taken to be 30 m. The "wood to ice volume" values are those shown in Fig. 7 and the "deflection reduction" used for the calculations are those provided in Fig. 11. The calculations show that the reinforcing material can add about 3 to 6% to the cost of the deflection experiment for wide spacing of the reinforcing material (every 2 m) but climb up to 19 to 32% for a narrow spacing (0.25 m).

Based on the findings in this study, the following recommendations are made:

(1) Reinforcement materials including branches, sawdust, wood pulp, wood boards, and other geosynthetic materials can contribute to increased bearing capacity of ice covers. Further modelling should be completed to provide a theoretical sampling of results for materials in order to inform about an effective, full-scale field test.
(2) In future research, tests on bending, tensile, and compressive stress and failure mechanisms of ice covers should be investigated for incorporation into the model.
(3) Further study and experiments are planned to investigate the orientation of reinforcing materials, behaviors and properties of ice covers under multiple points of load at the same time and the resilience to impact. In addition, further study on alternative reinforcing materials to wood is also suggested. Considering the restrictions in terms of local availability and environmental friendliness, bamboo, cork, straw and wood composite should be investigated.
(4) Calibration can improve ice cover modelling. Backcalculations from field deflection measurements for determining the effective elastic modulus is helpful and necessary. However, it is not feasible to measure field deflections on every winter road, so it makes more sense to analyze available data with an aim to validate confidence intervals for selecting an elastic modulus for ice and providing a reasonable value to

Table 1 Cost estimates of reinforcing material to the minimum total cost of the deflection experiment per km of a 30 m wide ice road

Reinforcing material through full thickness (per km of road)									Reinforcing material through half thickness (per km of road)								
Wood to ice volume (%)	Spacing of beams m (m)	# of boards/width (#)	Size of ice cover (m2)	Reinforcing material cost ($)	Minimum total cost for deflection experiment ($)	Total cost of deflection experiment ($)	Material cost: total cost (%)	Deflection reduction (%)	Wood to ice volume (%)	Spacing of beams m (m)	# of boards/width (#)	Size of ice cover (m^2)	Reinforcing material cost ($)	Minimum total cost for deflection experiment ($)	Total cost of deflection experiment ($)	Material cost: total cost (%)	Deflection reduction (%)
19.0	0.25	120	30,000	120,000	250,000	370,000	32.4	2.7	8.7	0.25	120	30,000	60,000	250,000	310,000	19.4	1.3
8.7	0.50	60	30,000	60,000	250,000	310,000	19.4	4.3	4.2	0.50	60	30,000	30,000	250,000	280,000	10.7	2.1
5.6	0.75	40	30,000	40,000	250,000	290,000	13.8	5.5	2.7	0.75	40	30,000	20,000	250,000	270,000	7.4	2.6
4.2	1.00	30	30,000	30,000	250,000	280,000	10.7	7.0	2.0	1.00	30	30,000	15,000	250,000	265,000	5.7	3.4
3.3	1.25	24	30,000	24,000	250,000	274,000	8.8	9.8	1.6	1.25	24	30,000	12,000	250,000	262,000	4.6	4.7
2.7	1.50	20	30,000	20,000	250,000	270,000	7.4	12.1	1.4	1.50	20	30,000	10,000	250,000	260,000	3.8	5.7
2.3	1.75	17	30,000	17,143	250,000	267,143	6.4	14.6	1.2	1.75	17	30,000	8571	250,000	258,571	3.3	7.2
2.0	2.00	15	30,000	15,000	250,000	265,000	5.7	17.3	1.0	2.00	15	30,000	7500	250,000	257,500	2.9	8.4

close the current gap between predicted and field recorded deflections.

(5) Field testing is strongly recommended in order to definitively evaluate and validate the modeling results for operational application.

(6) Wood planks with a cross-section of 5 by 10 cm or 5 by 25 cm are suggested to be used. For the areas with thinner ice covers, we recommend that the reinforcing materials should be installed with a spacing of 1 m. For the rest of the ice cover, the spacing can be larger.

In conclusion, this study provides a proof of concept for an ANSYS computer model investigation of reinforced ice. We have highlighted the confidence level in the development and stress analysis of reinforced ice covers, which can lead to improved safe bearing capacity on a given ice thickness. Increased predictability in the ability to support loading can also result in operational efficiencies and a better ability to counter the effect of climate change by applying appropriate measures to optimize operations on available ice.

6 Considerations for future work

In our model setup, only the reinforcing material in the ice cover was modelled, which provided reasonable results of a first assessment on the feasibility of implementing a reinforcing material to strengthen ice covers. However, for greater accuracy, the forces at the water–ice interface at the bottom of the ice cover should also be taken into account. This requires a coupling of ANSYS' transient structural analysis module to its computational fluid dynamics module, CFX, available in ANSYS version 18.0 and higher [21]. The solids-fluids coupling involves a much higher modelling complexity and steps have been taken to study the interactions of propagating water waves on continuous solid ice covers [21, 22]. Amendments to the coupled model setup can be made to incorporate reinforcing materials to these ice covers, a topic of future work.

An important extension of this work in the future is to model the reinforcing potential of other materials such as wood chips and pulp. Once several methods have been determined to be suitable for reinforcement and are operationally applicable, then a cost/benefit analysis can be carried out. Such an analysis is required to determine if the effort is worth the gain in regards to reinforcing ice crossings. Experimental work to test the reinforcement in the field is also planned.

Another consideration for further feasibility studies is the distribution of truck loads over additional axes.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

References

1. Stephenson SR, Smith LC, Agnew JA (2011) Divergent long term trajectories of human access to the arctic. Nat Clim Chang J. https://www.researchgate.net/publication/241605071_Divergent_long-term_trajectories_of_human_access_to_the_Arctic. Accessed 25 Mar 2019
2. CBC News (2016) Ice roads, access for first nations debated in house of commons. http://www.cbc.ca/news/canada/saskatoon/ice-roads-access-for-first-nations-debated-in-house-of-commons-1.3463233. Accessed 25 Mar 2019
3. Mesher DE, Proskin SA, Madsen E (2008) Ice road assessment, modeling and management. In: 2008 annual conference of the transportation association of Canada, Toronto, Ontario
4. Churchill WS (1951) Closing the ring: the second world war, vol 5. Houghton Mifflin, Boston, pp 75–76
5. Kingery WD (1960) Applied glaciology—the utilization of ice and snow in arctic operations. J Glaciol 3(27):577–588
6. Ohstrom EG, DenHartog SL (1976) Cantilever beam tests on reinforced ice. USA Cold Regions Research and Engineering Laboratory, CRREL report 76–7
7. Jarrett PM, Biggar KW (1980) Ice reinforcement with geotechnical fabrics. National research council of Canada workshop on winter roads, Ottawa, Ontario, pp 60–68
8. Fransson L, Elfgren L (1986) Proceedings on field investigation of load-curvature characteristics of reinforced ice, vol 1. POLARTECH'86, pp 175–196
9. Haynes FD, Martinson CR (1989) Ice reinforced with Geogrid. In: Proceedings of 8th international OMAE conference, vol 4, pp 179–185
10. Nixon WA, Weber LJ (1989) Alluvium-reinforced ice: a preliminary report of bending strength tests. Cold regions science and technology. Elsevier, Amsterdam, pp 309–313
11. Nixon WA, Weber LJ (1990) The effect of specimen size on the bending strength of alluvium reinforced ice. In: Proceedings of 9th international conference on offshore mechanics and arctic engineering (OMAE), vol 4. ASME, Houston, TX, pp 217–22
12. Nixon WA, Weber LJ (1991) Flexural strength of sand reinforced ice. J Cold Reg Eng ASCE 5(1):14–27
13. Nixon WA, Weber LJ (1995) Reinforcement percentage effects on bending strength of soil–ice mixtures. Cold Reg Sci Technol ASCE. 9(3):152–163
14. Haynes FD, Collins CM, Olson WW (1992) Bearing capacity tests on ice reinforced with Geogrid. USA Cold Regions Research & Engineering Laboratory, special report
15. Light B, Eicken H, Maykut GA, Grenfell TC (1998) The effect of included particulates on the spectral albedo of sea ice. J Geophys Res 103(C12):27739–27752
16. Sinha NK, Cai B (1996) Elasto-delayed-elastic simulation of short-term deflection of fresh-water ice covers. Cold Reg Sci Technol 24(2):221–235. https://doi.org/10.1016/0165-232X(95)00004-U
17. Gold LW (1981) Designing ice bridges and ice platforms. National Research Council Canada DBR, Quebec, pp 685–701
18. Masterson DM (2009) State of the art of ice bearing capacity and ice construction. Cold Reg Sci Technol 58:p99–112
19. Green DW, Winandy JE, Kretschmann DE (1999). Mechanical properties of wood
20. Wyman M (1950) Deflections of an infinite plate. Can J Res 28(3):293–302
21. Liu N, Kells J, Lindenschmidt K-E (2016) One-way coupled fluid structure interaction analysis of shallow hydropeaking wave propagation in a partially ice-covered river channel. In: 23rd IAHR international symposium on ice. Ann Arbor, Michigan, USA, 31 May–3 June, 2016
22. Liu N, Kells J, Lindenschmidt K-E (2017) Two-way fluid-structure interaction model of waves propagating in a channel with an ice cover. In: CGU HS committee on river ice processes and the environment, 19th workshop on the hydraulics of ice covered rivers, Whitehorse, Yukon, Canada, 9–12 July 2017. http://cripe.ca/docs/proceedings/19/Liu-etal-2017.pdf
23. Wikipedia. Pykrete. http://en.wikipedia.org/wiki/Pykrete. Accessed 25 Mar 2019