On the reinforcement of ice covers for surface transportation

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On the reinforcement of ice covers for surface transportation

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Summary

Winter roads are seasonal structures that only exist in the winter – they run over frozen land and frozen water surfaces (lakes, rivers). These roads can only open once the segments running over ice covers have achieved a thickness deemed safe enough to accommodate the weight of the vehicles expected to travel on them. A review of documented cases is presented in which reinforced ice was used for real operational scenarios as well as in field studies – these include a description of construction and/or deployment procedures. A review of laboratory investigations on reinforced ice is also provided, with a succinct account of the loading modes and types of testing that have been done, as well as their outcome. The difference between macroscopic and microscopic reinforcement is outlined, with examples. A distinction is made between the concepts of ice 'failure', linked with 'first crack', and breakthrough, as well as between linear and planar macroscopic reinforcement. Resistance to deformation of reinforced ice, the importance of bonding between ice and reinforcement materials, and the resistance to breakthrough are aspects that have been addressed by previous investigators. The outcome of a computational modeling exercise, aimed at assessing resistance to ice failure for linear reinforcement (lumber and steel), under specific assumptions, offers guidance in the choice of material size, type, spacing, aspect ratio and depth in the ice cover. Options for deployment procedures include: i) laid onto the ice, ii) in the water before freeze-up, iii) inserted through and below the ice, and iv) inserted into the ice surface. Breakthroughs are complex phenomena involving a sequence of radial and circumferential cracks. Retrieval of reinforcement after the winter road season is over is another aspect that warrant attention in a planning scheme, but very little information was found in that regard. Determining the bearing capacity of reinforced ice is seen as an outstanding challenge in being able to implement a safe and effective reinforcement procedure. The solution could be to perform real-scale, fully controlled ice testing, and most importantly, allow for breakthrough to be achieved, so as to avoid overly conservative designs. A simple reinforcement procedure would have to be devised beforehand, further guided by adequate computational modeling. This would lead the way toward guidelines on implementation.

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1. Introduction

As their name implies, winter roads are seasonal structures that only exist in the winter – they run over frozen land and frozen water surfaces (lakes, rivers)(Kuryk, 2003, Proskin et al., 2011a, Malbeuf, 2021). These roads cannot open if the segments running over ice covers (referred to in this report as over-ice segments, ice bridges or ice crossings) have not achieved a thickness deemed safe enough to accommodate the weight of the vehicles expected to travel on them. Various sources of information exist on building and maintaining winter roads and establishing what a safe ice thickness should be. They take the form of provincial and territorial guidelines, as well as reports from other organizations – for a brief review of these documents, the reader is referred to Proskin et al. (2011b) and Barrette (2015a).

Over-ice segments are particularly vulnerable to a warming climate (Hori and Gough, 2018, Chunesingh, 2019, Kuloglu, 2020, Malbeuf, 2021). Ice reinforcement for the purpose of sustaining higher loads, and/or for a longer duration, is not a new concept (Figure 1). This approach may be seen as an effective means to remediate to weak links along a winter road operation, i.e. ice bridges and shoreline crossings that are problematic because of higher air temperatures and consequences thereof.

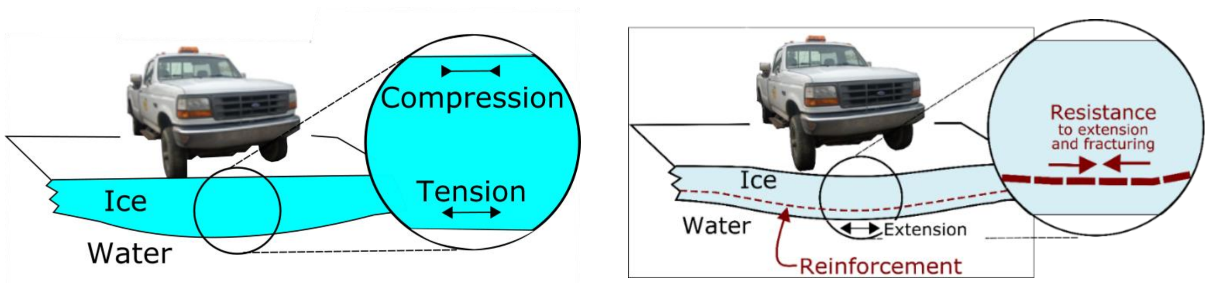

Figure 1: The principle of ice cover reinforcement. Left) State of stress in the ice. Right) Action of reinforcement.

According to Michel et al. (1974), referring to reinforced ice covers, *"[t]here is no known publication on their design as such, although much knowledge is available on bearing capacity of natural ice covers"* (p. 599). To this day, such guidance in reinforcing ice covers is still lacking. This is probably due to the effectiveness of the existing flooding techniques to artificially increase ice thickness to the required level. However, we have reached a stage where the traditional modus operandi no longer suffices, and ice reinforcement strategies should be given due consideration.

2. Rationale

A review of the history and past investigations on ice reinforcement is summarized in Vasiliev et al. (2015). Trees, branches and logs are probably the most commonly recognized reinforcement materials, but there are others. Although there has been a number of experimental or laboratory investigations on the effectiveness of this concept, only a few actual operational scenarios have been documented. Some of those cases contain information on how this technique has been implemented, e.g. a description of the procedures and the outcome thereof.

In practice, there are two response of interest in assessing the ability of an ice cover to sustain a load. One, which is sometimes referred to as 'first crack', is when the strength of the ice has been mobilized (beyond the elastic response). This corresponds to a structural *failure* ('failure' in this report). It may happen for a number of reasons, namely the vehicle that caused the failure exceeded the allowable weight. Another is that the ice thickness was not sufficient – this can happen if it is not well monitored. Or the route crossed an area where a current existed (inducing thermal erosion of the lower surface). Excessive speed can also promote ice failure.

After failure, the ice cover can still withstand the load but its capability is reduced. When this happens, water may make its way to the surface, which is an indication to the winter road operator that this segment should be closed to traffic, until it freezes again.

If a load that has caused failure is not removed, or if it significantly exceeds what is required for failure, or if the ice is not repaired before the next vehicle accesses that location, this can lead to a *breakthrough*. This is the second parameter that needs to be understood. It is the outcome of a process that is much more complex than the first one (failure), involving extensive crack development.

Added complexity to these two responses, failure and breakthrough, is the nature of the ice cover, which varies considerably in internal structure, as well as the nature of the applied load, which can be static or moving.

3. Objectives

The objectives of this report are:

- To describe what has been documented in terms of the operational usage and real-scale testing of reinforced ice covers.
- To provide a cursory review of investigations that have been done in a laboratory set-up (or otherwise, in a well-controlled experimental set-up), to assess the effectiveness of ice reinforcement.
- To explore the effects of reinforcement material and geometry on first crack (failure) via computational modeling.
- To address means of deployment and implementation of a reinforcement scheme.
- To evaluate the conditions under which breakthrough can occur.

The bulk of the background information and the sources that are enclosed herein are meant to be representative of the topic, and do not constitute a comprehensive listing. They are from Canada or North America in general and, to a much lesser extent, from Europe and Russia (when the sources were written in English). The target audience is everyone that has an interest in winter roads – consultants, operators, users, decision-makers from the various jurisdictions overseeing this type of operations. A number of illustrations have been produced for the sake of clarity. In order to make this report accessible to a wider audience, elaborate academic material (e.g. equations) was minimized. All imperial units, including those in quotes, were converted into SI units.

4. Operational scenarios and field studies

In this section, a review of documented case examples is presented in which reinforced ice was used for real operational scenarios, or for real-scale evaluation. The relevance of this review may be best understood by considering that the winter road community in Canada is not fully aware of the potential that ice reinforcement techniques represent. In the vast majority of scenarios where an ice crossing is problematic, other solutions are envisaged, such as more effective flooding or re-routing of over ice segments over land.

According to Vasiliev et al. (2015, p. 56):

> *"[d]uring World War II in the USSR different ways of ice reinforcement using logs, branches and twigs were used to permit motor traffic on the ice of Ladoga Lake on the "Life Road" during the siege of Leningrad. The reinforcement of river ice roads on ice cover (ice ferries) with these materials was also used for heavy military transport in other areas of the military action (Bregman and Proskuryakov, 1943)."*

The cited document is in Russian and was not consulted by the authors of this report, but this could be one of the earliest source of information on an operational scenario.

4.1. The Engineer (1964, p. 60)

In this source, a very short description is presented on a procedure to reinforce ice:

> *"According to two Soviet inventors, Alexei Ozherelyev and Vasili Chervyakov, reinforced ice only 200 mm thick can withstand convoys of loaded lorries while reinforced ice 500 mm thick can withstand railway trains. Even ice only 80 mm thick can be reinforced to withstand heavy loads. The proposed method of reinforcement consists in cutting 30 mm wide longitudinal and transverse grooves, using a circular saw, and laying cables made of fibreglass or other synthetic material in them. Holes are then drilled in the bottom of the grooves to admit water. When it freezes the cables in the ice play the same role as steel reinforcement in ferro-concrete."*

An idealized representation of this procedure is shown in Figure 2.

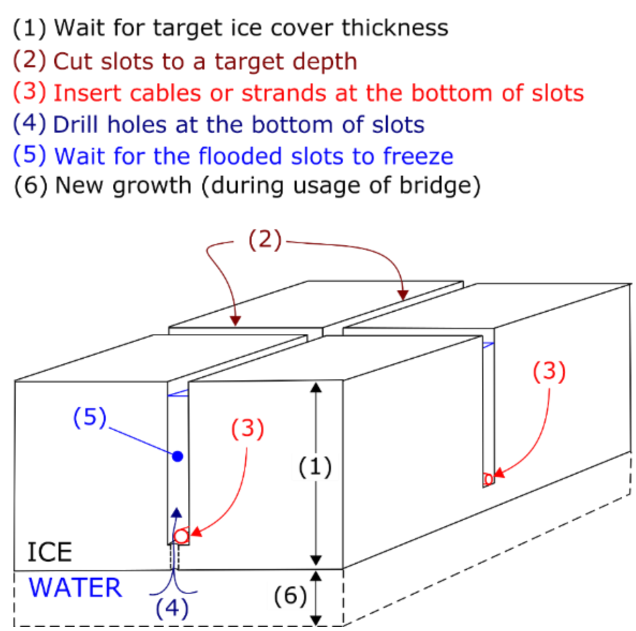

Figure 2: Procedure to reinforce an ice cover, based on the description in The Engineer (1964). For the purpose of this illustration, it is divided into six steps. The reinforcement is indicated by arrows (3).

4.2. Carnes (1964)

This source describes an ice bridge that was built in January 1963 (for military purposes) over the Imjin river in South Korea. At the time, the daily temperatures ranged from 10ºC to -26ºC. The aims were:

> *"[t]o determine if such a bridge could be successfully constructed on a tidal river in a temperate zone area with a relatively mild climate; to find out if an ice bridge could be constructed which could carry heavy wheeled and tracked vehicles; and if so to ascertain if an ice bridge have a true tactical value (p. 104).*

The crossing was 150 m in length – this was the narrowest point in the sector of interest. The construction began after the ice achieved about 150 mm in thickness, following these steps:

- After deciding on the route, wooden stakes 100 mm in diameter were frozen into the ice at a distance of about 3.8 m from a center line on both sides.
- Logs 100 to 150 mm in diameter were placed end to end all along both edges of the road, against the inside edge of the wooden stakes, and frozen in place. The gaps between them were filled with grass. The logs served two purposes: one was to delineate the road; the other was to retain flood water for the following step.
- Rice straw mats 100 mm in thickness were then laid inside that corridor, directly on top of the ice and in random orientation. These were flooded, and allowed to freeze.
- The subsequent layer was made from branches, brush and twigs varying in diameter from about 10 mm to 25 mm. The thickness of that layer was about 100 mm.
- The previous step was repeated until a total thickness of about 250 mm of reinforced ice was achieved.

At the end of this procedure, which required at least one week, the total thickness of the ice bridge, including both natural and reinforced ice, was about 500 mm (Figure 3). Note that the reinforcement is about the center of the ice thickness. A treadway – a surface onto which vehicles drove on – was assembled from wood planks and laid on the reinforced ice surface. The joints between them was staggered, and the assembly was held together with narrow pieces of lumber (Figure 4). Information about the construction of shoreline ramps, which is said to be the "most involved", is also provided in the source. Controlled crossings were initially conducted with lighter vehicles, up to about 700 kg. This was followed by an armored ('SPAT') vehicle, whose weight is not mentioned in the source, but which is here estimated at about 6,500 kg. A final, ultimate test was done with an M-41 tank, reported to be 23,000 kg in weight. All trials were successful, and the bridge was then open for unlimited use by small vehicles and light trucks. The bridge was closed around February 25, due to a warm spell.

According to today's provincial and territorial guidelines in Canada, the smallest thickness for an ice cover required to support an M-41 tank would have been about 750 mm *without* reinforcement (Government of the NWT, 2015)[1].The procedures used for the construction of the Imjin ice bridge therefore allowed for an ice cover that was 33% thinner. Note that the reinforcement was above the center of the ice column, i.e. not inside the compression zone. No information is provided on the ice response, e.g. cracking and creep displacements over the bridge's operational time span.

[1] For such a scenario, the guidelines instruct the operator to seek advice from a Professional Engineer.

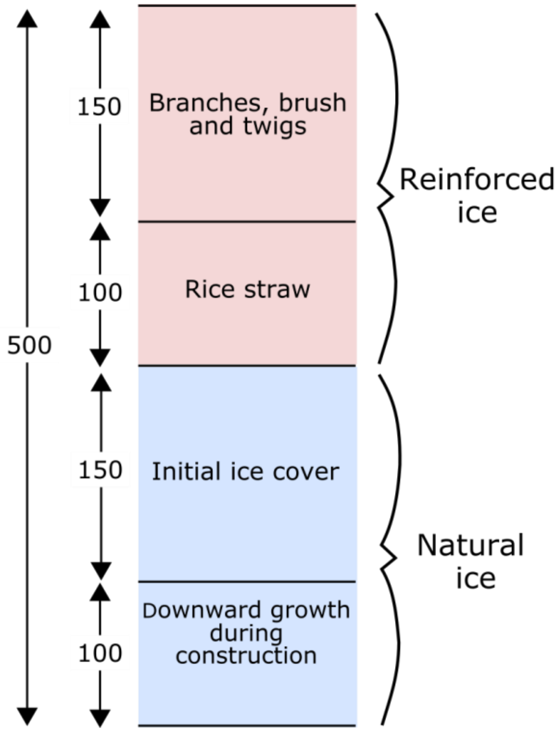

Figure 3: Simplified cross-section of a reinforced ice crossing in South Korea, based on information provided in Carnes (1964). Dimensions are in millimeters.

Figure 4: Top) Passage of the first vehicle across the Imjin River, in Korea. Bottom) Passage of the largest load across that river – an M-41 tank. From Carnes (1964). Reprinted with permission of the Society of American Military Engineers.

4.3. Gold (1971) – Case 1

Gold (1971) briefly describes three instances of reinforced ice crossings. The first crossing was built at a location where the river was 430 m in width, and a water depth of 2 m. There was a water current of 2-3 km per hour at that location. Following is the description provided by the author:

> *"A 75 m wide route was cleared across the river when the ice was 300 to 450 mm thick. A 45 m wide roadway was flooded to level out the surface. Small logs, 200 to 300 mm in diameter, were placed diagonally across the bridge at 0.6 m centers to form a 7.5 m wide road surface. The ice was built up by flooding until the average thickness of the roadway was about 1.5 m. […] The ice bridge was used for 8 weeks to transport about 17,000 tonnes of freight. The heaviest load was a truck and tractor weighing 118 tonnes. Regular checks were made on the condition of the bridge to ensure that no weak areas were present."* (p. 180)

An idealized representation of that construction is shown in Figure 5.

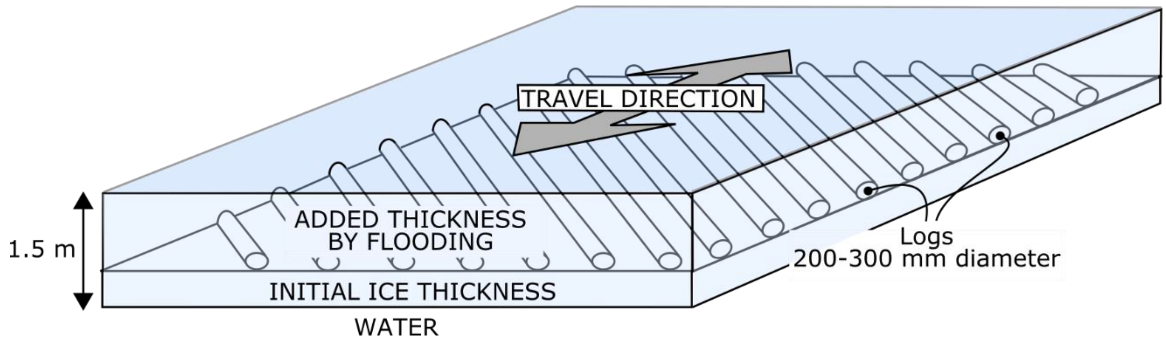

Figure 5: Ice crossing built from logs placed diagonally on the ice surface (drawn following the description provided by Gold, 1971). Not to scale.

4.4. Gold (1971) – Case 2

The second crossing described in Gold (1971) was with steel cables and logs (Figure 6):

> *"When the ice was 700 mm thick, three 28.6 mm steel cables of 55-tonnes breaking strength were laid and anchored at each shore. Logs were placed across the three cables and frozen into position. The pumping of water onto the crossing was continued until the total thickness was about 1.30 m. Snow was removed from the adjacent cover over a width of 15 to 30 m on both sides. 1185 vehicles of gross weight less than 14 tonnes, 2034 of gross weight between 14 and 22.5 tonnes, and 52 of gross weight between 22.5 and 45 tonnes, used the crossing over the period 16 January to 15 April. The maximum load was 45 tonnes".* (p. 180-181)

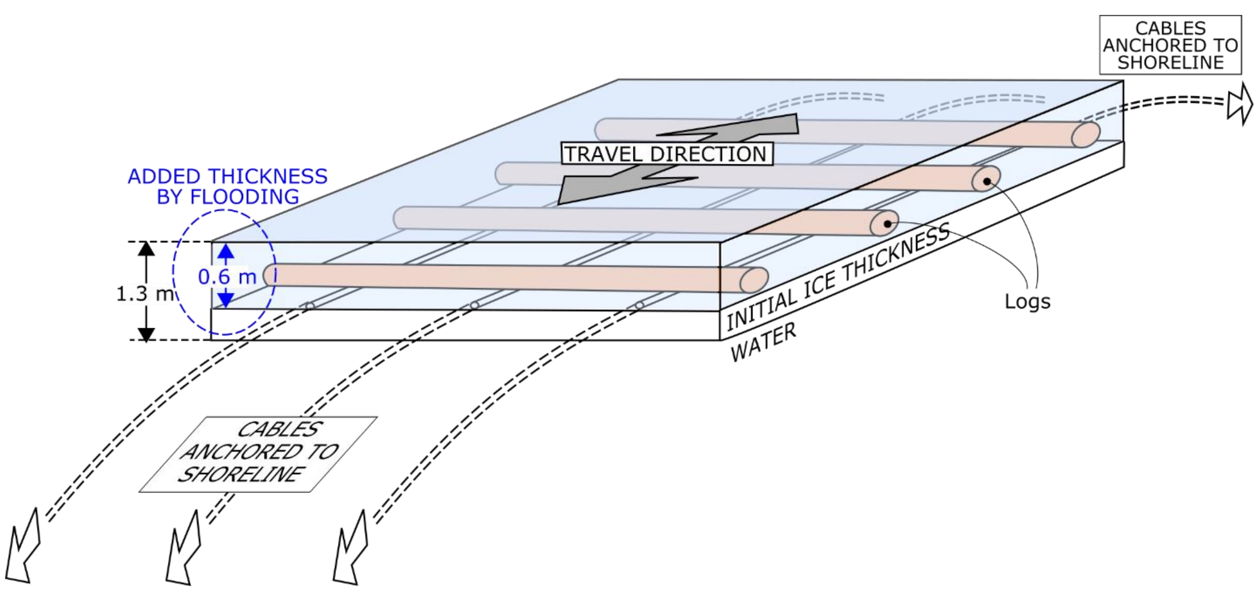

Figure 6: Ice crossing built from logs laid on top of steel cables that were anchored to both shorelines (drawn following the description provided by Gold, 1971). Not to scale.

4.5. Gold (1971) – Case 3

The third crossing described in Gold (1971) was with four layers of logs (Figure 7). At that location, the river was about 110 m in width and the water depth was from about 2 to 4.5 m. Following is the description provided in the source:

> *"Four layers of logs, 200-250 mm in diameter, were frozen into the ice. The first layer was placed crosswise, the second lengthwise, the third crosswise and the fourth lengthwise. The logs were frozen in as laid at a spacing of about 1.22 m between centers. The width of the reinforced area was about 9 m, and the total thickness about 1.5 m. Strips about 7.5 m on either side of the reinforced area were flooded so that the width of the built-up crossing was about 25 m. A hole drilled 7 m from the center line and fifty from shore indicated 1.25 m of solid ice and 0.13 m of weak ice near the surface. About 35 m from shore and 8.5 m from the center line there was 1.5 m of good ice. The water rose to the top of these test holes. The maximum thickness of the natural ice was about 0.61 m. A tower-erecting crawler crane weighing 90 tonnes was moved over the crossing. The crane was supported on four tracks about 4 m long and 1.4 m wide. The distance between the center lines of the tracks was 2.3 m along the width of the crane and 6.3 m along the length. Contact pressure under the tracks was 41 kPa. No cracking was heard as the crane traveled over the ice. The crossing was used regularly for carrying loads of up to about 45 tonnes".* (p. 181)

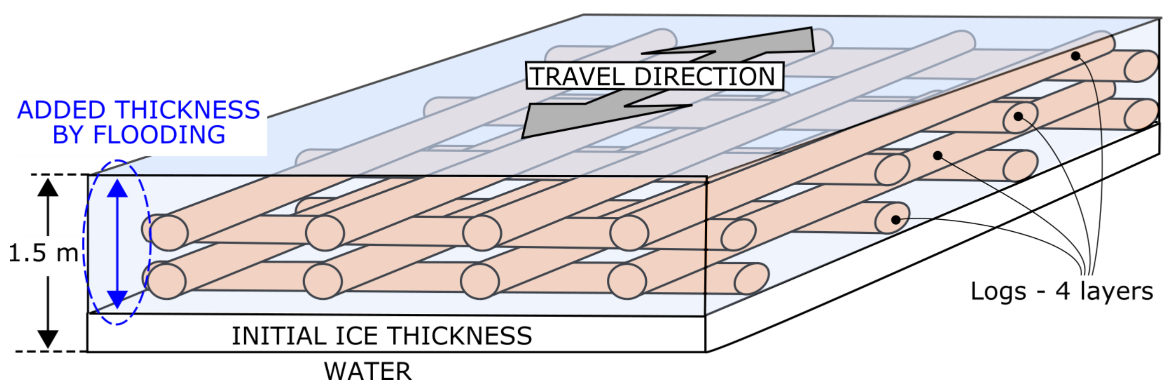

Figure 7: Ice crossing built from four layers of logs (drawn following the description provided by Gold, 1971). Not to scale.

4.6. Michel et al. (1974) – Three crossings

The work by Michel et al. (1974) was to support development of large hydro-electric dams in Northern Quebec, east of James Bay. A winter road, about 600 km in length, was built for that purpose. It comprised eight major ice crossings and a number of smaller ones. The road was used over two winters (1971-72 and 1972-73). The objective of the paper was to present the theory for assessing bearing capacity of reinforced ice for those crossings. It also discusses the design, site selection construction and testing of these structures. The load requirement was 70 tonnes, which was the weight of a "*D-9 bulldozer carried on a float*" (although higher loads have been achieved). Their design is depicted in Figure 8.

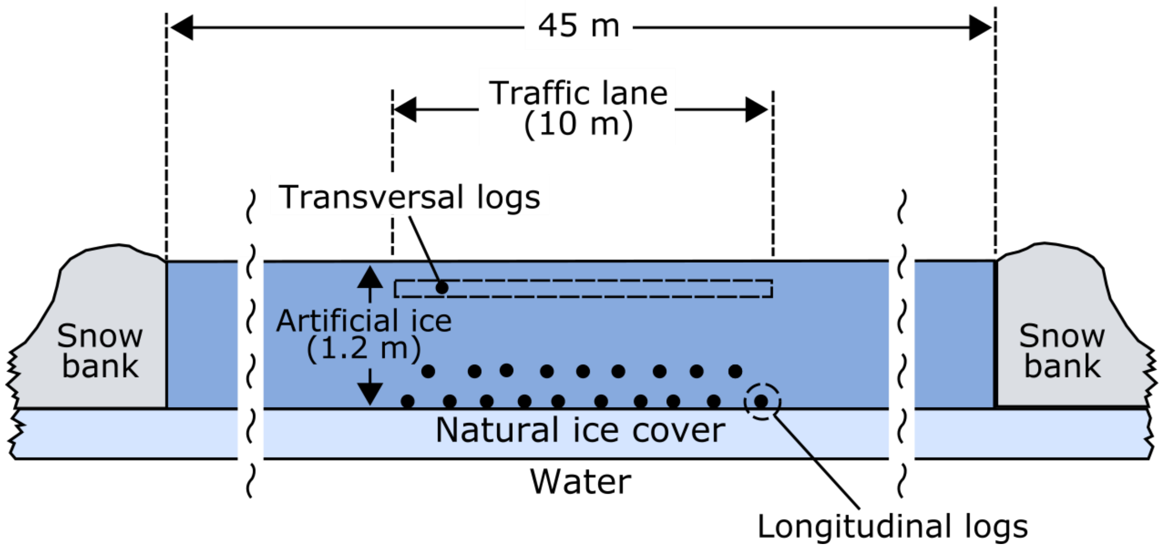

Figure 8: A "typical design" for the ice crossings described in Michel et al. (1974, Fig. 8, p. 609). Reinforcement comprises two longitudinal rows of logs and one transversal row of logs.

From the source:

> "*The bridges were reinforced with wood logs of aspen and black spruce averaging 150 mm in diameter. They were set a distance of 1.2 m center to center in the longitudinal direction with an overlap of 0.9-1.2 m. Two rows were first placed and a transversal layer was placed on top at distances of 12.2-24.4 m center to center, close to the surface of the ice bridge. […] The first row of logs was placed when the natural ice cover had a minimum thickness of 380 mm. It can be considered that this natural ice was a mixture of snow and columnar ice of poor quality. The second row was placed about 300 mm above the first one. The transversal row was set about 1270 mm from the bottom of the bridge.*" (p. 607)

The authors further commented that the logs were suspected to delay ice growth from below, especially if snow accumulated between them. The design assumed ice failure in tension, while the logs would take up the full load. However, ice thickening was expected to cause the reinforcement to approach the neutral axis, thereby becoming less effective. It was also determined that the "*the type, quality and presence of wet cracks"* (p. 618) played an important role. For instance, although the crossings' design thickness was 1.6 m, that thickness was found to be insufficient for some crossings, which had to be up to 2.54 m. This meant that the ice had to be monitored (in situ) on an on-going basis. Nonetheless, the conclusion was as following (p. 618): "*More than 3000 loads crossed safely the bridges during the two winters of 1972 and 1973 without delay*."

4.7. Fransson and Elfgren (1986)

A field investigation was conducted by Fransson and Elfgren (1986) to assess the effectiveness of laying the reinforcement at the top of the ice, then flooding it, in such a way it could resist compression. Three different materials were used for that purpose: sand, birch branches and lumber (Figure 9). The site of that study was a lake in Sweden, about 40 km northwest of Luleå. Per the source:

“Initially the ice cover had a thickness of approximately 0.5 m. First, a 25 m wide surface across the lake (~ 120 m) was cleared from snow. Then the ice road was reinforced with:
(a) a layer of 50 mm sand, and water on top of the original ice
(b) branches of birch with a spacing of 0.3 m in two perpendicular directions
(c) [lumber] (pine approx. 50x50 mm^2) with a spacing of 0.3 m in two perpendicular directions.
The temperature was about -25°c during the flooding. In order to decrease the number of air pockets in the new ice, a light tracked vehicle was driven over it when it was partially frozen.” (p. 182)

Table 1: Thickness and surface area of the different reinforcement materials used in the trials reported in Fransson and Elfgren (1986).

Type of reinforcement	Thickness of reinforcement (m)	Total ice thickness (m)	Area (m x m)
Sand	*0.10*	*0.65*	*10 x 30*
Birch branches	*0.20*	*0.65*	*10 x 31*
Lumber	*0.13*	*0.66*	*10 x 40*

A dump truck weighing 18.2 tonnes was used to load the reinforced ice (Figure 10). The variation – with time – in curvature of the ice surface was monitored with displacement gauges mounted below the vehicle. The loading event lasted 20 minutes. The truck was then removed and the deflection was monitored for another 10 minutes. Deflection of the ice reinforced with sand and lumber was one tenth of that of the ice reinforced with the birch branches. As pointed out by the authors:

“[…] the birch branch reinforcement hardly improved the ice load-curvature characteristics at all. This was probably due to the fact that the branches have low stiffness in compression. Thus they cannot help the ice to withstand the compressive forces but instead deform, when compressed, just as easily as the ice.” (p. 189)

What this study demonstrates is that reinforcement may be effective, depending on which material is used, even it is inside the compression zone (Figure 1). This is an important observation, as in real-case deployment scenarios, it can be difficult to achieve a given target depth (within the tensional zone) for the reinforcement, i.e. the material may end up being higher than anticipated, in which case it could still contribute in strengthening the ice cover.

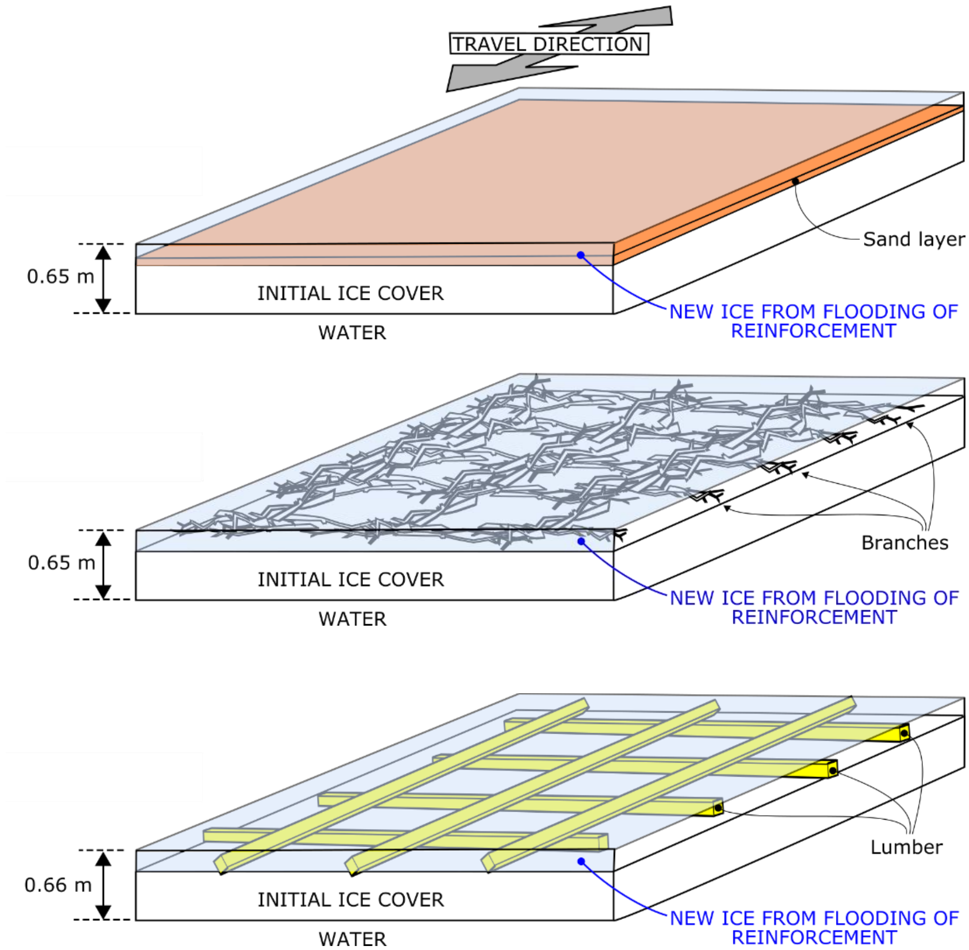

Figure 9: Three types of reinforcement reported in Fransson and Elfgren (1986): Top) A sand layer. Middle) Birch branches. Bottom) Lumber. Note that all are near the top of the ice cover. Not to scale.

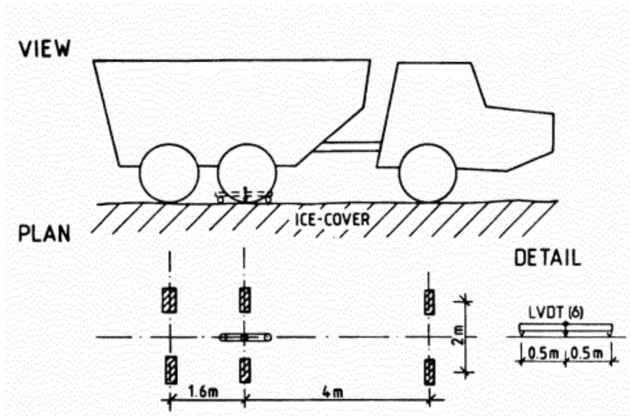

Figure 10: Vehicle and loading configuration for the reinforced ice covers shown in Figure 9. The footprint is depicted, including distance between the wheels and the axles, and the location of displacement gauges ('LVDT') below the vehicle.

4.8. Haynes et al. (1992)

Field testing, conducted in Alaska, was designed to determine the bearing capacity of an ice cover reinforced with a geogrid. This was done in a large pond (500 m x 400 m) inside a gravel pit. In October 1988, an opening was cut out from a 76 mm-thick ice cover, and a piece of geogrid was laid to float on the water inside the opening (Figure 11). The opening was later flooded, so as to increase thickness above the geogrid. In January 1989, the ice thickness was 530 mm in thickness but the geogrid was only 76 mm below the top of the ice, which was also overlain by 460 mm of snow. A Small Unit Support Vehicle (SUSV) weighing 4364 kg was moved onto that surface so as to exert a load on it.

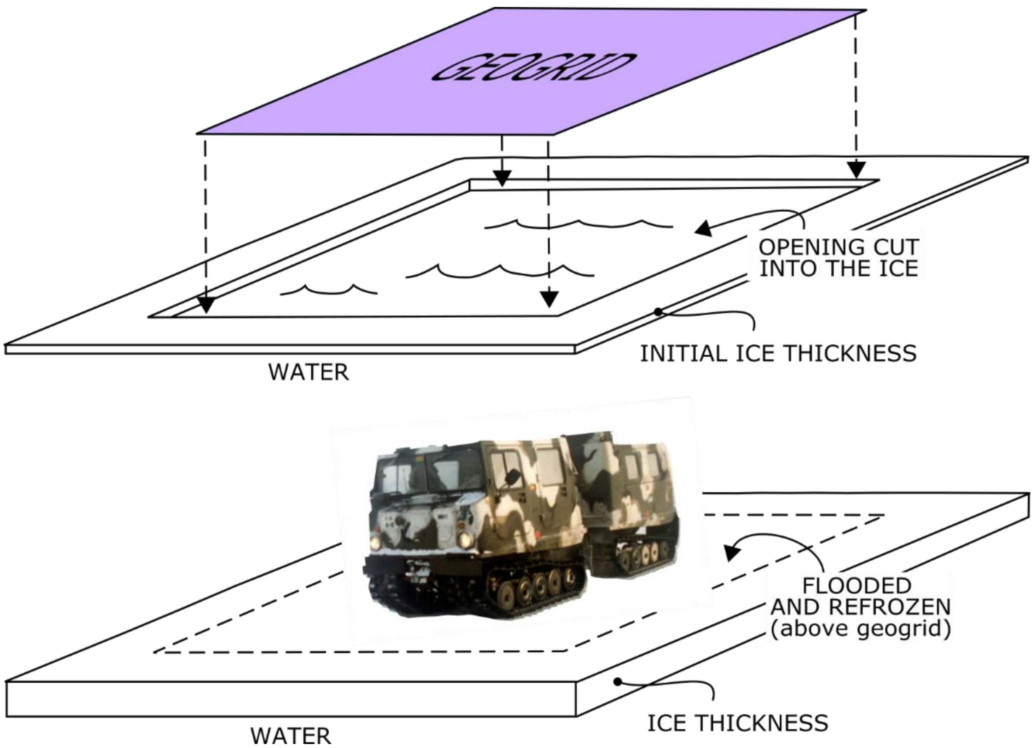

Figure 11: Schematic description drawing from the procedures used by Haynes et al. (1992) to study the effectiveness of an ice cover reinforced with a geogrid. Top) A geogrid was laid floating inside an opening that was cut out of an existing ice cover. Bottom) After flooding and refreezing, the bearing capacity of the reinforced ice was tested using a small military vehicle. Not to scale.

The progressive downward deflection of the ice was then recorded. It was found that, despite being so far up in the ice column, the geogrid contributed to reducing initial deflection, compared to an equivalent ice surface area devoid of reinforcement (Figure 12). This was explained as follows (Figure 13):

> *"The initial tangent modulus for ice and Geogrid are about the same, which lets the Geogrid carry some of the stresses in the ice sheet and stiffen it. However, the secant tangent modulus for Geogrid is less than that for ice and, therefore, the deflections during [the later deformation stage] are about the same for ice with and without Geogrid."* (p. 10)

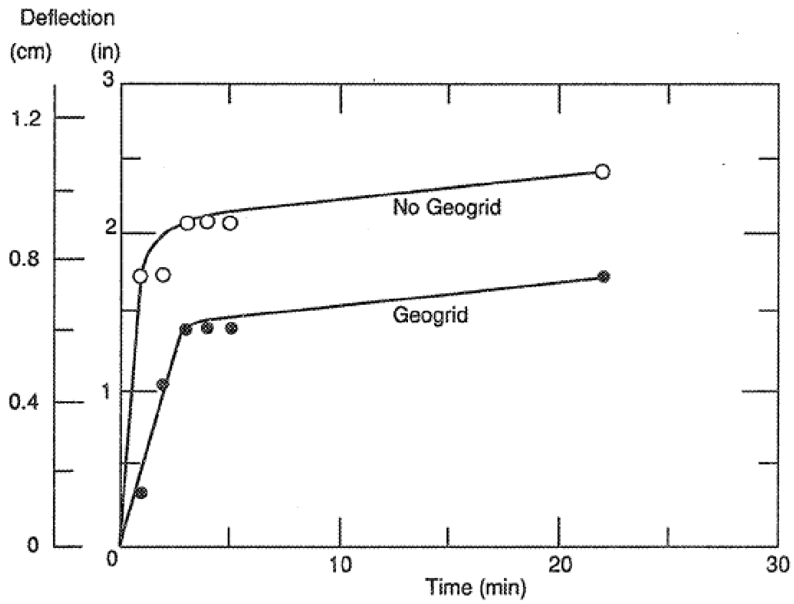

Figure 12: Outcome of testing by Haynes et al. (1992). Note that the difference was with respect to the amount of initial deflection only – later deflection was comparable.

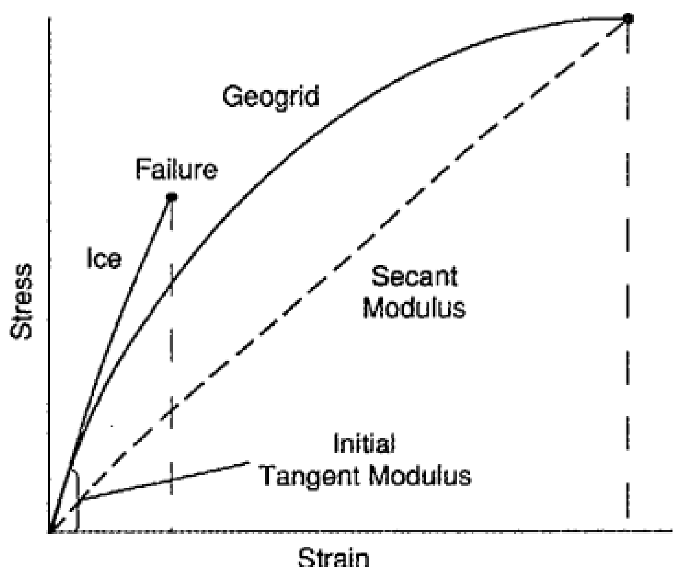

Figure 13: Difference between tangent and secant modulus, as explained by Haynes et al. (1992) to account for the geogrid's effectiveness for reinforcement.

Advantages of using a geogrid are as follows:

- Increasing the bearing capacity of the ice cover
- Increasing the load-bearing after failure
- Low cost
- Light weight
- Relative ease of deployment
- Potential for recovery and re-use
- Excellent bonding characteristics
- Availability in light color

According to these same investigators:

> *"The greatest potential application for Geogrid for ice bridging may be in climatic areas that are marginal for growing ice and for relatively lightweight loads. It may have potential use on ice roads in critical areas that have thin or highly cracked ice".* (p. 11)

4.9. Barrette et al. (2018)

This case is entirely hypothetical, i.e. it has not been implemented, but was recommended to address a challenge affecting one particular operation: the Dawson City ice crossing. The purpose of the proposed scheme was to build an ice bridge across an open lead in the Yukon River (Figure 14). This would involve the deployment of three cables – one on the upstream edge of a geogrid, the other on the downstream edge, where a boom would be located, a third one to a spray ice unit. Such a system could be appropriate for any stream crossing. There would be a few aspects to address beforehand, such as deployment of the cables (prior to freeze-up) and the forces exerted on the cables.

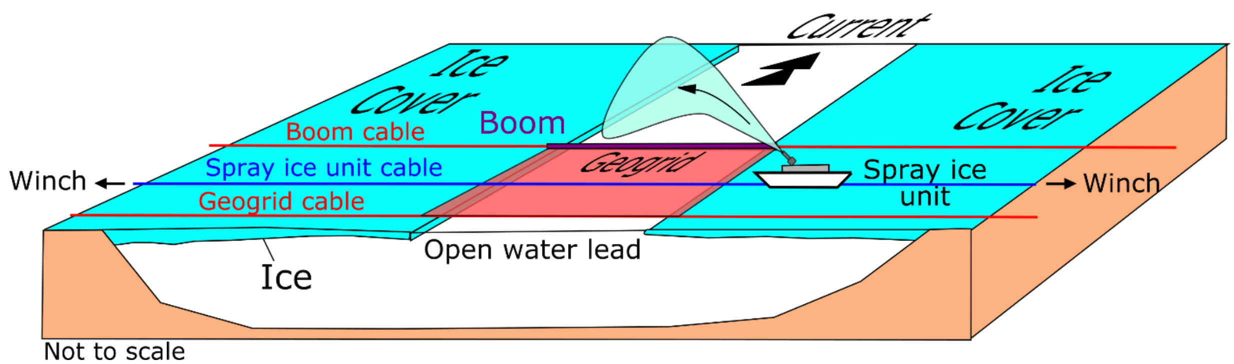

Figure 14: Schematic description of a procedures proposed to bridge an open lead in the Yukon River. The procedure included the laying out of a geogrid straddling the lead, with a boom at its downstream edge, so as to capture the spray ice. More information is provided in Barrette et al. (2018).

4.10. Summary

A compilation of the information provided in all sources is shown in Table 2

Table 2. A distinction is made in that table between 'Operational', crossings that were used for the transport operations, and 'Field study', which was testing under actual field conditions, but not an ice crossing per se. The former may be seen as 'proven' concepts'; the latter affords useful information on real scale testing. Further discussion is provided in Section 7.2.

Table 2: Summary of real-scale scenarios in which reinforcement ice was used. Note that the information from Michel et al. (1974) are for a series of trial tests that were done on three crossings (before being used for the transport operations). See discussion in Section 7.2.2.

Source	Purpose	Length (m)	Reinforcement material	Total thickness (mm)	Maximum load achieved[2]	'A' value[3]
The Engineer (1964)	Operational	Not mentioned	Fiberglass cables	200	"convoy of loaded lorries"	-
				500	"railway trains"	-
Carnes (1964)	Operational	150	Branches, brush, twigs, rice straws	500	23 tonnes (M41 tank)	9.2
Gold (1971)	Operational	430	Logs	1500	118 tonnes ("truck and tractor")	5.2
Gold (1971)	Operational	Not mentioned	Logs over steel cables	1300	45 tonnes	2.7
Gold (1971)	Operational	110	Logs	1500	90 tonnes ("crawler crane")	4.0
Michel et al. (1974) – *Waswanipi crossing*	Operational	640	Logs	1730	90 tonnes	3.0
Michel et al. (1974) – *Pontax 1 crossing*	Operational	90	Logs	1600	90 tonnes	3.5
Michel et al. (1974) – *Rupert crossing*	Operational	550	Logs	2230	118 tonnes	2.4
Fransson and Elfgren (1986)	Field study	30 – 40	Sand, birch branches, lumber	650	18.2 tonnes	4.3
Haynes et al. (1992)	Field study	50	Geogrid (polymer mesh)	530	4.4 tonnes	1.6
Barrette et al. (2018)	Operational (proposed)	Not mentioned	Geogrid	-	-	-

[2] Imperial tons in the sources were converted to metric tonnes.
[3] This parameter is discussed in Section 7.2.

5. Laboratory investigations

Laboratory investigations are meant to answer specific questions on a given topic – they are conducted under fully controlled conditions. For ice, this is typically done inside an environmental chamber (i.e. a cold room), and also outdoors, albeit less frequently because the air temperature cannot be controlled. In the context of winter roads, we are focusing on the ability of an ice cover to withstand a vertical load (i.e. a vehicle)(Figure 1).

5.1. Ice testing configurations

The material's resistance (ice, in this case) to mechanical loading is typically determined by applying a force on a specimen at a constant displacement rate. Three common types of testing are: in compression, tension and flexure (Figure 15). For the purpose of understanding the response of a vertically loaded ice cover, testing in flexure is the preferred approach, because it simulates more closely an ice cover with a weight on top of it.

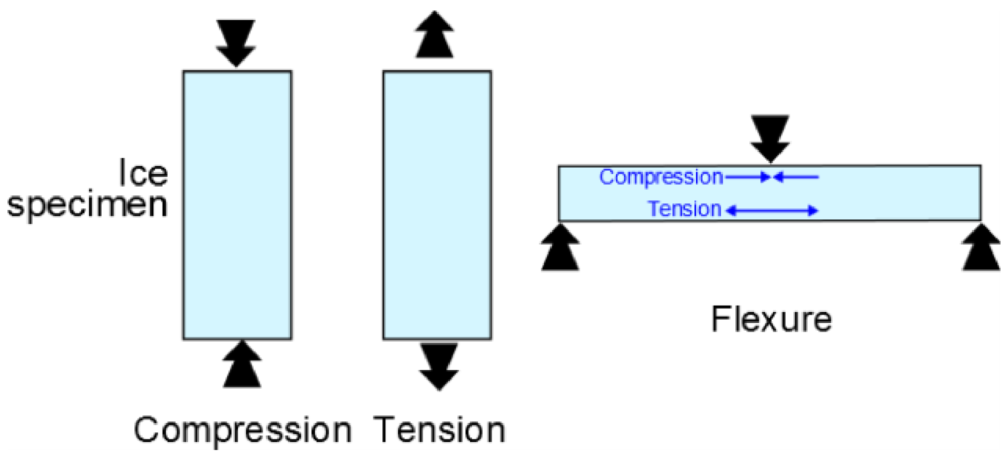

Figure 15: Three loading modes: compression, tension and flexure – note that flexure is a combination of both compression and tension.

5.2. Loading modes

A vehicle on a real ice cover may either be stopped (e.g. parked), thereby exerting a constant vertical load, or it can be moving, thereby exerting a more complex loading regime. Laboratory investigations can simulate these scenarios with simplified loading modes:

- *Displacement-controlled*: A constant load (or 'dead' load) for the first scenario, in which case deflection proceeds according to the ice response, and the displacement is then the 'dependent' parameter (i.e. it depends on the amount of load).
- *Load-controlled*: A constant displacement rate for the second scenario, where the indentor is programmed so as to move at a constant speed, and the load is then the 'dependent' parameter (i.e. it depends on the displacement rate chosen to do the test).

Both modes provide information on ice response. The displacement-controlled mode is easier to implement in the field; the load-controlled mode is more commonly in a laboratory environment.

5.3. Testing on reinforced ice

Test set-ups for the investigations on reinforced ice were in flexure and included a means of exerting a load onto ice, using small beams, plates or sheets. Figure 16 and Figure 17 are examples from our own work at NRC. The data that are typically collected are load (or force)[4], and displacement (amount, rate). Additional information include visual observations of the ice response, i.e. the way cracking develops, and acoustic emission, i.e. sound 'waves' from individual cracking events recorded with a sensor designed for that purpose (Barrette et al., 2020).

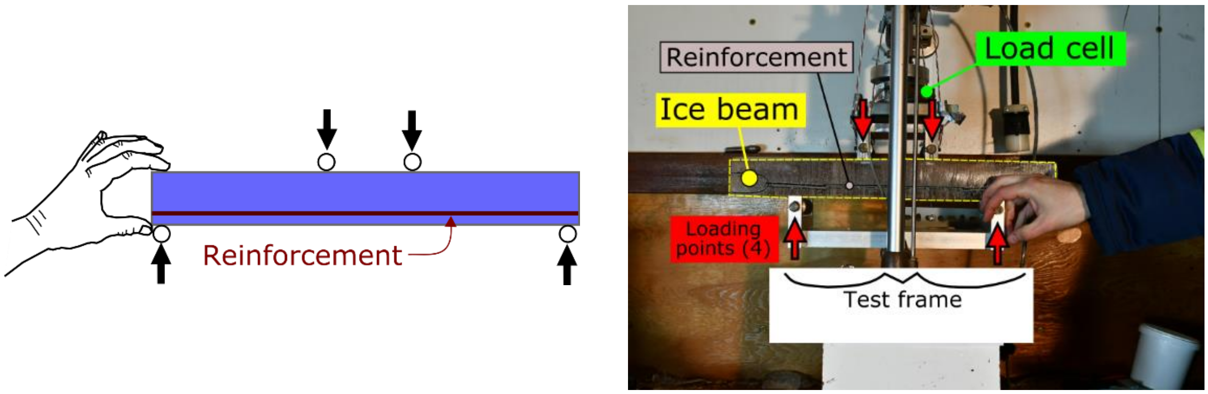

Figure 16: Left) Four point beam testing configuration. Right) Example of an actual test set-up (Barrette and Butt, 2020)

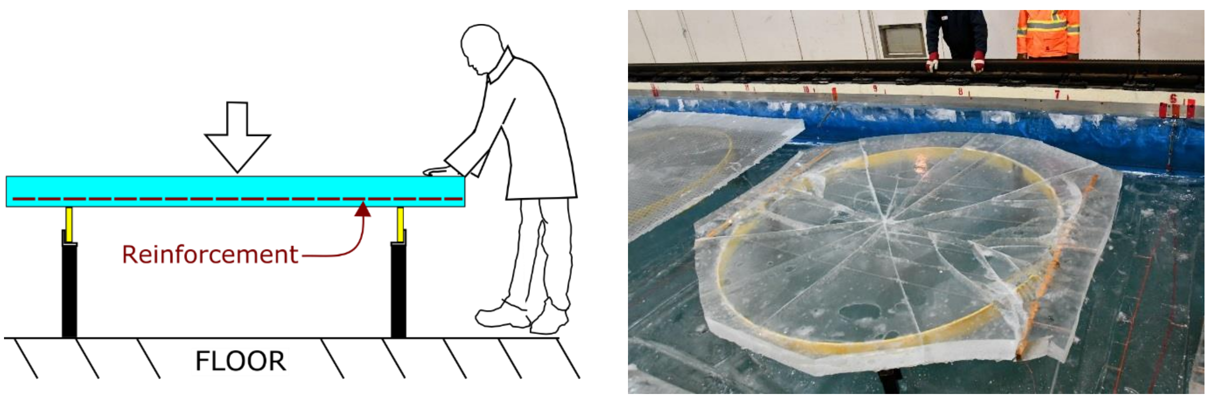

Figure 17: Left) Plate testing configuration. Right) Example of an actual test set-up (Barrette et al. , 2020), here showing the outcome of a test on reinforced ice (no collapse occurred).

The most important difference is that unreinforced ice displays only one peak load, which was followed by a sudden load drop. Reinforced ice displays an initial peak, but this is followed by a small drop in the load, then an increase up to a peak load again. This leads to a 'saw-tooth' pattern in ice response, corresponding to the cracking activity inside the ice.

[4] Measured in kilograms (kg) or in Newton (N), where 1 N is about 1/10 kg, and 1 kN is 1000 N.

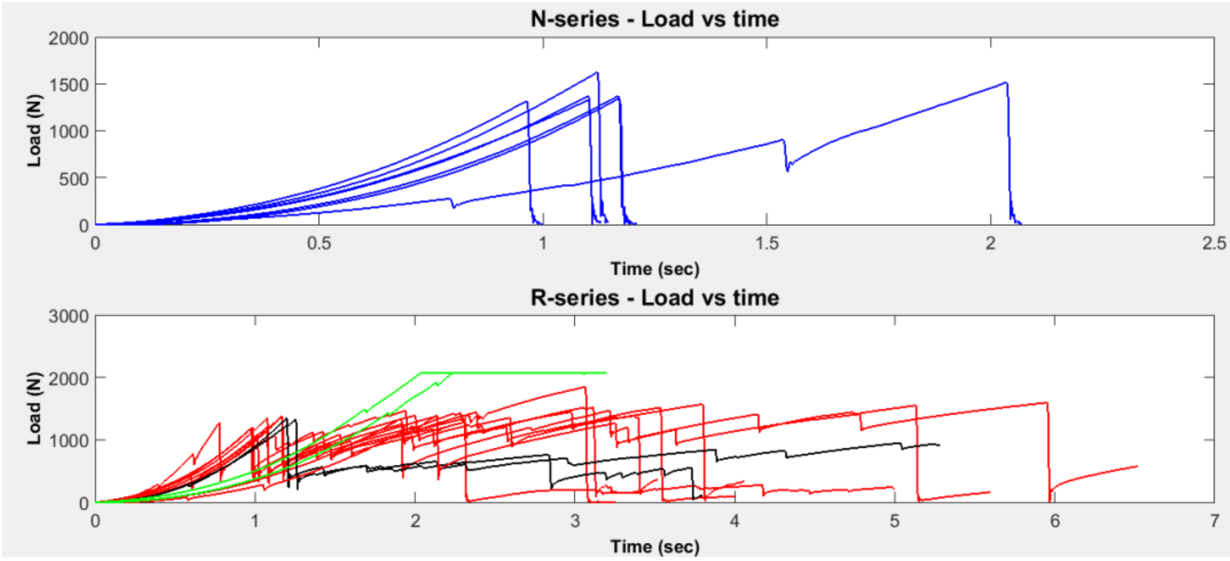

Figure 18: Outcome of beam testing with the test set-up shown in Figure 17. Top) Unreinforced ice breams. Bottom) Reinforced with steel rods (green – these reached the maximum load cell range), propylene geogrid (red) and a steel mesh (black).

Figure 19 shows a similar example (from Haynes et al. , 1992), but observed with floating ice sheets (as opposed to a beam, as is the case for Figure 18). In that situation, a cracking sequence also occurs in the unreinforced ice, because the ice is more confined than in a beam (testing is inside a large water basin), i.e. there is an interaction within the plane of the ice. The sequence of radial and circumferential cracking is described further in Section 7.2. The final load drop in the unreinforced ice documented by Haynes et al. (1992) corresponds to a punch-through failure (Figure 19).

5.4. Macroscopic and microscopic reinforcement

Ice cover reinforcement is divided into two types: macroscopic and microscopic (Vasiliev et al. , 2015, Charlebois and Barrette, 2019)(

Table 3). By analogy, this is like using re-bars and microfibers, respectively, to reinforce concrete. As pointed out by Vasiliev et al. (2015), *"[m]icroscopic reinforcement may be applied for all types of ice engineering structures, while macroscopic reinforcement is mainly used for foundations of ice roads*" (p. 58).

It should be pointed out that there is no clear-cut division between the microscopic and macroscopic reinforcement in terms of their size. For instance, fibers can be short or long and the line between what may fall into either type is indeterminate. In this report, the emphasis will be on the macroscopic reinforcement of the kind that has been used, or can be used, for the purpose of reinforcing ice covers. For those, there is no ambiguity.

The general morphology of macroscopic reinforcement may be linear (e.g. logs, cables) or planar (geomembrane or geogrid, layers of branches or fibers, mesh, net, etc.). The difference has implications on material effectiveness, applicability and deployment. Materials representative of both categories will be discussed in this report.

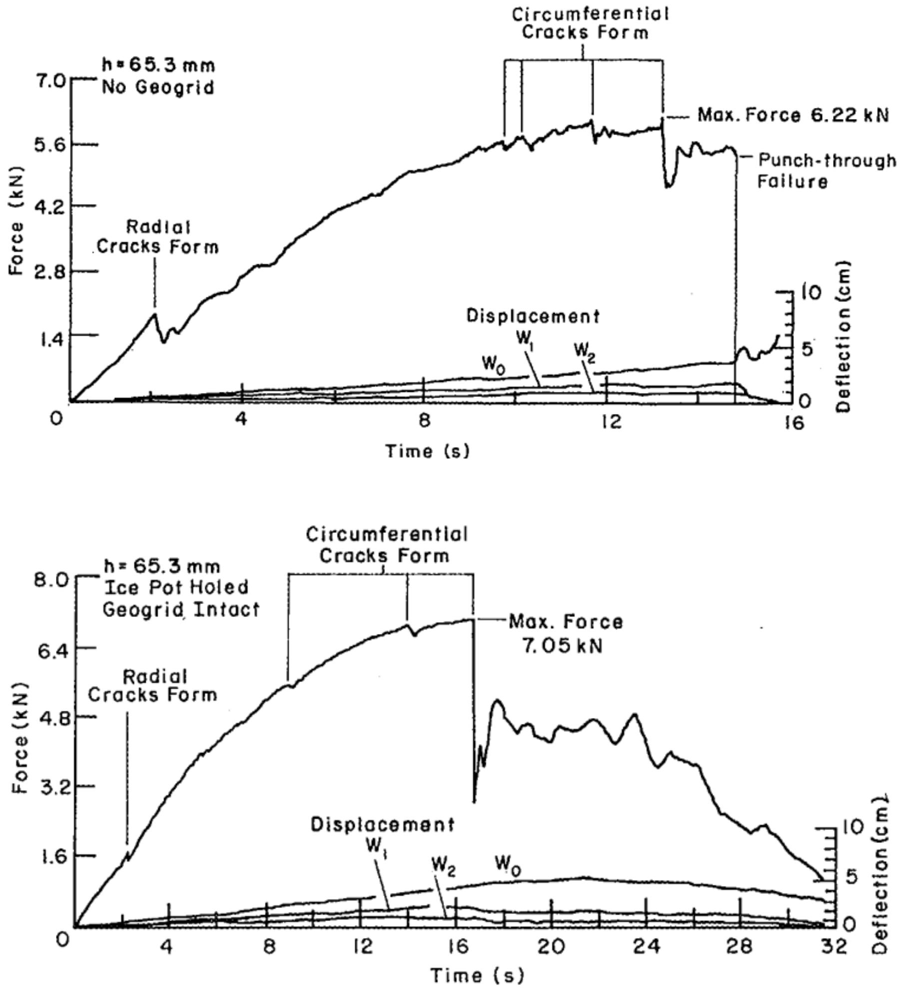

Figure 19: Test outcome from Haynes et al. (1992): Top) Without geogrid. Bottom) With geogrid. Note the difference in ultimate failure (at the end of the loading episode). The deflections (W_0, W_1, W_2) were at three different locations, with W_0 being the point of load application, and W_3 being furthest away from it.

Table 3: Material used to reinforce ice (based on Vasiliev et al. , 2015).

Macroscopic reinforcement		**Microscopic reinforcement**	
Cotton cloth Geogrid Fiberglass matrix Hay Newspaper mash Steel cables	Straw Tree components and products: twigs, branches, logs, wood dowels	Algae Asbestos fibers Cryotropic gel Fiberglass Gravel Hay	Peat mass Sand Sawdust Starch Wood chip Wood pulp

5.5. Performance of reinforced ice

5.5.1. Resistance to deformation

In the majority of cases, reinforced ice showed a higher resilience to deformation and to breakthroughs. An example of this effect is shown in Figure 20, which is the outcome of constant load tests on beams in flexure (Grabe, 1986). In that figure, the amount of deformation ('Curvature', vertical axis) in relation with time (horizontal axis, in hours) becomes less with an increase in the number of strands, from unreinforced to eight strands, each with a cross-section of 2.66 mm^2.

Similar observations are documented by Kingery (1960), also with fiberglass. Although internal cracking occurred, it was delayed and complete fracturing was prevented – resistance values were almost ten times that for unreinforced ice. It decreased creep deformation by almost two orders of magnitude, and the resistance to creep varied as a function of fiberglass content.

Figure 21 is a set of tests demonstrating the value of reinforcement (Coble and Kingery, 1963). This was also done on beams, but with a constant displacement rate of the indentor. The 'Modulus of rupture' (vertical axis) is the load at which the ice beam broke, as a function of the amount of reinforcement (horizontal axis). In all cases, more reinforcement lead to higher loads. The most effective material was fiberglass and asbestos.

An important consideration is that material effectiveness depends on its elastic properties, i.e. its resistance to elastic deformation. That resistance, or stiffness, has to be higher than that of the ice itself (Coble and Kingery, 1963, Jarrett and Biggar, 1980, Vasiliev and Gladkov, 2003). If that is the case, and assuming there is no slippage at the material-ice interface, then the reinforcement will absorb the load before the ice matrix does. This was shown by the work of Haynes and Martinson (1989) and Haynes et al. (1992), who demonstrated the effectiveness of geogrids – it increased the ability the withstand a load by 300% in the laboratory, and increased resistance to deflection in field tests (an example of the difference is shown in Figure 12).

5.5.2. Resistance to de-bonding

Resistance to slippage at the material-ice interface, or de-bonding, has been investigated by Stanley and Glockner (1975)(Figure 22). They demonstrated that the longer the strand ('embedment'), the higher the force required to pull it out of the ice (see also Glockner, 1988). Interestingly, the response was expected to be linear ('Anticipated minimum bond strength' in that figure), but it turned out to be exponential. This is attributed by Stanley and Glockner (1975) to a better penetration of water into the strand material for longer strands, i.e. as a result of a slightly longer soaking time.

The resistance to de-bonding may be seen as an equivalent to resistance to 'first crack' (i.e. failure, as defined earlier). An example is provided in Figure 23, from Vasiliev and Gladkov (2003), in which the initial linear response for both the unreinforced and reinforced test (segment A in that figure) is defined as the stress related with resistance to first crack. That segment is not only steeper but also longer for reinforced ice. Segment BC in that figure represents the "*simultaneous cracking and composite fracture*", which precedes the ultimate failure, the latter corresponding in turn to breakthrough.

Shear resistance to de-bonding was also described in Barrette et al. (2020). With an increasing load and time, that resistance was mobilized and gradually overcome, indicating an energy transfer from the load to that interface. This is the reason why the reinforced plates did not collapse, but the unreinforced plates did, i.e. a similar response as that shown in Figure 23.

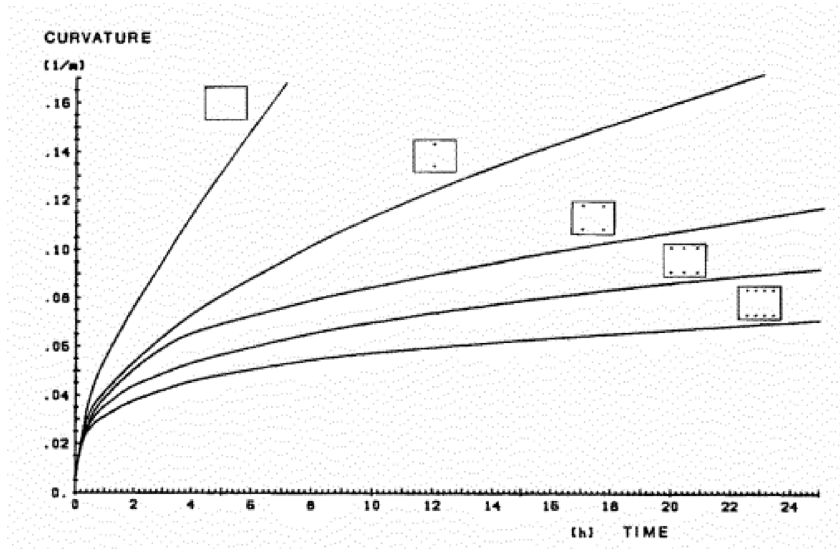

Figure 20: Test outcome from Grabe (1986) – beam bending over time, for five specimens, including one unreinforced (the strands location is shown for each test). The beam with eight fiberglass strands shows the highest resistance. 1/m on the vertical scale is a measure of beam curvature during deflection.

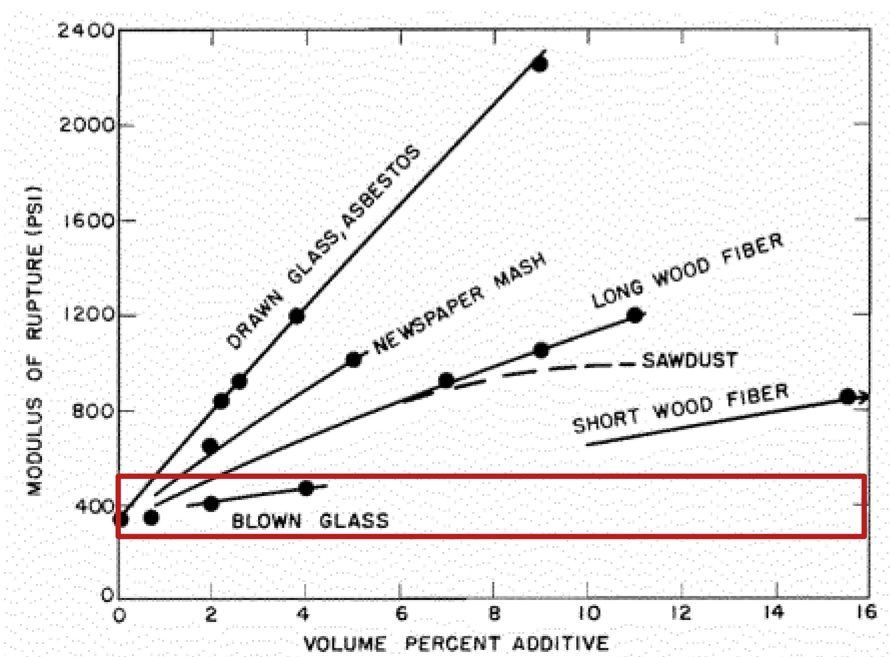

Figure 21: Influence of reinforcement addition on the strength of the ice (Coble and Kingery, 1963). For unreinforced ice, the value ranged between 300 and 500 psi (rectangular outline). PSI: pound per square inch.

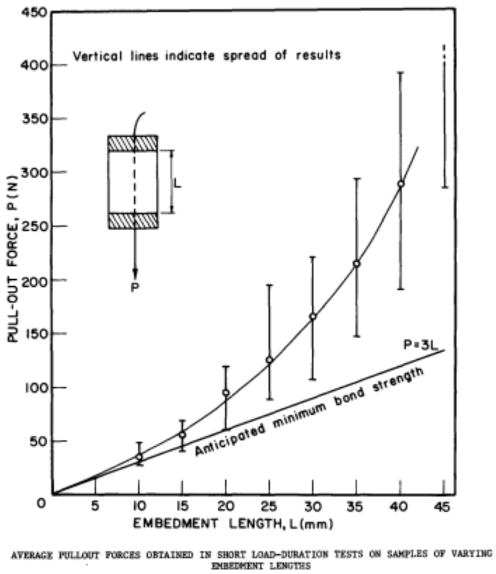

Figure 22: Assessment of the force required to pull out fiberglass strands from an ice specimen, as a function of embedded length (Stanley and Glockner, 1975). N: Newton.

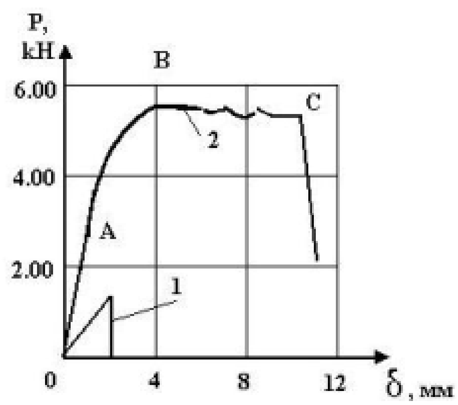

Figure 23: Load deflection of two beams – (1) unreinforced and (2) reinforced ice. kH on the vertical scale is Russian for 'kN' (Vasiliev and Gladkov, 2003).

5.5.1. Resistance to breakthrough

Ice reinforcement can allow for very large deflection during which the ice cover retains its strength, as observed by Ohstrom and DenHartog (1976). That ultimate failure point, which they also attribute to de-bonding of material from the ice, occurred with steel cables and wood dowels, but not so much with branches (which showed no evidence of such de-bonding). According to these investigators, this resistance allowed the ice to carry heavier loads even after crack development, because the broken ice pieces are still tied together (also assumed by Michel et al. , 1974). They further state that "*catastrophic failure is much less likely and the bridge has a chance to refreeze [or to 'heal'] between usages*" (p. 11). In view of the above, reinforcement may be considered a 'safety net', as pointed out by Jarrett and Biggar (1980), and supported by other investigators (e.g. Haynes et al. , 1992).

6. Computational modeling

The computational (or numerical) approach is a valuable complement to field and laboratory investigations in many research areas. It is a simulation exercise based on theory, albeit simplified to some extent, but which captures the essence of the mechanisms and processes at play. Because of the power of computational hardware and software, this modeling is highly adaptable and can be used as a predictive tool. There is only a limited amount of such studies dedicated to reinforced ice (Bai et al., 2020 and references therein).

This section provides information, derived via computational modeling on the effectiveness of macroscopic reinforcement in an ice matrix in preventing failure (first crack). Two reinforcement materials were used in these simulations:

1. Lumber poles[5] (red spruce) with a square cross-section
2. Steel rods with a square cross-section

This reinforcement is representative of a linear configuration, mentioned earlier (as opposed to, say, a geogrid, which is a representative of a planar reinforcement). The choice of these materials was based on laboratory testing we anticipate to do in the near future, in which ice plates incorporating these materials will be loaded vertically while monitoring load and surface deflections.

6.1. Assumptions

Linear elastic deformation theory is employed for the purpose of this exercise. A number of assumptions were made:

- The ice matrix is uniform.
- The variation of stress as a function of strain, and of deformation as a function of strain, are linear.
- The amount of displacement and rotation is very small.
- Nonlinear, time-dependent material response, is negligible.
- The deflection of the ice is much smaller than its thickness.
- There is no de-bonding between the material and the ice matrix, i.e. the deformation field across the interface is continuous.

These assumptions are considered reasonable in the context of an ice cover when loading is rapid, such as the action exerted on it by a moving vehicle. This also the case for the matrix if the ice is produced in a controlled environment, but not if it is a natural ice cover, which is typically not uniform in internal structure.

6.2. Scenario

The test set-up is shown in Figure 17. The plate rests on a circular steel frame 2.5 m in diameter. For this modeling exercise, the plate is loaded statically – the force does not change – in a downward direction, and uniformly distributed across a central circular region 100 mm in diameter. The ice is reinforced with ten elements made from lumber or steel. They are laid out symmetrically with respect to the load center and all elements are at the same vertical level with respect to the top surface of the plate; they are spaced equally in that horizontal plane. The elements extend beyond the edge of the plate. The plate cannot move vertically (since it sits on the steel frame as

[5] Referred to as 'Lumber' in this report – these are wood bars of pre-cut dimensions, a standard construction material. Dimensions are generally in imperial units (e.g. a '2 by 4' in inches) but were converted to SI units.

it is pushed downward). All other motions are allowed – for instance, the plate can rotate about the line of contact with the underlying steel frame.

6.3. Method

Computations were carried out with COMSOL Multiphysics® (COMSOL AB, 2014), a proprietary finite element toolbox – a graphical output is shown in Figure 24. Because of the symmetry in the scenario that is being simulated, the exercise only needs to be done on one quarter of the plate (Figure 25). This reduced data storage requirements and computational time. In an earlier study (Babaei and Barrette, 2020), where these simulations were compared with the outcome of physical testing, the deformation of the ice plate was found to be consistent with the deformation based on the finite element solution used in the present analysis. The sensitivity to the mesh resolution was also briefly studied in that 2020 report, and an appropriate finite-element mesh, i.e. that is able to capture the deformation field, was determined. The number of computational elements in the mesh (which is illustrated in Figure 25b), and the simulation times vary mainly depending on the size of the reinforcement. Typical numbers of elements and computational duration for a given simulation were 1.5 million and 7 minutes, respectively.

An orthogonal three-axis '*xyz*' coordinate system is used throughout this analysis – it is displayed in the lower left of the figures. The *x* axis is horizontal and parallel to the reinforcement; the y axis is horizontal and perpendicular to it; the *z* axis is vertical and thus perpendicular to x and y.

On the lower surface of the ice plate, all stresses (σ) are normal (not shear) and tensional, and all strains (ϵ) are normal (not shear) and extensional. A normal stress labeled σ_{xx} is a tensional stress parallel to the x axis, acting on a plane that is perpendicular to the *x* axis (hence, the notation '*xx*'). Similarly, a normal strain labeled ϵ_{yy} is an extensional strain parallel to the *y* axis, affecting a plane that is perpendicular to the *y* axis (hence, the notation '*yy*').

The stresses and strains considered in this analysis are those that exist along the lower edge of two vertical surfaces running through the plate's center bottom surface of the plate, in two directions:

a) One surface is parallel the *x* axis – the *xz* plane
b) One surface is parallel to the *y* axis – the *yz* plane

The deflection is that occurring along the bottom edge of the yz plane. The rationale for the selection of the components of stress and strains and their location is two-fold:

a) First crack in the ice is known to occur along the bottom surface of ice covers under a vertical load, where it is under maximal tension.
b) Deflection and normal stresses and strains in ice at the bottom surface are highest in these planes than in any other plane *not* going through the center.

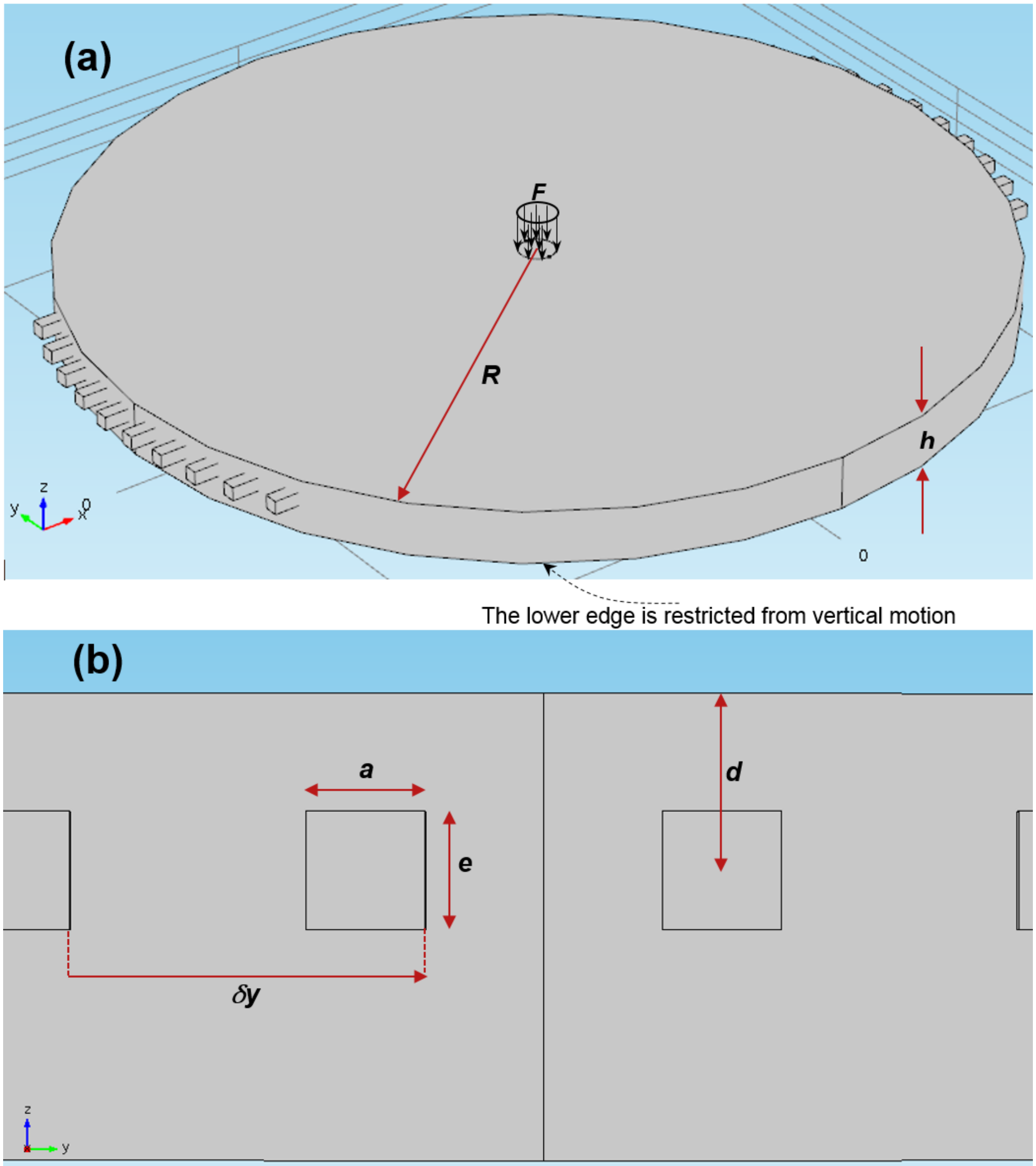

Figure 24: (a) Geometry of the ice plate and loading location. (b) Geometry and vertical location of reinforcement inside the plate (with a square cross-section). See text for an explanation on the symbols.

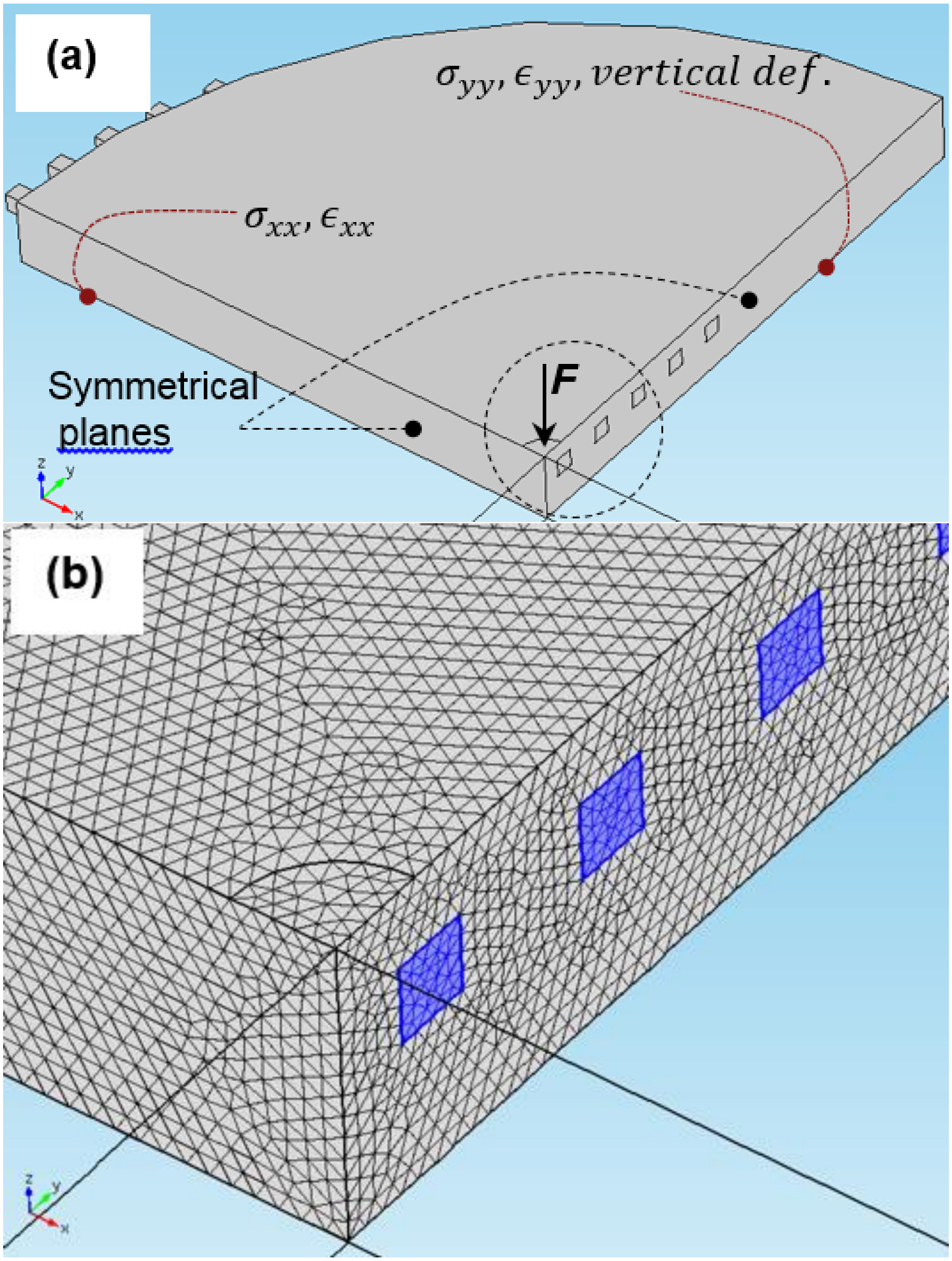

Figure 25: (a) Parameters considered in the analysis. 'Vertical def.' refers to the deflection. (b) This is an enlargement of the circled area in (a) – a typical finite-element mesh is shown, with the reinforcement (in blue). See text for an explanation on the symbols.

6.4. Analysis

A parametric analysis[6] was done on the influence of the reinforcement – the constants and the variables are listed in Table 4 and Table 5, respectively. The value that was selected for the force in Table 4 is based on the earlier analysis (Babaei and Barrette, 2020), and is an approximation of that required to initiate cracking in a slightly thinner ice plate.

Table 4: Constants in the analysis (see Figure 24).

Parameter	Symbol	Value	Unit
Radius	R	1.25	Meter - m
Thickness	h	0.15	Meter - m
Poisson ratio	ν	0.33	Dimensionless
Vertical force	F	3820	Newton - N
Loaded area (diameter)	-	0.1	Meter - m

Table 5: Variables in the analysis (see Figure 24). The numbers separated with a comma are the different values assigned to the variables.

Cross-sectional geometry of the lumber		Lumber spacing and location in ice		Effective modulus[7] of ice, *GN/m²*	Reinforcement material – (Young's modulus, *GN/m²*, Poisson's ratio, dimensionless)	
Width, *a*, mm	Thickness, *e*, mm	Spacing, δy, mm	Depth in ice, *d*, mm		Red spruce[8]	Steel
38, 76, 114	38, 76, 114	114, 164.4, 214.8	57, 75, 93	3, 5	(10, 0.45)	(205, 0.28)

The simulations consisted of all combinations of the parameters given in Table 5, for a total of 162 simulations. Note that in two cases, either the top or bottom surfaces of the lumber are flush with (i.e. at same vertical location as) the top or bottom surfaces of the plate – these cases are associated with *e* = 114 mm when *d* is either 57 mm or 93 mm, respectively. For reinforcement with steel, only a few simulations were conducted, so as to assess the influence of a stronger reinforcement.

In addition to the simulations related to reinforcement, two unreinforced ice plates with different effective moduli were also simulated for comparison.

A comprehensive analysis of all simulations was conducted, with the aim providing a general understanding of the influence of reinforcement on plate response. The following variables are the controlled parameters:

- Cross-sectional size (*a*)

6 An analysis in which only one controlled parameter is varied (the others remain constant), to see its influence on the dependent parameter. A parameter is either a constant or a variable.

7 For an explanation of effective Young's modulus, see Barrette, P.D., 2015b, Overview of ice roads in Canada: Design, usage and climate change adaptation. OCRE-TR-2015-011. National Research Council of Canada. Ottawa, 51 pp..

8 https://amesweb.info/Materials/Youngs-Modulus-of-Wooden.aspx, viewed on March 22nd 2021, https://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr113/ch04.pdf, viewed on March 22nd 2021

- Thickness (*e*)
- Horizontal spacing (δy)
- Vertical positioning, i.e. depth below the plate surface (*d*)
- Effective Young's modulus of the ice
- Young's modulus of the reinforcement material

The dependent parameters are:

- The deflection of the points along the bottom edge of the *yz* plane
- The normal (tensional) stresses (σ_{xx},σ_{yy}) along the bottom edge of both *xz* and *yz* planes
- The normal (extensional) strains (ϵ_{xx},ϵ_{yy}) along the bottom edge of both *xz* and *yz* planes

6.5. Outcome

Representative examples of plate response are now provided. Unless indicated otherwise, all results are from the simulations with lumber. Note also that, although deflections are negative according to the *xyz* coordinate system described earlier, only absolute values are referred to in this report.

The figures alluded to in the following sections are plots indicating the behavior of the four dependent parameters as a function of plate radius. In these plots, there are small 'residuals' (non-zero values) in σ_{yy} and ϵ_{yy} away from the plate center. These are numerical artifacts and can be ignored.

6.5.1. Reinforcement cross-sectional size

An increase in the cross-sectional size, corresponding to an increase in lumber volume, generally improved reinforcement effectiveness. However, the determination of how much material would be needed to achieve a given target resilience is not trivial. As seen in Figure 26, the lumber with the smallest cross-sectional area (38 mm x 38 mm) has minimal influence. As will be mentioned later, if the lumber's bottom surface is flush with the plate's bottom surface, the addition of lumber could have adverse effects. This can also be the case even when the lumber is fully embedded in the ice, while the center of the lumber is below the horizontal mid-plane of the plate. In this condition, the maximum value of ϵ_{yy} could be slightly more than that of the unreinforced case.

Result: In general, a larger cross-section leads to a more effective reinforcement. But due consideration should be given to other parameters, such as depth below the plate surface.

6.5.2. Reinforcement spacing, δy

A smaller horizontal spacing of the lumber is associated with a more substantial reduction in deflection, maximum stresses and maximum strains. This response is expected because it means more reinforcement in the central region of the plate, where it is loaded and where the deflection is at its peak. That reduction is more pronounced when the reinforcement has a stronger impact. As an example, lumber 38 mm x 38 mm in cross-sectional area only reduces the maximum deflection by approximately 2.4% when δy = 214.8 mm. In this case, the maximum deflection when the spacing δy is reduced to 114 mm undergoes a corresponding additional reduction of only 0.83%. In comparison, a larger cross-sectional area (114 mm x 114 mm) reduces the maximum deflection by approximately 16% for the largest spacing (Figure 27), and is therefore more effective (than the 38 mm x 38 mm cross-sectional area). And here, the corresponding additional reduction of maximum values for the smallest spacing are much higher than the aforementioned 0.83%: deflection (14%), σ_{xx} (15%), σ_{yy} (24%), ϵ_{xx} (14%) and ϵ_{yy} (25%).

Additionally, the influence of spacing is more pronounced on the maximum values of σ_{yy} and ϵ_{yy} than it is on those of σ_{xx} and ϵ_{xx}.

Result: A denser reinforcement is more effective, especially when other parameters also contribute to enhanced effectiveness.

6.5.3. Reinforcement width, *a*

An increase in the width of lumber enhances the reinforcement. Here again, this enhancement is more pronounced when reinforcement effectiveness is greater. As an example, when *d* = 57 mm, the enhancement due to an increase in width is typically as small as a few percent (in maximum values of deflection, σ_{xx}, σ_{yy}, ϵ_{xx} and ϵ_{yy}), when *e* = 38 mm and δy = 214.8 mm. And it is as high as 40% for the case when *e* has the highest value (114 mm) and when δy has the lowest value (114 mm), both of which favor effectiveness. Additionally, an increase in the width of the lumber has a similar influence, in general, on the maximum values of σ_{yy} and ϵ_{yy}, when compared with those of σ_{xx} and ϵ_{xx} Figure 28 is a typical outcome, for different width values, on the deflection, stresses and strains.

Result: The wider the reinforcement, the more effective, especially when other parameters also contribute to enhanced effectiveness, such as increased thickness and smaller spacing.

6.5.4. Reinforcement thickness, *e*

An increase in the thickness of the lumber reduces the maximum deflection of the plate, σ_{xx} and ϵ_{xx}, but not necessarily σ_{yy} and ϵ_{yy}, which depends on depth below the plate surface. If the center of the lumber is at or above the center of the plate, an increase in depth is desirable, since it reduces σ_{yy} and ϵ_{yy}. However, when the center of the lumber is below the center of the plate, the general observation is that the most reinforced cases are when the difference between the width and the thickness of the lumber is the smallest. If the lower surface of the lumber is flush with that of the ice plate, reinforcement effectiveness is marginal, and may even increase σ_{yy} and ϵ_{yy}. Figure 29 shows a case where the center of the lumber is below the center of the plate. Note that the discontinuity in the plots for σ_{yy} and ϵ_{yy} is due to the difference between material properties of wood and ice.

Result: The thicker the reinforcement, the more effective it will be parallel to it (in the *x* direction), but not necessarily perpendicular to it (in the *y* direction), because it then depends on where it is located vertically with respect to the plate's top or bottom surfaces.

6.5.5. Aspect ratio

The influence of lumber width to thickness with a constant cross-sectional area and the same in-ice depth (*d*) was briefly investigated. This was to answer questions such as: would a 57 mm x 38 mm lumber be more effective than 38 mm x 57 mm? Different combinations of widths and thicknesses were investigated, and it was found that the deflection is reduced when the thickness is more than the width. Further, σ_{xx}, ϵ_{xx}, σ_{yy} and ϵ_{yy} are also reduced under these conditions if the lumber is fully embedded in ice. When the lower surface of the lumber and the plate are at the same vertical location, maximum values of σ_{xx} and ϵ_{xx} are reduced while those for σ_{yy} and ϵ_{yy} are increased.

Result: For the same surface area, when the lumber is fully enclosed in the ice, thickness is more effective than width, which is to be expected.

6.5.6. Reinforcement depth (below the plate surface), *d*

As indicated in Table 5, values assigned to *d* were 57 mm, 75 mm and 93 mm. When the lumber is at a depth of 75 mm, its center coincides with that of the plate. When at 57 mm and at 93 mm, its center is 18 mm above and below the plate's center, respectively. In the latter two cases, i.e. for eccentric cases, the deflection is smaller, up to about 5%, depending on other parameters. The deflection is identical for these two cases, due to the symmetry with respect to the plate's mid-plane. The stresses σ_{xx} and ϵ_{xx} are also generally reduced with an increase in depth. The influence of the depth on σ_{yy} and ϵ_{yy}, on the other hand, is complex and differs from one case to another. In general, if the lumber is fully embedded in ice, an increase in depth leads to smaller values along the radius, but the maximum values (at the center of the plate's lower surface) can become slightly higher or lower. An exception is when $\delta y = a = 114$ mm, in which case the lumber defines a continuous surface (there is no gap between the pieces of lumber). In this case, σ_{yy} and ϵ_{yy} are significantly reduced with an increase in depth. A maximum depth in this condition is associated with approximately 14% reduction in maximum values of σ_{yy} and ϵ_{yy}. When the lower surface of the lumber is at the same vertical location as that of the lower surface of the plate, the conditions for σ_{yy} and ϵ_{yy} are generally undesirable due to generally larger values over the radius and either only a marginal improvement of reinforcement effectiveness or the opposite at the center. Figure 30 shows influence of the depth for one case.

Result: Deflection is reduced even in cases where reinforcement is above the plate's center (in the compression zone). The stresses parallel to the reinforcement are reduced with depth. A continuous reinforcement layer (when there is no gap between the lumber) is effective at reducing stresses in all directions.

6.5.7. Choice of the ice effective modulus

It is known that ice exhibits time-dependent behavior under load. This behavior could be significant depending on the rate of loading and the time scale at which ice is studied. The Young's modulus of ice in the present report is an 'effective' Young's modulus accounting for the time-dependent behavior. In a previous study (Babaei and Barrette, 2020), it was concluded that the effective modulus of ice is approximately 3 GPa under the loading conditions considered in the present analysis. However, this value could change for different reasons, including the loading rate and the temperature of the ice. To gain an understanding about the influence of the effective Young's modulus of ice on the reinforcement, another realistic value of 5 GPa was studied (Table 5). Reduction of deflections, stresses and strains due to the reinforcement with lumber is smaller when the effective modulus of ice is larger (Figure 31). Reinforcement-induced reduction are as follows: maximum deflection (7%), σ_{xx} (13%), ϵ_{xx} (16%), σ_{yy} (13%) and ϵ_{yy} (11%).

Result: When the difference between the modulus of ice and that of the reinforcement material is reduced, the influence of reinforcement is reduced. The extreme case is when the lumber and the ice have the same elastic properties in which case the plate will not be reinforced at all.

6.5.8. Material

Steel is about 20 times less compliant than wood. As seen in Figure 26, reinforcement with a smallest cross-section is least effective. With steel, however, the reinforcement is significantly improved (compared to wood)(Figure 32) – the improvement for all parameters is about 15%.

6.5.9. Summary and relevance

The reinforcement of a circular ice plate with ten pieces of lumber with rectangular cross-sections was approached computationally. This is a powerful yet simple way of studying the reinforcement of ice in the context of the prevention of a first crack. The focus of the work was the generation of knowledge into the influence of different parameters on reinforcement effectiveness. Those parameters included side lengths (width and thickness) of the rectangular cross-sections, vertical position, horizontal spacing and orientation. Additionally, the influence of the effective modulus of ice and the influence of the reinforcement material (by replacing wood with steel) was also addressed. In general, the results were case-specific as opposed to universal. This was so particularly when the reinforcement was located below the horizontal mid-plane of the ice plate and when the lower surface of the lumber was flush with that of the plate.

Nonetheless, some general trends can be derived, which could provide guidance for field deployment:

- If the lumber's cross-sectional size is too small, there could be limited benefit. But if a stiffer material is used instead, e.g. in the form of steel cables, then the effectiveness would be improved. On the basis of the foregoing analysis, it is also expected that thicker cables will perform better. In a real scenario, a thicker cable would also be able to sustain a greater load if a breakthrough does occur. A drawback with this material, however, is its density – transportation and handling of steel cable rolls may be a challenge.
- For the same cross-sectional area, thickness is more effective than width in improving reinforcement. That this would be the case for lumber alone is to be expected intuitively – it is also true for a lumber-reinforced ice matrix.
- Reducing the horizontal spacing between the lumber, which is equivalent to increasing the number of elements, is expected to improve reinforcement.
- The deeper the reinforcement (below the top of the ice cover), the more effective it is expected to be. The analysis also provided evidence that, even if the reinforcement is in the compression zone (above the neutral axis), it can still be effective – this supports the findings discussed earlier in this report.
- The selection of a proper effective Young's modulus for the ice is important. The reason is, the higher that number, the less effective the reinforcement is expected to be. This could mean that a given reinforcement scheme will be less effective under faster loading. Although an appropriate value can be determined from laboratory testing, it is difficult to know what it would be for a real-case scenario.

The outcome presented in this report only draws on a very small portion of the total amount of data (about 9 GB) that were generated during this computational exercise. Other data sets from this outcome could be analyzed further so as to obtain additional insights on the scenario that was investigated. Moreover, this work could be further extended to address other important questions, including:

- What is the influence of the parameters on the failure of the ice plate when the failure is characterized by a well-validated failure theory? The state of stress and strain needs to be evaluated against an ice failure theory representative of first cracks in ice. Possible examples are Mohr–Coulomb, von Mises, or Tresca, which can realistically estimate the onset of cracking in a real-world three-dimensional loading condition.
- Will the bonding between the reinforcement and the ice matrix fail prior to failure of ice on its lower surface (due to tension)? A computational approach can provide an estimate of shear stresses along the ice-reinforcement interface. The shear stresses can be subsequently compared with data on the adhesion strength between ice and the reinforcement to study the potential of de-bonding.
- What if the reinforcement elements have random shapes and cross sectional characteristics?

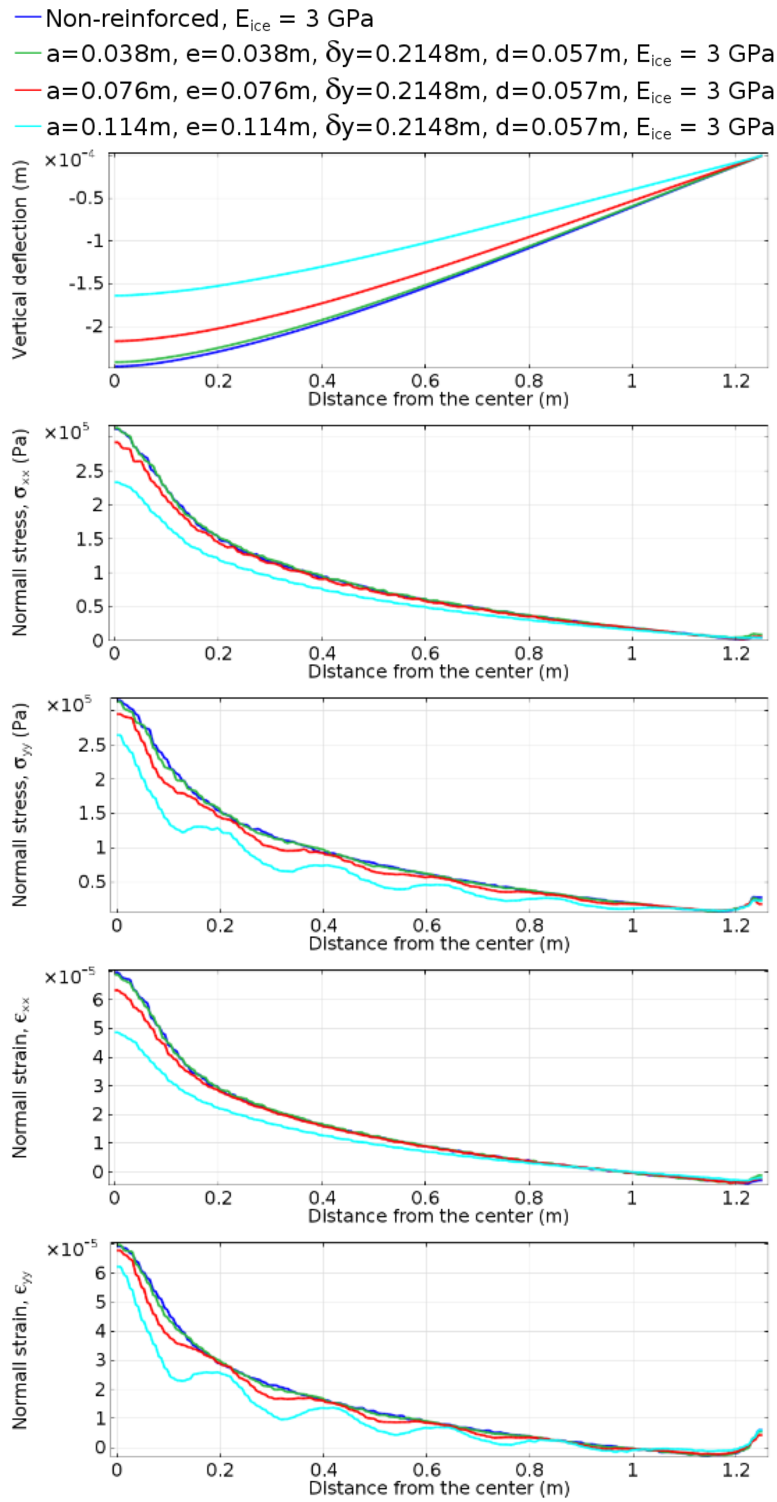

Figure 26: Influence of cross-sectional area (i.e. volume) of reinforcement with lumber on deflection, stresses and strains. A larger area improves reinforcement.

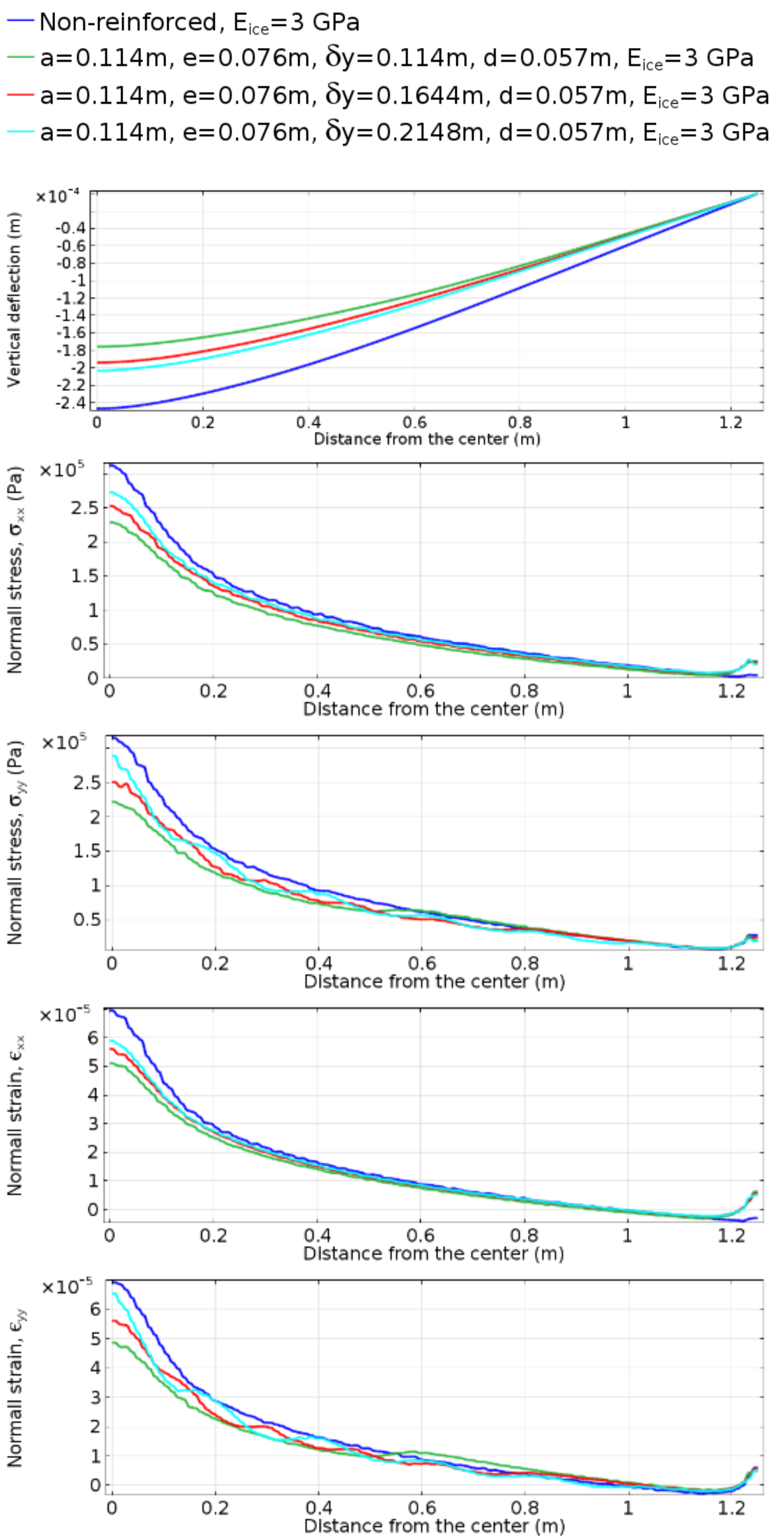

Figure 27: Influence of horizontal spacing of lumber on deflection, stresses and strains. A smaller spacing improves reinforcement.

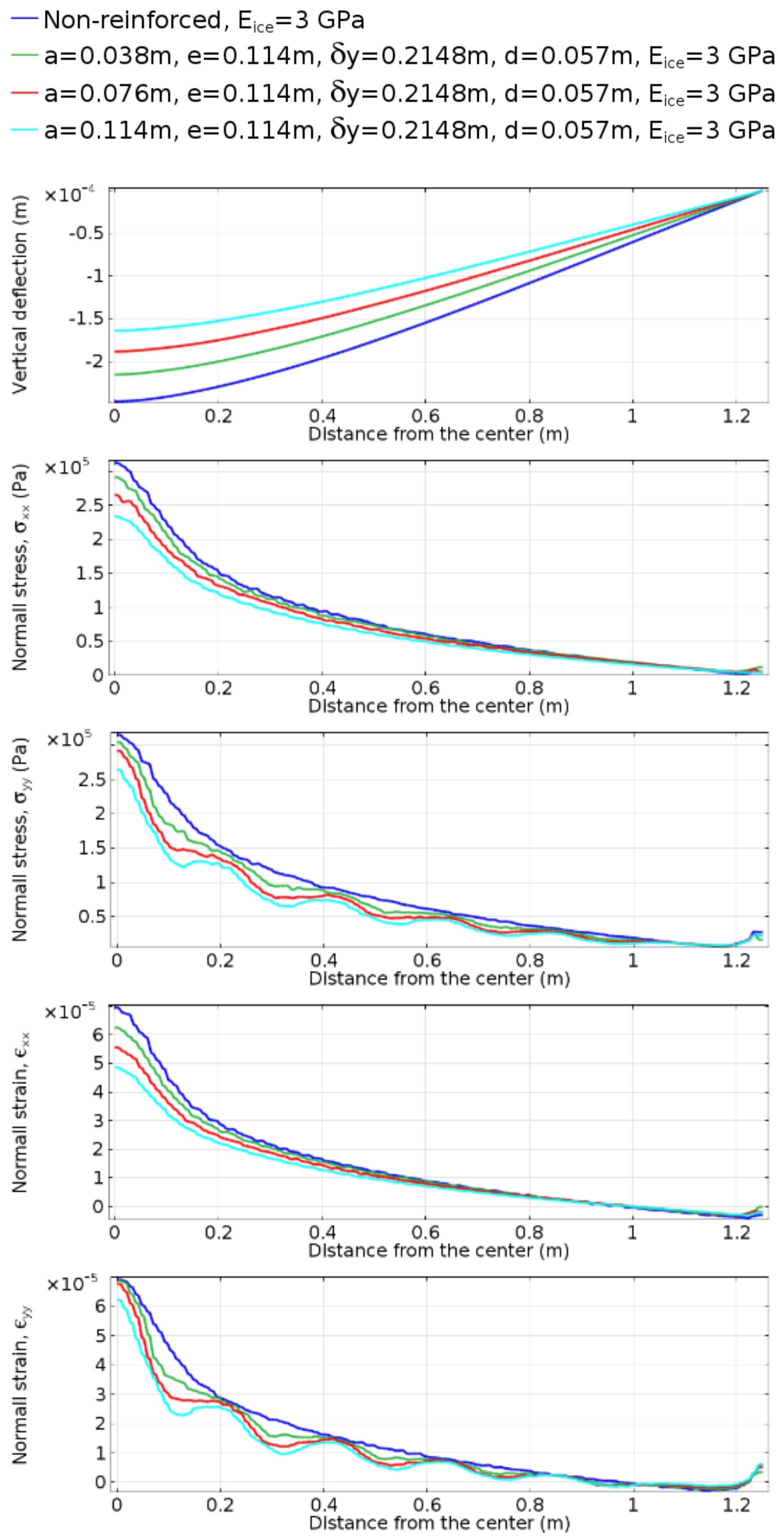

Figure 28: Influence of width of the lumber on deflection, stresses and strains. Wider lumber improves reinforcement.

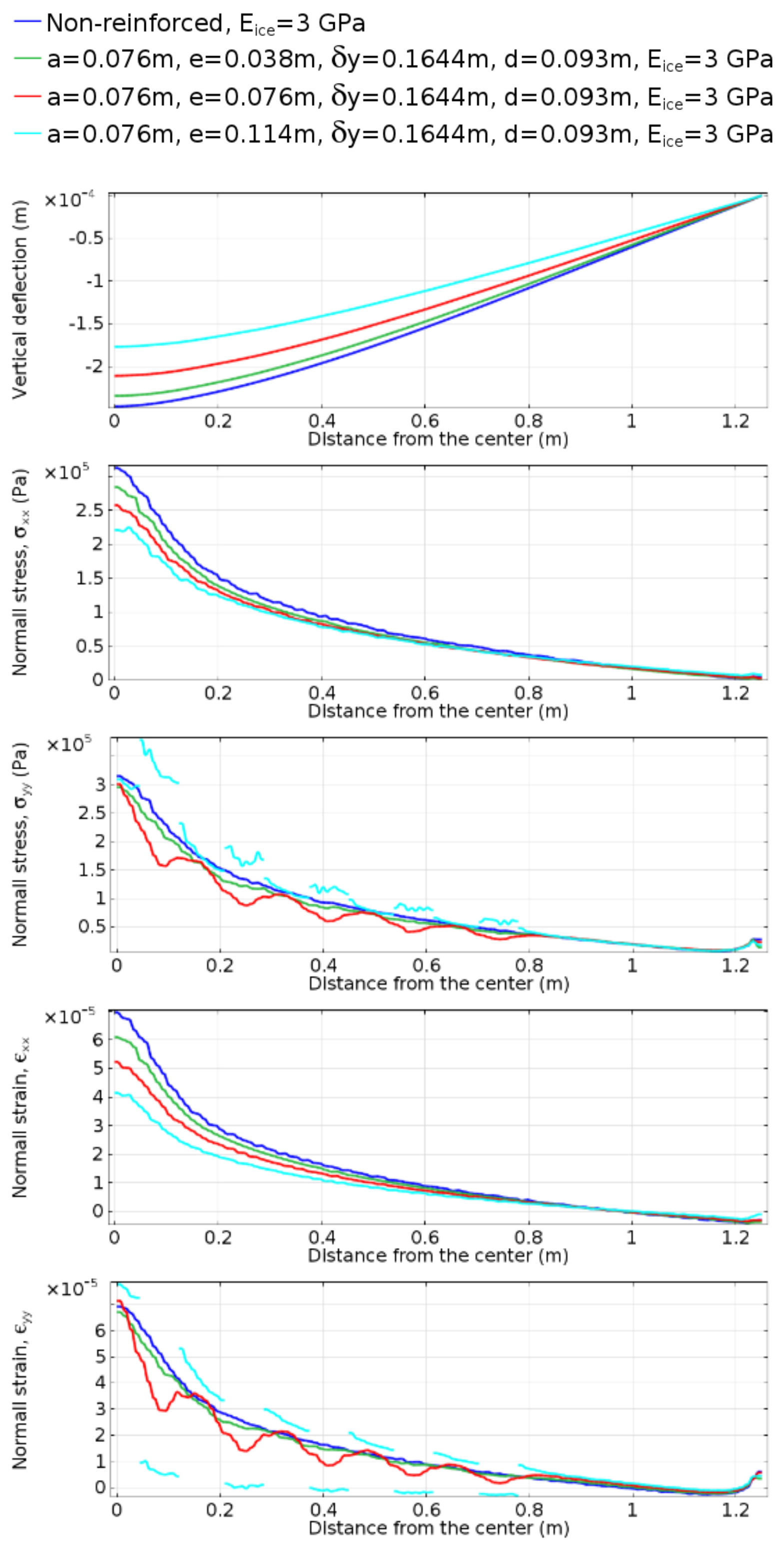

Figure 29: Influence of lumber thickness on deflection, stresses and strains. Thicker lumber reduces maximum deflection of the plate, σ_{xx} and ϵ_{xx}. For the σ_{yy} and ϵ_{yy}, the influence generally depends on where the lumber is located below the plate surface.

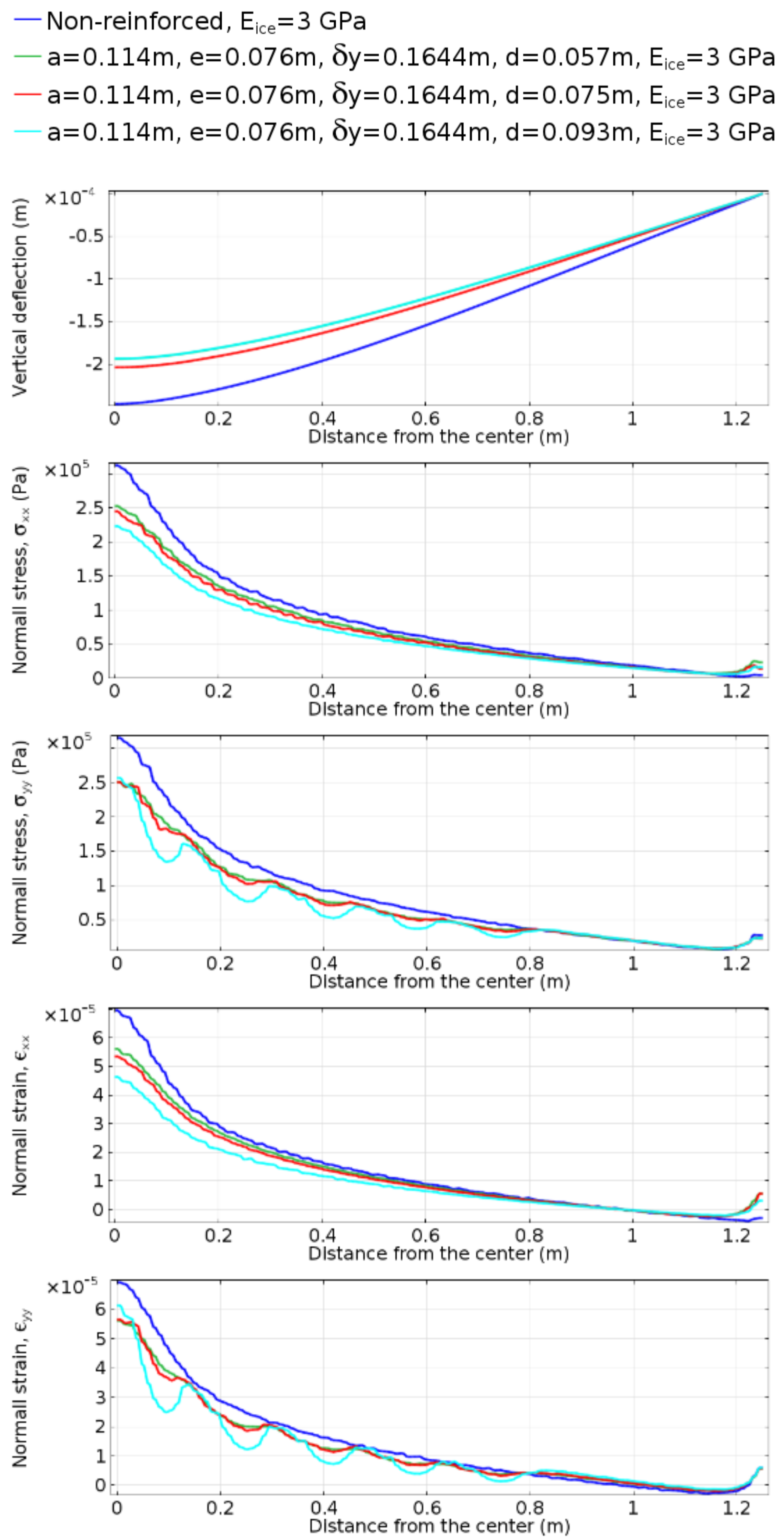

Figure 30: Influence of lumber depth (below the plate surface) on deflection, stresses and strains. Deflections are larger when the lumber is at the plate's mid-plane than when it is away from it. σ_{xx} and ϵ_{xx} are generally lower the deeper the lumber is. For ϵ_{yy} and σyy, the conditions are complex and differ from case to case.

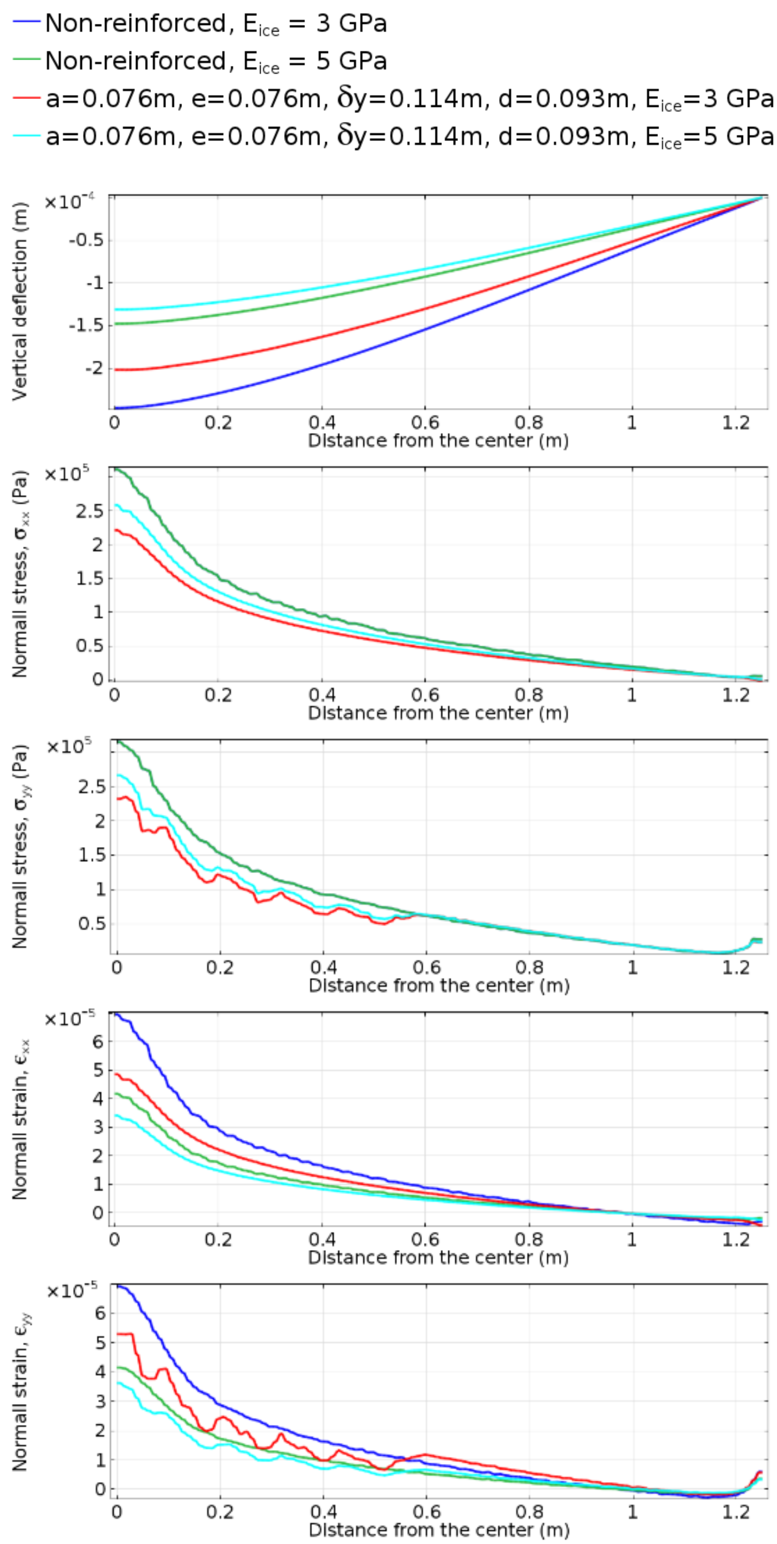

Figure 31: Influence of the effective Young's modulus of ice on lumber deflection, stresses and strains. Note that, in the unreinforced case, stresses do not depend on the effective Young's modulus and the traces for the two moduli coalesce.

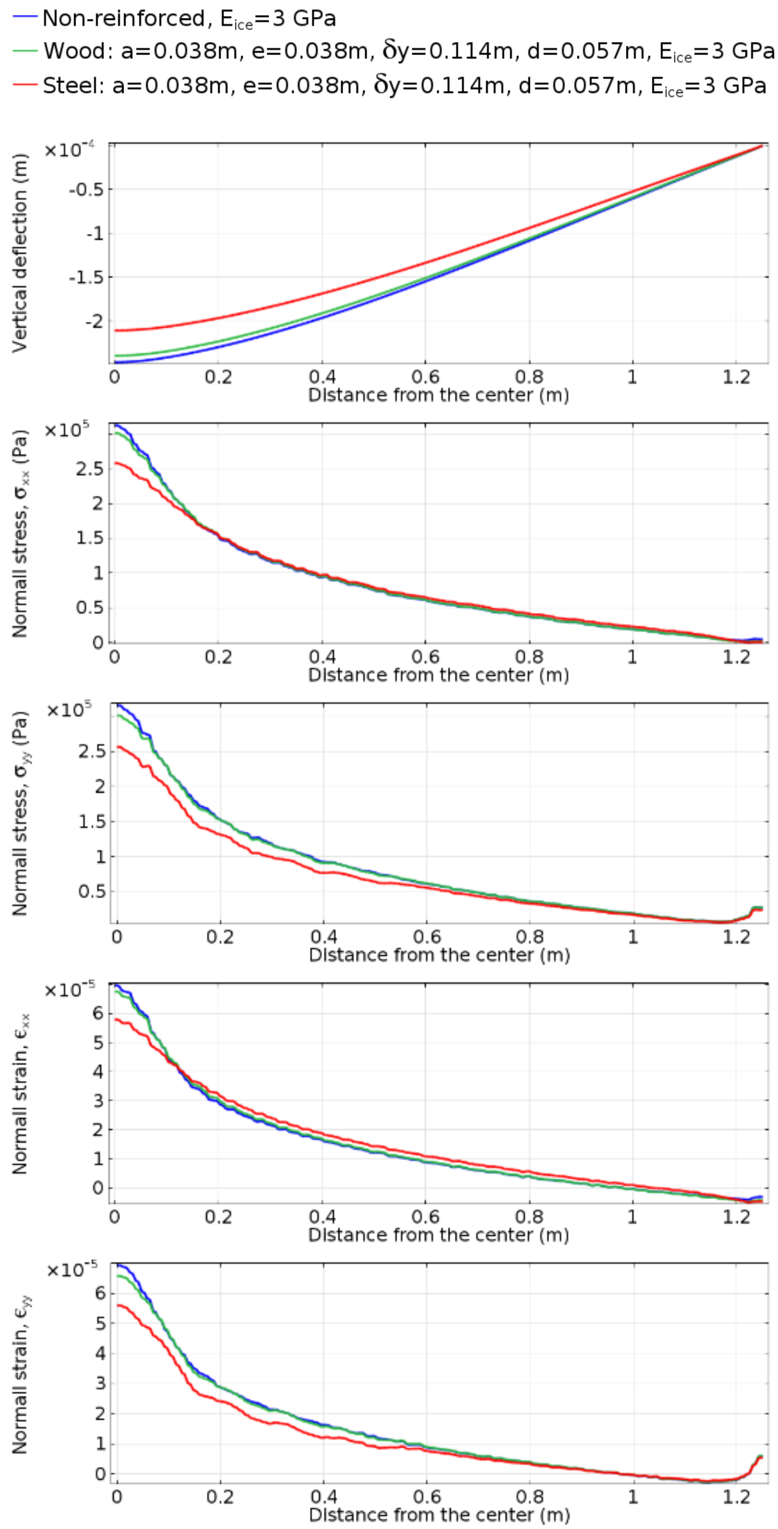

Figure 32. Steel has a stronger reinforcement potential than does lumber.

7. Discussion

Although the reinforcement of ice covers for the purpose of surface transportation is well known, in general, winter road operators in Canada do not rely on it. As mentioned earlier, this could be because they have been able to overcome their challenges through effectual management practices, namely the judicious usage of surface flooding. Another reason is the lack of guidance to do so. For the implementation of reinforcement procedures, deployment is a significant uncertainty. Another is the ability of reinforced ice in being able to support the loads. A third uncertainty is the retrieval of the material at the end of the winter road season.

7.1. Deployment procedures

Based on the information from all available sources {The Engineer, 1964 #1810;Carnes, 1964 #7382;Gold, 1971 #664;Michel, 1974 #1155;Haynes, 1992 #708;Barrette, 2018 #6714;Fransson, 1986 #6721;Cederwall, 1981 #1447;Karpushko, 2020 #7334}, deployment schemes are here divided into four different procedures: laid on the ice surface, laid below the water surface before freeze-up, inserted through and below the ice surface, and inserted into the ice surface (Table 6).

Table 6: Deployment procedures, with applicable material and estimated level of difficulty.

Procedure	Feasibility	Level of difficulty
The reinforcement material is laid on the ice surface	All material	Medium
The reinforcement material is laid below the water surface before freeze-up	Cables and geogrids	High
The reinforcement material is inserted below the ice surface	Cables and geogrids	Medium
The reinforcement is inserted into the ice surface	Cables	Low

7.1.1. Reinforcement laid on the ice surface

This procedure is the most common – a few cases were discussed earlier. Its main advantage is its relative simplicity, and that it can use any reinforcement material (including microscopic). Material incorporation may also accelerate the ice thickening process, depending on how much and how it is used. The material is laid onto the ice cover as soon as it achieves a safe thickness to work on. It is then flooded, and that water allowed to freeze. The amount of labor and resources in the implementation of this procedure depends on the type and amount of reinforcement material, e.g. layers of logs are more involved than a geogrid. Depending on how thick the ice build-up is, snow banks may be required on each side of the road (e.g. Figure 8).

One drawback with this deployment procedure is that the reinforcement may end up being closer to the upper surface of the ice, i.e. inside the compression zone (Figure 1), which is where it is the least effective (Ohstrom and DenHartog, 1976, Barrette and Butt, 2020). However, as indicated in the studies reported by Fransson and Elfgren (1986) and Haynes et al. (1992), supported by the outcome of the computational exercise, even when this happens, the material can still make the ice stronger. According to Fransson and Elfgren (1986) the limiting factor for deflection, at least in a constant load scenario, and since "*ice creeps so easily in tension*" (p. 189), is actually within the compression zone. The reinforcement has to be stiffer than the ice matrix and would be more effective in a thicker ice cover.

7.1.2. Reinforcement laid below the water surface before freeze-up

This procedure can make use of any macroscopic reinforcement – e.g. cables or geogrid – and assumes that access to the site is possible outside the winter road operational time frame (which is not always so in remote areas). In order to reach the target depth below the ice surface, due consideration must be given to the hydraulic conditions at the deployment site, i.e. it is best suited for calm waters. Also, weights or buoys (depending on material density) would have to be used so as to keep the reinforcement material at the target depth below the water surface. In the case of geogrid, which usually comes in a roll, it would have to be sufficiently flattened prior to lay-out. Whatever precaution is taken, the reinforcement would likely vary, perhaps significantly, in depth below the ice surface. Downward growth of the ice-water interface is expected to capture the material, albeit possibly leading to the formation of a cleavage-prone surface along the ice-material interface (Barrette and Butt, 2020).

7.1.3. Reinforcement inserted through and below the ice surface

This method has been used in the laboratory (Haynes and Martinson, 1989, Haynes et al. , 1992) and is also described by Karpushko et al. (2020) – see Figure 33. It can be applied to any macroscopic reinforcement – e.g. cables or geogrid. It is done by cutting two slots across the width of the planned reinforced road segment – one slot at the beginning, the other at the end of the segment. If the material is denser than water (e.g. steel cables), buoys would have to be used in order to keep it against the undersurface.

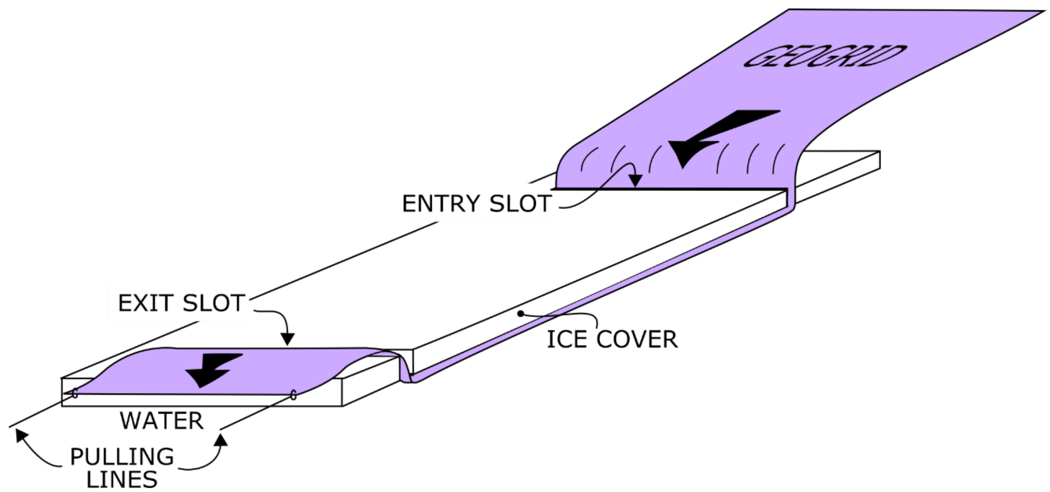

Figure 33: Schematic diagram illustrating a deployment procedure, here used for a geogrid, whereby the material is inserted below the ice through an 'entry' slot, and retrieved through an 'exit' slot.

This procedure's main challenge is in being able to drive the material (below the ice) across the distance over which the ice cover is meant to be reinforced. An ice jigger[9], or similar device, could be used for pulling two lines attached to the material below the ice (see also Sprules, 1957, Hill et al., 1996). Another challenge is that, since geogrids tend to come in rolls, "*it unrolls in an undulating shape and does not lay flat up against the underside of the ice sheet*" (Haynes et al. , 1992 p. 10). Additional considerations include: a light-colored material is preferable, remove the snow from the ice surface so as to promote downward ice growth, and insert the material sideways along the full length of the road, rather than from one end to the other (Haynes et al. , 1992).

https://www.youtube.com/watch?v=Q9vHIsDZ8_I

7.1.4. Reinforcement inserted into the ice surface

This procedure, depicted in Figure 2
Figure 2, is an appealing alternative for cables (but not geogrids), and may be seen as the most practical and easiest option. There is no need for additional freeze-up time after deployment, i.e. the procedure is carried out once the target ice thickness is achieved. The deployment at a target depth below the ice surface ensures the material is initially within the tensile zone as close as feasible to the ice-water interface.

The source mentions that a circular saw was used for installation purposes (The Engineer, 1964). A hand-held chainsaw could also be used for short segments. Ideally, a better system would have to be devised for longer segments. It could take to the form of a walk-behind saw[10], modified to handle that particular application, e.g. with a thick saw blade.

7.2. Avoiding breakthroughs

7.2.1. With unreinforced ice

A conservative approach to prevent breakthrough in a standard (unreinforced) ice cover is to avoid failure (first crack). In Canada, Gold's formula (Gold, 1971) is alluded to implicitly or explicitly in most guidelines, as a first-order approach. This formula has the following form:

$$P = Ah^2 \qquad \text{Eq. 1}$$

where

P: Design load, in kilogram
h: Ice thickness, in centimeters
A: Empirical parameter with pressure units, in kilogram per square centimeters

The thickness *h* is assumed to be representative of the ice road as a whole (or a section thereof) with due consideration to variations, i.e. the thinnest area along the route should be used for the calculation. The parameter *A* is related with the ice flexural stress. Values assigned to it varies (Proskin et al. , 2011a, Barrette, 2015b). The most conservative value is 3.5 kg/cm^2, which has been used historically in most guidelines (e.g. Government of Alberta, 2013, IHSA, 2014). That number is now at 4 kg/cm^2 in the latest guidelines (e.g. Government of the NWT, 2015). Higher values can be used under controlled conditions (e.g. Government of Alberta, 2013, Government of the NWT, 2015). With this formula, a plot can be produced, as shown in Figure 34. The load on the vertical axis is the maximum that should be allowed for the ice thickness on the horizontal axis. The 'A' values used in this plot are 3, 5 and 7 kg/cm^2, as examples.

From the moment the load is applied to breakthrough, a sequence of events has been identified (Sodhi, 1995). Here, we focus on short-term loading (less than a minute), and we overlook more elaborate scenarios, such as dynamic loading related with vehicle speed. We also assume an idealized, axisymmetric deformation in the elastic range (i.e. instantly and fully recoverable), with a concentrated load in the center (Figure 35).

[10] https://en.wikipedia.org/wiki/Concrete_saw#/media/File:Concrete_saw2.jpg

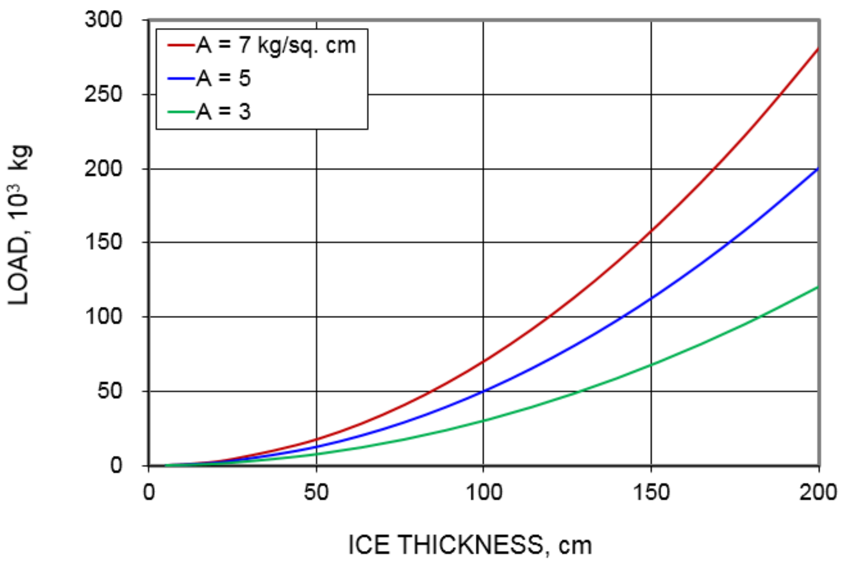

Figure 34: Load as a function of ice thickness for three different 'A' values, using the equation of Gold (1971).

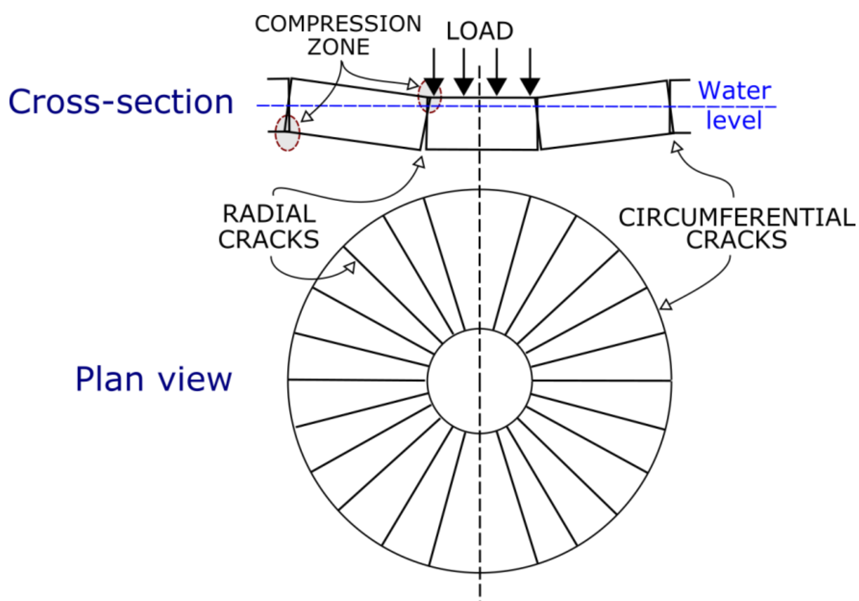

Figure 35: Idealized representation of cracking patterns in a vertically loaded ice cover (from Sodhi, 1995).

- The maximum tensile stress (induced by loading) occurs directly below the load, along the lower surface of the ice. When that stress exceeds the tensile strength of the ice, radial cracks start forming. They may not be noticeable initially because they are hidden under the ice (and the snow cover, if there is any). The amount of load required to achieve this state is much lower than that required for a breakthrough.
- A further increase in load causes additional cracking, this time in circumferential patterns – the tensile stresses are then at the top. At this point, the amount of load reaches 40-60% of that required to produce a breakthrough. This means that, despite the existence of radial and circumferential cracks, the damaged ice is still able to sustain a load.

- Once all tensile stresses have been relieved via fracturing, compressive stresses dominate. This is because of the interaction between individual pieces in the broken ice cover.

While Sodhi (1995) offers a model that approximates a breakthrough scenario, he states that *"[an] exact analysis is not available at [the time of writing]*" (p. 8). Note also that the ice is assumed to be uniform and devoid of structural flaws, which is rarely the case in a natural ice cover.

7.2.2. With reinforced ice

Reinforced ice may be considered a 'composite' (Vasiliev et al. , 2015) – its response to loading is more complex than that of ice only. The configuration of the material, its mechanical properties and how it binds to the ice matrix all factor in that response. Computational modeling, such as that described in section 6 to assess conditions required for failure (first crack) in reinforced ice, is able to provide some measure of guidance, conditional upon the validity of the simplifying assumptions. This type of analysis can help decide on what material to use, and how.

Methods to determine the ultimate bearing capacity of reinforced ice, i.e. beyond which a breakthrough can occur, have been provided in a few investigations.

- For the scenario illustrated in Figure 8, Michel et al. (1974) first considers the layering, by factoring in non-dimensional parameters that take into account the 'form of the load' and the 'width of the bridge'. According to this theory, which makes use of a modified 'Gold formula', the 'state of plasticity' of the ice, which refers to the mobilization of time-dependent deformation mechanisms (creep), would contribute to increasing the allowable load.
- Fransson and Elfgren (1986)'s scenario (Figure 9, Figure 10) is mostly about the creep response, and is empirical, i.e. 'creep constants' were determined from the tests and incorporated into their formulations. One of these is presented as a means of anticipating loss of freeboard, when the water from wet cracks will flood the ice, a situation which is best avoided.
- Karpushko et al. (2020) follows Russian guidelines ("Industry Road Norms 218.010-98 Instructions for the design, construction and operation of ice crossings"). They first use a formulation equivalent to Gold's formula to determine the bearing capacity of the crossing. If it is deemed insufficient for the expected loads, they then calculate the reinforcement required to accommodate the additional load (with a safety factor), using empirically-derived formulations.
- Vasiliev and Gladkov (2003) employs formulations used for applications on reinforced concrete, also involving empirically-derived parameters.

An important consideration is that even if the reinforcement is above the neutral axis, it can still contribute to an increase in resistance. This would need to be investigated further.

7.2.3. Gold's 'A' value and tolerance to risk

In Table 2, which summarizes the real scale ice reinforcement scenarios, an 'A' value was derived from the reported thickness (h) and maximum load (P) in each case. In almost all cases, that value was within the same range as that recommended by recent guidelines, i.e. from 3.5 to 5 (Proskin et al. , 2011a, Government of Alberta, 2013, Government of the NWT, 2015). One may then wonder about why reinforcement was used in those scenarios since the ice, *without it*, could have carried the required loads. The answer to that question has likely to do with a low tolerance to risk on the part of the designers. The only exception is the military scenario documented by Carnes (1964), which has the highest tolerance. Yet, the crossing was a successful operation.

Interestingly, the Cold Regions Research and Engineering Laboratory (CRREL), a research organization supporting the U.S. Army, recommends an 'A' value of 10 (CRREL, 2006), consistent with that shown in Table 2 for Carnes (1964)'s scenario.

What this suggests is that the reinforced ice covers documented in Section 4 either could have handled much heavier loads, or were over-designed, i.e. they were built stronger than they had to be. As pointed out by Michel et al. (1974, p. 618), "*It was indeed not feasible to fail one bridge to test its bearing capacity and thus verify theory with measurements*." Without verification, any theory or assessment aimed at determining bearing capacity of these complex structures is of limited value. The designers' prudence was warranted.

7.3. Retrieval

Means of retrieving the reinforcement is generally not discussed. Karpushko et al. (2020) is an exception – a brief allusion is made in that source about the challenge of extracting the reinforcement material from the water following the winter road season. Lack of access, until the ice has completely melted (so as to release the reinforcement material), is certainly an important consideration. A boat could be required if anchoring has been resorted to. A vehicle could also be needed to pull the material onto the shoreline. If dispensed on rolls, this would make retrieval (and transport) easier. The material could be stored on site, and await re-deployment the next winter.

The reason information on this topic is limited could be that retrieval was not seen as an issue by the few operators and engineers who documented ice reinforcement. That is so especially if logs were used, as is commonly the case. They would be abandoned at the end of the winter road season, and new logs would be used the following winter.

8. Conclusion

In Canada, the majority of winter road operators do not use ice reinforcement techniques. There would be a learning curve to climb and a good dose of faith would be required in relying on this approach. Understandably, therefore, this could translate into a reluctance in implementing them. This is the reason why the awareness that ice reinforcement has been used successfully in the past, and in various ways, is brought to light in this report. Several real-scale cases are presented.

The ability to foresee a breakthrough is probably the most daunting challenge. Even unreinforced ice has not been elucidated in that respect. Instead, all crossings are designed, and conservatively so, against 'first crack' (referred herein as 'failure'). This circumvents the need to assess resistance to breakthrough, because first crack happens beforehand: a crack forms across the entire thickness, typically leading to surface flooding. The road is then closed by the operator until the surface gets repaired. For reinforced ice, however, designing against first crack is not as feasible, because its response to loading is much more complex. This is where computational modeling can play a role, as shown in this report. It is a potent tool to explore ice failure, and can take into account the nature of the reinforcement material and the loading geometry. But it has to be validated against physical testing.

Building on the experience acquired to date and developing our knowledge-base about reinforced ice is desirable at this time, given the increasing amount of uncertainty regarding winter road safety and effectiveness in the context of a warming climate. Gaining sufficient confidence is key – it will help avoid over-conservativism while defining safe and cost-effective solutions. This can be best accomplished by performing more real scale, fully controlled, ice testing. Such testing should allow for breakthrough to be achieved, so as to capture the full response history. Alternatives to logs should be considered, as the latter are not always available and may be seen as objectionable. Simple (and repeatable) reinforcement procedures would also have to be devised, with enough flexibility to address all deployment contingencies. Together, this would lead the way toward guidelines on implementation.

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