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Optimum Load Spacing for Safer Transportation on Floating Ice

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ABSTRACT

Floating ice roads provide temporary access to areas with no permanent roads in subarctic regions. However, there is a limited period of time a particular vehicle is able to travel on the floating ice safely. This period depends mostly on the flexural strength of the ice, the vehicle gross weight and loading distribution. An appropriate loading pattern can improve ice safety and extend the operative period with other parameters being identical. The Finite Element Method has been used to identify key parameters for a Long Combined Vehicle (LCV) loading and to propose ways to improve operation safety on the ice and to reduce transportation costs. It is shown that the ice flexural stress is highly dependent on the axle spread in the axle groups and it is possible to reduce ice stresses by increasing the axle spread. The distance between axle groups is another parameter that influences the ice stresses. Increasing the inter-axle group distance helps to reduce the induced moments in the ice. Numerical studies have been conducted for a typical vehicle to estimate the level of improvement that may be achieved.

INTRODUCTION

Ice covers the surface waters every winter in the subarctic region. The floating ice sheet is not permanent and melts every year. Surface ice thickness increases during winter and provides safe passage for vehicles. For example, during winter the road from Tibbitt to Contwoyto was open for 72 days in 2007 and 11000 vehicles up to 65 tonnes travelled along this road (Mesher et al., 2008). The road is about 600km and crosses 65 lakes with 64 overland portages in Canada (Hayley and Proskin, 2008).

The ice bearing capacity should be controlled prior to opening an ice road. The floating ice performs like a plate on an elastic foundation and the bending strength is the primary measure of the ice strength. The ice bending stress depends on the flexural stiffness of the ice, the Gross

Vehicle Weight (GVW) and the load distribution applied to the ice. A trailer (or semitrailer) axle arrangement can be adapted to reduce ice stresses. This trailer can work with a higher safety margin with respect to the ice break.

It is shown that the axle spread controls local ice bending and by adopting the axle group design it is possible to reduce the number of axles without adversely affecting the ice stresses. This potentially reduces the weight, the fabrication cost and reduces both wear and operation costs. The other parameter is the inter axle group distance which has a significant effect on the ice moment. These parameters can be used to design a semitrailer with enhanced performance on floating ice.

Ice mechanical properties and loading are discussed in next sections and then the Finite Element (FE) model is introduced. The local ice stress under an axle group and inter-axle spacing are discussed based on the FE analysis results. The parameter study showed potential improvement of a trailer axle arrangement toward safer and more cost effective operation on ice.

FLOATING ICE MECHANICS

Ice strength and mechanical properties are not physical constants and depend on ice composition and the environment in which the ice crystals have developed. Ice strength is normally lower in tension and the loading on a floating ice sheet results in ice fracture due to flexural tension for a quasi-static load. Ice failure criteria can be based on either stress, deflection, strain or strain-energy (Beltaos, 2002). The flexural strength of floating ice is the primary measure of ice strength under moving loads. The ice sheet cracks in tension when the bending stress reaches its limiting value. Ice crack may stop after limited propagation or continue to complete rupture. A stable crack redistributes the loads and may be followed by another crack system. This sequence is continued until the fractured ice forms a mechanism and the load breaks through the ice sheet.

Ice sheet fracture under single vehicle load consists of three steps. At first, cracks initiate at the bottom surface under the load where the bending moment is maximum. These cracks are like rays emanating from the higher loaded area. Circumferential circular cracks are the second set of cracks that develop on the upper surface. These cracks develop at some distance from the load where the negative bending moment is high. The circumferential cracks develop at load levels close to the breakthrough load and provide warning that the ice is about to break (Figure 1). Finally circumferential vertical shear cracks develop close to the loading point. These cracks in combination with the radial cracks break the ice into unstable wedges and the load falls into the water (Figure 2). This normally happens at a load level that is 2-4 times greater than the initial cracking load (Best practice for building and working safely on ice cover in Alberta, 2009).

An ice road should be operational for frequent use and ice cracking is not tolerable for a single vehicle pass. Peters et al. (1982) and Masterson and Gamble (1986) have proposed that the bearing capacity of floating ice be based on serviceability criterion associated with the initial radial cracks at the bottom of the floating ice. The safety factor is then applied to the flexural strength to cover variation in ice strength and thickness. The ice performs mostly elastic in this stress level under quasi-static loads.

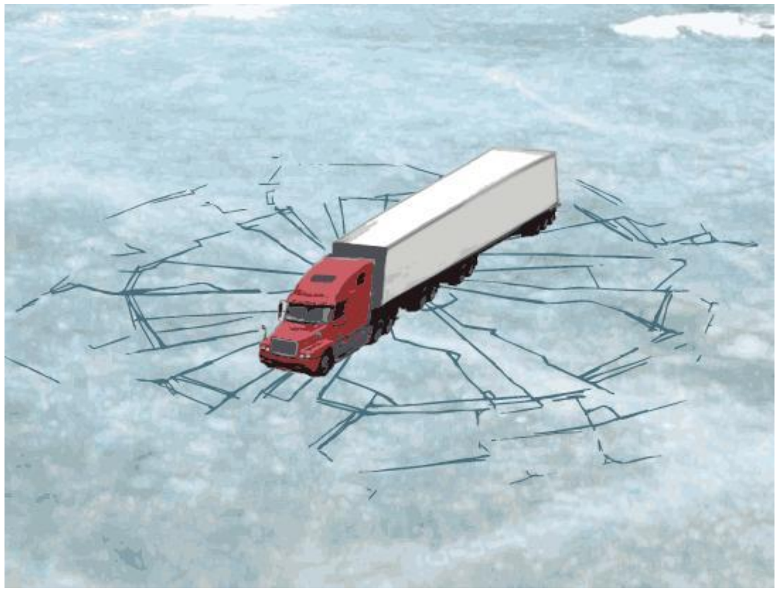

Figure 1. Radial and circumferential cracks forming on overloaded ice.

(Best practice for building and working safely on ice cover in Alberta, 2009)

Figure 2. Breakthrough of a D10 Caterpillar tractor following a circumferential crack pattern.
(Best practice for building and working safely on ice cover in Alberta, 2009)

The ice elastic modulus (E) and Poisson's ratio (v) define the elastic material properties. The elastic modulus of ice depends upon the rate of loading when the process of deformation is not purely elastic. Under these conditions the term 'effective' modulus is used to describe the ice behaviour. For quasi-static rates the 'effective' elastic modulus is in the range of 3 to 5 GPa and for quasi-static bending, it is about 3 GPa. The Poisson's ratio of ice is about 0.25 for sound propagation speeds, about 0.3 for quasi static engineering loads, and about 0.5 for long-term creep loads. For quasi-static bending the Poisson's ratio is about 0.3 (API Recommended Practice 2N, 1995).

VEHICLE LOAD

Long Combined Vehicles (LCV) are usually used for road transportation. These vehicles are able to transport the loads efficiently and reduce shipping costs. A LCV consists of a driver (tractor) and a single or several semitrailers (or trailers). The number of trailers, geometry and pattern of axles varies giving rise to a variety of loading footprints on a road. An axle has one or two wheels on each side. The axles can consist of an individual axle or a group of several axles to support heavier loads. There are groups of two (tandem), three (tridem) or even four axles. A sample LCV is shown in Figure 3 and load footprint in Figure 4.

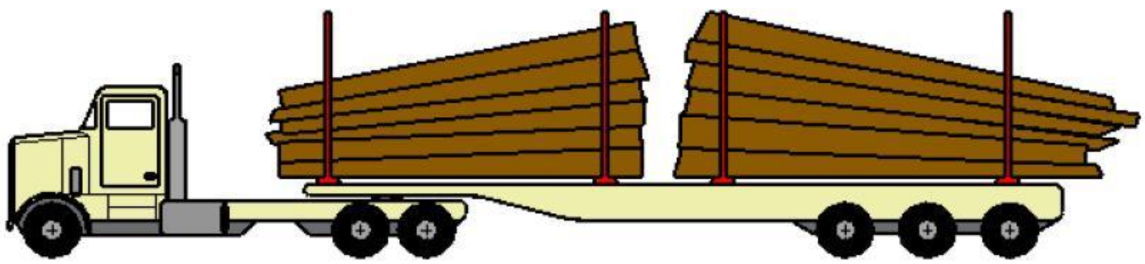

Figure 3. Tandem drive tridem semitrailer.

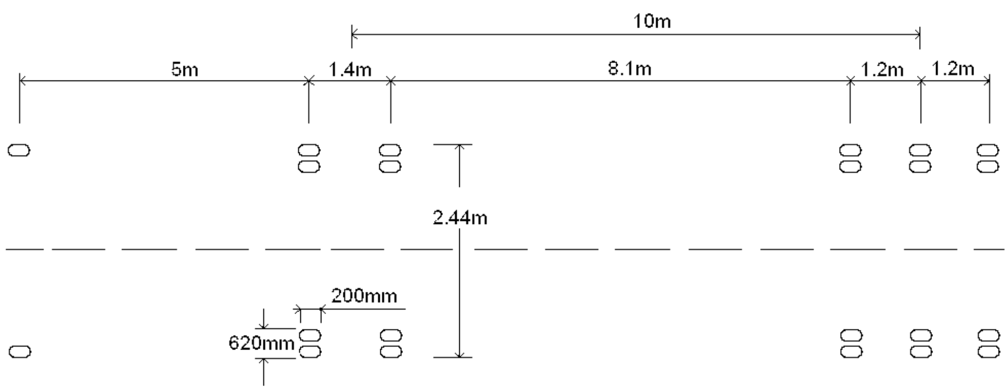

Figure 4. Sample LCV load footprint.

THE FINITE ELEMENT MODEL

The Finite Element Method (FEM) is a standard tool for stress analysis in structures and enables geometric details and complex applied loads to be taken into consideration. The Finite Element (FE) mesh density is normally increased in the high stress zones of concern. The technique is used here to perform stress analysis for the axle groups and multiple-axle vehicle loads. A FE model has been implemented using the ANSYS software. The program has a wide range of elements and is able to handle large models.

The floating ice behaves as a plate on an elastic foundation. An ice sheet of 700mm thickness has been modeled covering an area of 200 x 200m (Figure 5). Free boundary conditions have been applied to the model outer boundary. Solid shell elements have been used to capture the stress variation through the ice thickness (SOLSH190). The elements have six degrees of freedom at each corner node and it is able to model stresses normal to the element plane as well as out-of-plane bending. The ice sheet has been divided into three zones and the FE mesh density has been increased towards the loaded area (Figure 5). The ice thickness has been modeled with five layers of 300 x 300mm elements over a 40 x 40m area where the loads are applied. The number of layers has been reduced to 3 in the intermediate zone (100 x 100m) and down to one element in the outer zone up to 200 x 200m. The in-plane element size increases gradually from zone 1 to zone 3. The boundaries between the zones are bonded by means of contact elements (TARGE170 and CONTA174). Buoyancy is modeled by a uniform spring foundation attached to the bottom of the solid-shell model. The bottom face of the ice sheet has covered with element (SHELL63) capable to model the spring support automatically.

The wheel load has been applied as a uniform load over the contact area. The wheel load is passed to the ice by dummy thin solid elements (SOLID185), sized in-plane to equal the effective wheel contact on the ice surface and the narrow area between the two wheels in a double-wheeled axle (620 x 200mm). These load paths are then bonded to the ice sheet by contact elements (TARGE170 and CONTA174). These paths control the loading footprint and load intensity independent of the ice sheet FE mesh geometry.

It is noted that the ice geometry and loading are symmetric about the vertical plane passing to the vehicle longitudinal axis. It is possible to model half the geometry and apply symmetric boundary condition on the cut boundary. This gives the benefit of a faster solution and less use of system resources (Figure 6).

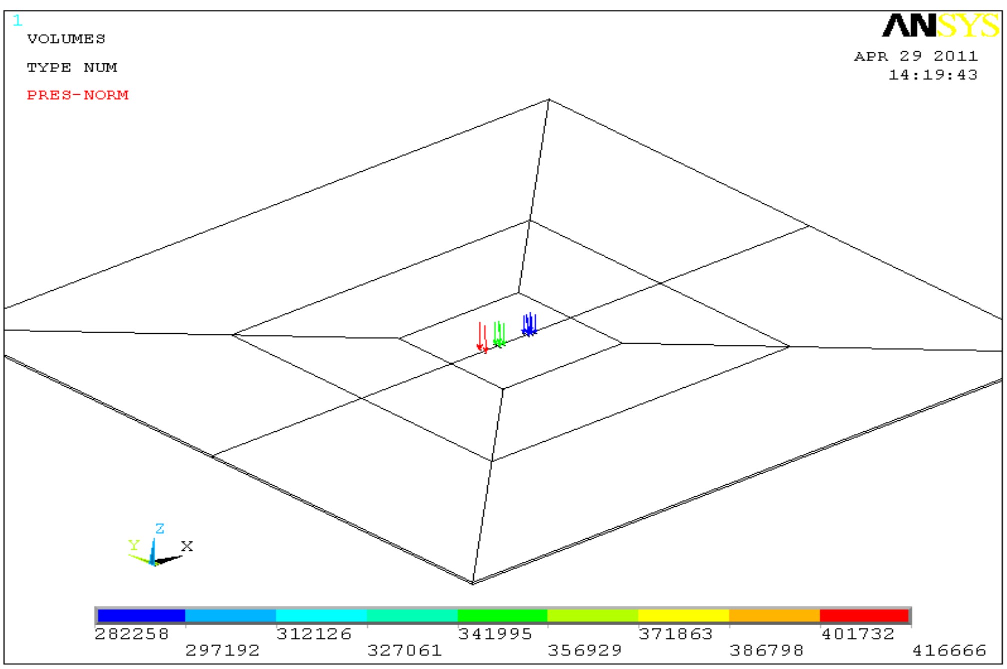

Figure 5. Finite Element zoning for a floating ice model and applied pressure loads (Pa).

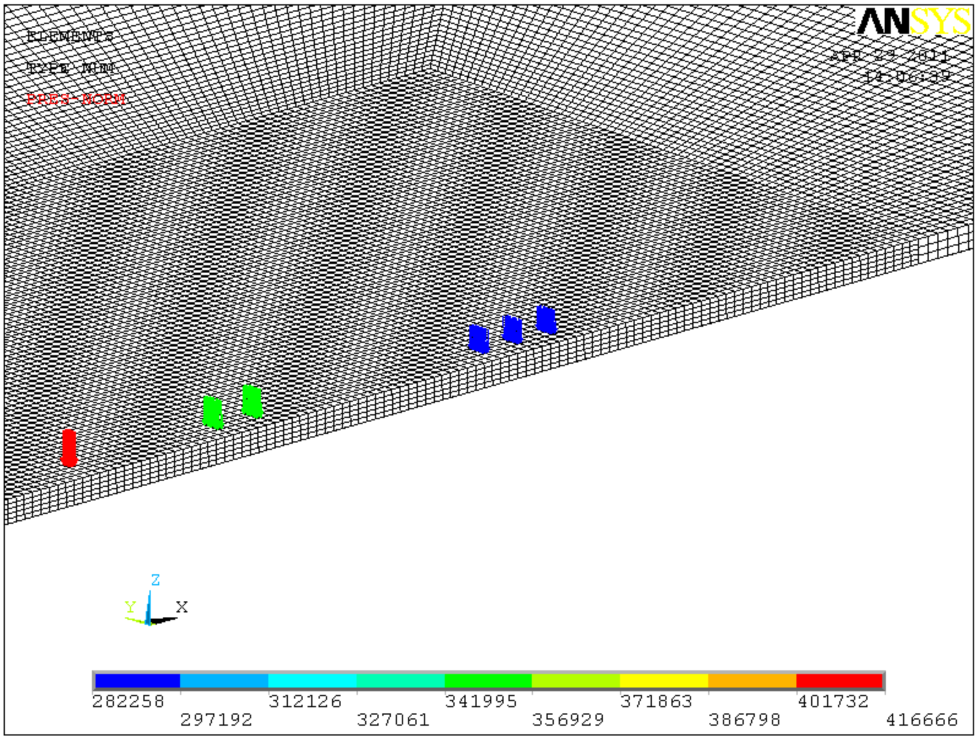

Figure 6. Applied loads (Pa) on the half-model.

LOCAL ICE BENDING UNDER AN AXLE GROUP

A single axle is the basic load footprint and can be used to construct multi-axle loads. The unit axle load is shown in Figure 7 and the principal ice stress on the bottom face of an ice sheet is depicted in Figure 8. The principal tensile stress (S_{11}) reaches its maximum at 600mm from the vehicle centre line. A multi-axle vehicle has several high stress areas at the same distance from the vehicle axle. A line at a distance of 600mm from the vehicle centre on the bottom face passes all the high stress zones. This line is considered as the reference line for critical ice stresses. The ice stresses are plotted on this critical line in Figure 9. The principal stress (S_{11}) is close to the higher normal stress. This is S_{xx} in the vicinity of the wheel load and then S_{yy} after about 0.6m. The axle spacing is more than 1.2m in a practical cases and S_{yy} has higher contribution in maximum ice stresses.

The principal stress has relatively slow attenuation curve and the ice stress is more than half of the peak stress at 3m distance from the axle. This distance is larger than the axle spacing in an axle group and, in a tridem axle group, this implies that more than half of the ice stress under the centre axle could be from the two adjacent axles. This high participation of other axles can lead to little or no benefit for a tri-axle (Tridem) axle group when compared with tandem axle with a similar axle distance (axle spread).

Three axle groups are modeled to compare the ice stresses with a single axle. These are tandem axles with 1400mm and 2800mm axle spacing and a tridem axle 2 x 1400mm axle spacing (2800mm axle spread). All axle groups are supporting 10kN load. The ice stress on the critical line is shown in Figure 10 for different groups. The single axle has the highest ice stress and the wide tandem group (2800mm axle spread) has the lowest ice stress. The ice stress under a tandem axle depends on the axle spread and the stress level for the wider 2800mm spread is significantly lower than that for a closer tandem with 1400mm axle spread. The ice maximum stress under a tridem axle is slightly higher than that in the wide tandem axle in spite of 50% heavier axles in the tandem group. The axle spread is a more influential parameter on ice peak stress than axle load itself.

Total transportation cost can be reduced by avoiding tridem axles which are heavier and have higher wear and operational cost compared to a wide spread tandem.

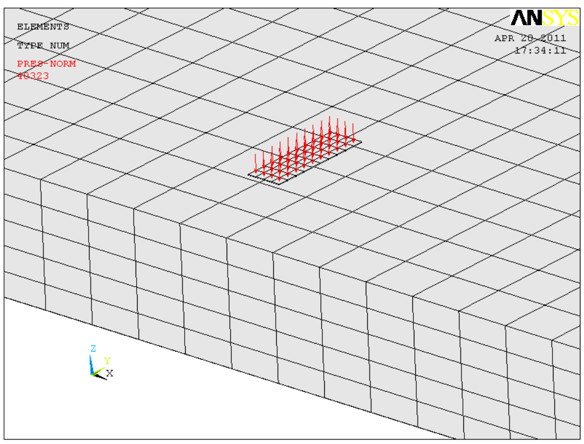

Figure 7. Single axle loading footprint.

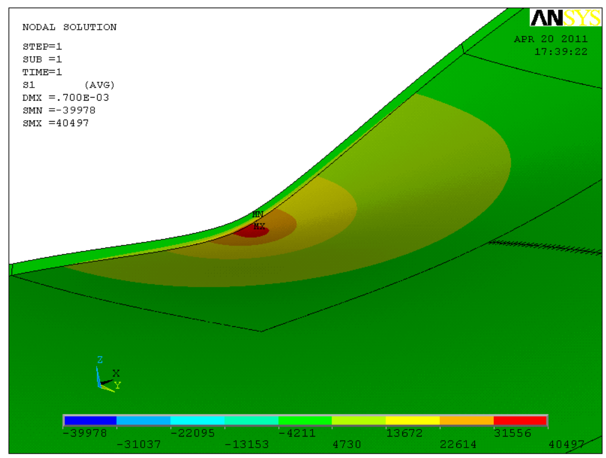

Figure 8. Principal tensile stress on bottom face (Pa).

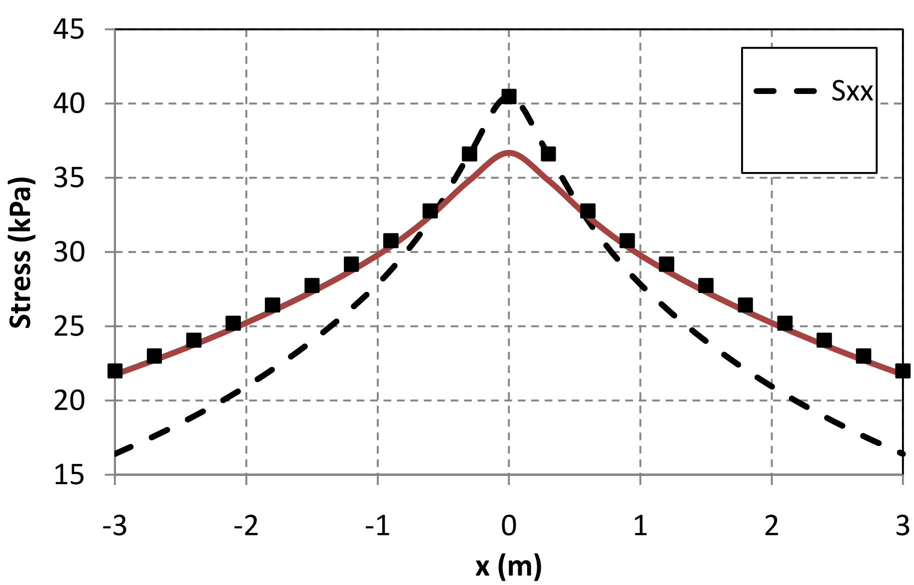

Figure 9. Ice stresses on critical line parallel to the vehicle and Passing maximum stress (10kN).

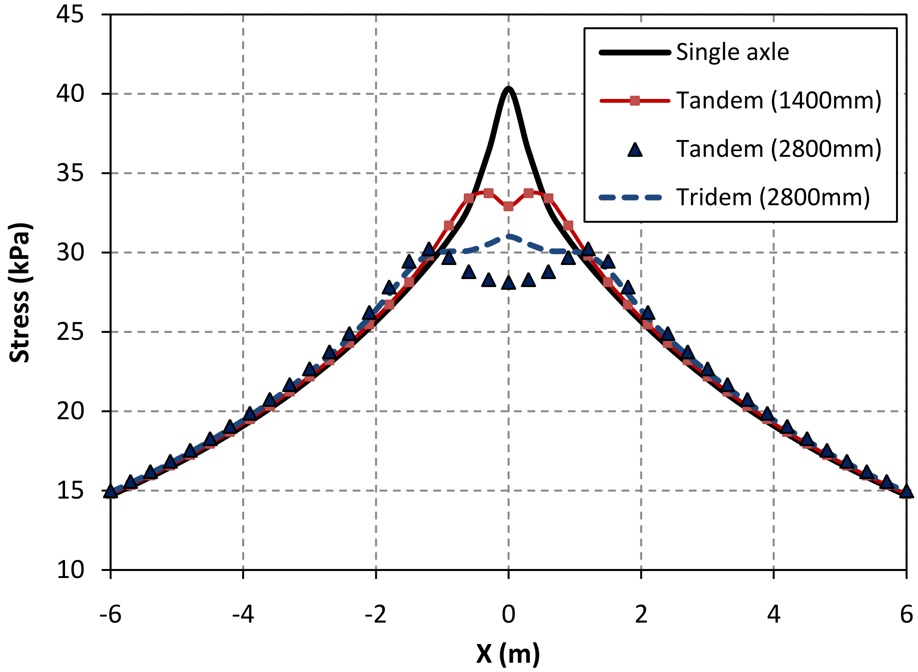

Figure 10. Maximum principal stress in ice sheet for 10kN load on axle groups.

Case Study: Semitrailer Vehicle

The procedures discussed for an axle group can be implemented for a practical case of a vehicle with several axle groups. A tandem drive tridem semitrailer is considered for the case study (Figure 3 and 4). The axle loads are as follows:

Front single axle: 50 kN

Tandem axle (1.4m): 170 kN

Tridem axle (2.4m): 210 kN

The maximum tension is 852.1 kPa in the Finite Element model and this high stress is located under the tridem axle group (Figure 11). As an alternative, the middle axle is eliminated from the rear tridem. The axle group load is kept the same (210 kN) therefore the individual axle load is increased to 105 kN from the original 70 kN. The ice tension is compared on the critical line (line passing the high local flexural stresses) in Figure 11. The ice stress is mostly identical in the two cases and the only difference is under the rear semitrailer axle group. The tandem axle has two peaks and reduces in between and the tridem axle has the maximum ice stress under the centre axle. The highest tension in the ice is slightly reduced from the original 852 kPa to 851 kPa after converting the tridem to a tandem with the same axle spread. This case study confirms the previous finding about the importance of axle group spread on the ice maximum stress.

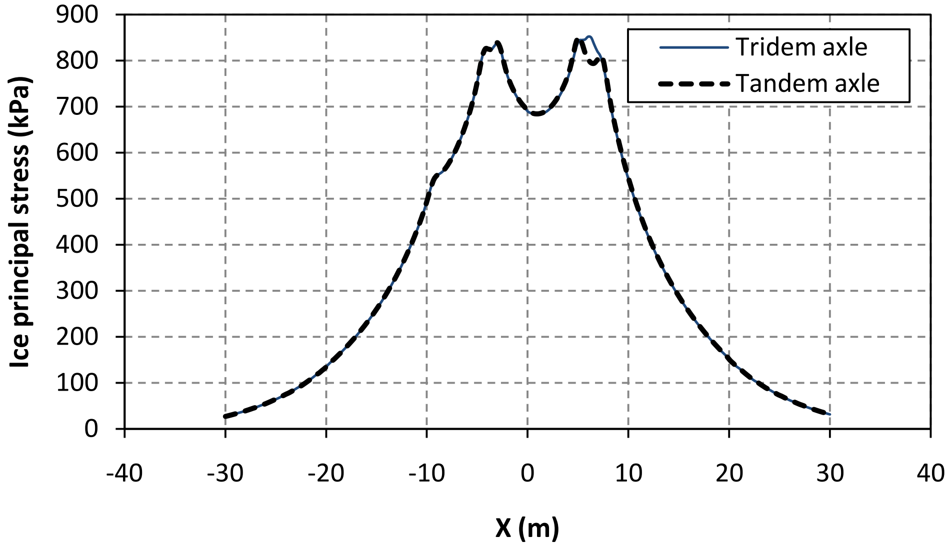

Figure 11. Ice stress loaded by a LCV with a tandem or tridem rear semitrailer axle.

INTER-AXLE DISTANCE

The axle load has an influence on the ice stresses at a reasonable distance from the axle as noted for a single axle case. This characteristic of the floating ice can effectively limit the axle group load if other axle groups are loading the ice close by. The practical influence of this parameter is reviewed for a LCV in use on ice roads. This is a tandem truck, tandem semitrailer (Figure 12). The distance between the two tandem centers is considered as the design parameter.

The axle spread is 2.4m for both tandems similar to the optimum group discussed in the case study above. The steering wheel is 5t and is spaced 5.7m from the truck tandem centre. The two tandems are assumed to have the same load and this load has been adjusted to limit the ice stress to 850kPa. The GVW is shown in Figure 13 as a function of inter-axle spacing noted in Figure 12. There is a strong trend that a longer semitrailer can take a heavier load and that, for example, GVW can be increased by 70kN (16%) when the inter-axle spacing (centre to centre) increases from 10 to 18m. The rate of change in GVW gradually reduces for longer vehicles but the trend is strong up to 20m. A longer semitrailer increases the vehicle safe load capacity and allows safer operation on the ice.

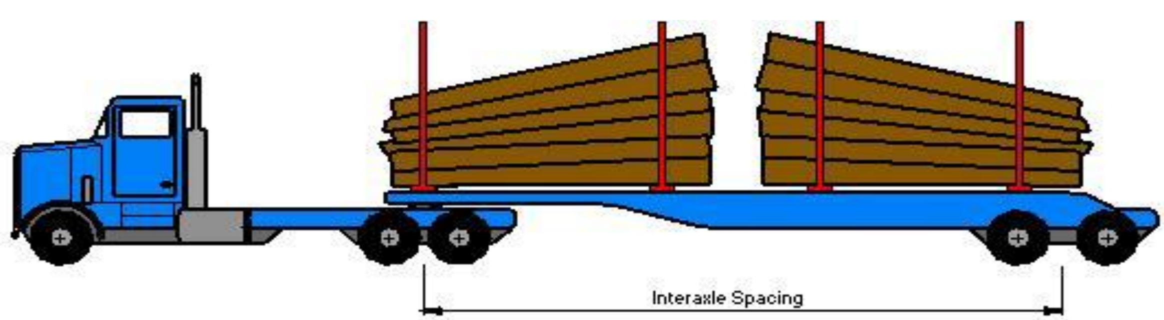

Figure 12. A tandem truck tandem semitrailer side view.

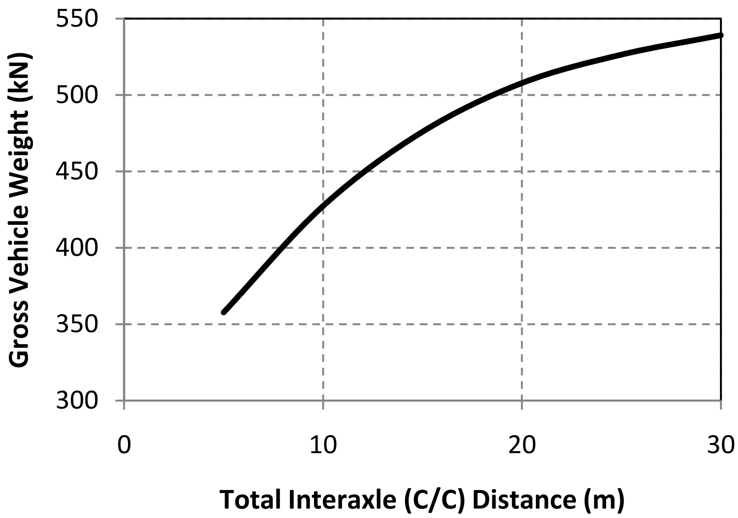

Figure 13. Contribution of inter-axle distance on GVW for limiting ice tension of 850MPa.

CONCLUSION

Stress induced in floating ice has been assessed for axle group and inter-axle spacing. The ice stress reduces as the axle spread increases within an axle group. FE analysis has shown that the ice stress is the same for a tandem and a tridem axle with the same axle spread. An optimum axle group is a tandem with a large axle spread. The distance between axle groups has been identified as another parameter controlling the ice stress. A longer semitrailer can reduce the ice stresses and improve transportation safety.

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