Bridge Load Rating: is GVW the sole consideration?

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Abstract

Load limits on bridges are determined using a design vehicle configuration. This paper examines the maximum shear force and bending moment exerted by different forest vehicles on three bridge lengths. Parameters were inputted into BRIDGEframe software for analysis. Machines that have a different load configuration than the design vehicle can exert a maximum shear force and maximum bending moment that is higher than the design vehicle, even if the GVW is lower. Results show that a professional engineer should be consulted about the safety of the crossing of a vehicle that is significantly different from the design vehicle configuration.

Key Words:

Bridge, Load Rating, Design vehicle configuration, axle load, GVW

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Introduction

British Columbia has over 60 000km of resource roads, spread across the land base which are used to develop the Province's rich natural resources, such as minerals, oil, gas, and timber. Many streams, both large and small are present in resource extraction areas. Consequently, bridges on resource roads are both abundant and important for the extraction of BC's natural resources. Resource bridges are designed using a design vehicle configuration, such as the L series from the BC Ministry of Forests. The GVW rating of the bridge is based on the specific configuration of the design vehicle (BC Ministry of Forests and Range Operations Division, 2009). A vehicle of the same or lower GVW than the design load could exert a higher shear force or bending moment on the bridge than the design load, depending on the weight distribution, which could result in failure of the bridge.

This essay will compare the maximum shear stress and bending moment resulting from 4 different vehicle configurations. The vehicle configurations that will be considered are the Cat 740 articulated truck, Madill 144 swing yarder, BC L165 design vehicle configuration and BC L100 design vehicle configuration, and the bridge lengths that will be considered are 10m, 15m and 20m. Axle loads will be calculated, then inputted into BRIDGframe bridge analysis software to determine the shear force and bending moment on the bridge with each vehicle.

Vehicles

Vehicles were chosen for analysis because of their popularity, in the case of the Cat 740 articulated truck and the Madill 144 swing yarder, or because they are used as the design vehicle configuration during the design of a bridge, in the case of the L165 and the L100. The Cat 740 articulated truck is frequently used during the construction of forest roads for hauling rock ballast and surfacing materials. Large tires and an articulated frame allow this truck to move safely on sub grade without becoming stuck and to navigate tight corners and steep grades with payloads of up to 39.5 tonnes.

Powered by Caterpillar's C15 ACERT engine, which has a gross power rating of 350Kw, the Cat 740 has a loaded weight of 72600kg and a total wheelbase of 6.39m (Caterpillar, 2009). Refer to Figure 1 for load distribution and dimensions. The Madill 144 swing yarder has an unloaded weight of 89 358kg, and an approximate loaded weight, with fuel and lines of 90 718kg. This large swing yarder is used on the BC coast and is typically transported from block to block on a trailer. A type 047 crawler base, equipped with 4.64m tracks provides mobility to this large machine (S. Madill Ltd., 1988). Refer to Figure 2 for dimensions and load distribution.

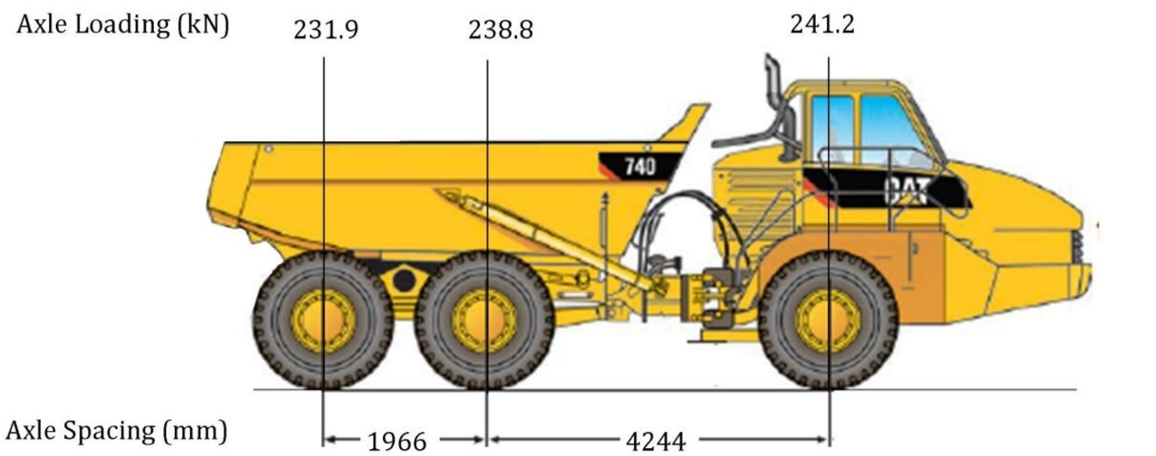

Figure 1: Axle Loading for Cat 740 Gravel Truck

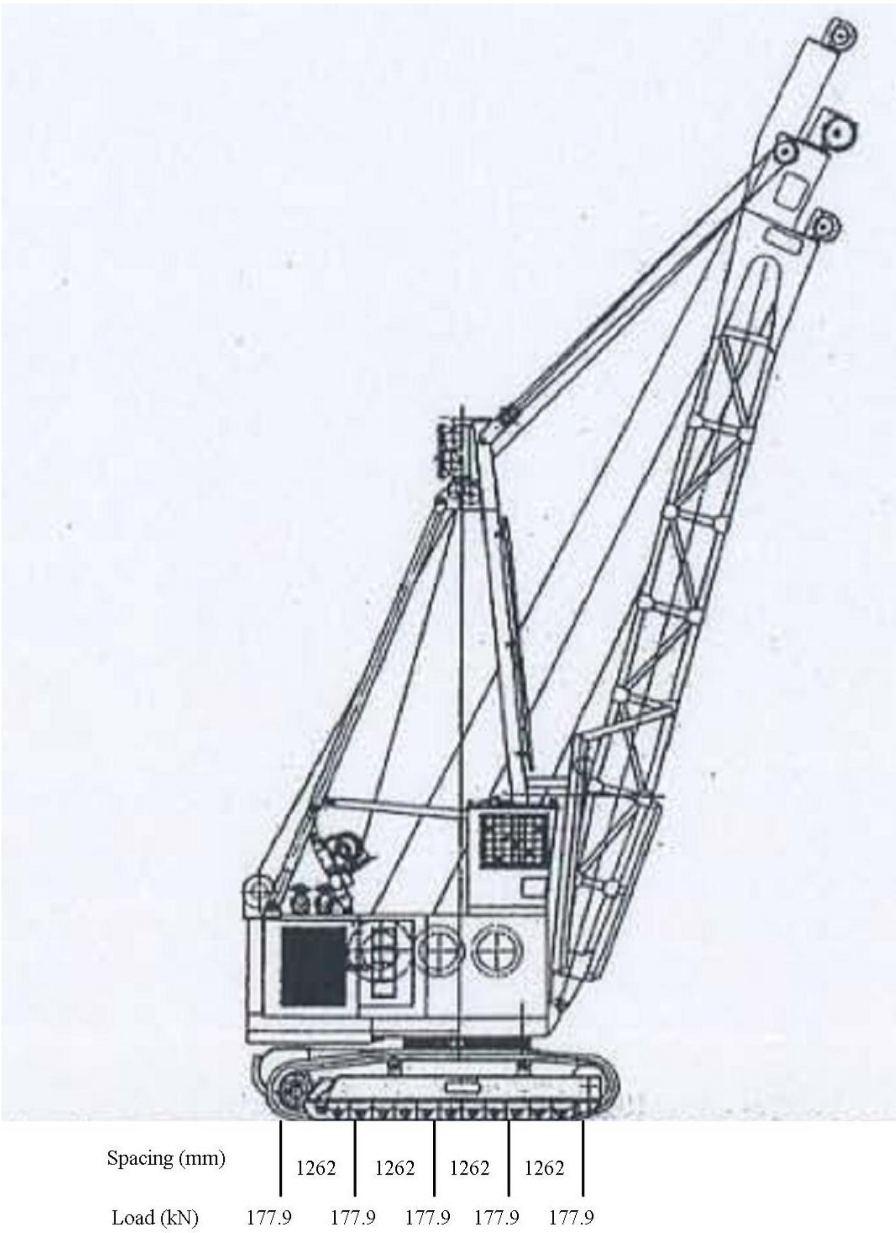

Figure 2: Load Distribution of Madill 144 Swing Yarder

The BC L165 is a design vehicle configuration used by the British Columbia Forest Service in setting standards for bridge construction and design. It represents the largest off-highway design configuration, such as a Pacific P-16, or other similar designs. The wheelbase of this vehicle is 14.79m and the GVW is 149 700kg (BC Forest Service Resource Tenures and Engineering Branch, 1999). Refer to Figure 3 for dimensions and load distribution. The BC L100 is also a design vehicle configuration used by the British Columbia Forest Service. It represents a lighter off-highway design configuration. The wheelbase of this vehicle is longer, at 15.25m but the L100 is narrower than the L165 and has a GVW of 90 680kg (BC Forest Service Resource Tenures and Engineering Branch, 1999). Refer to Figure 4 for dimensions and load distributions.

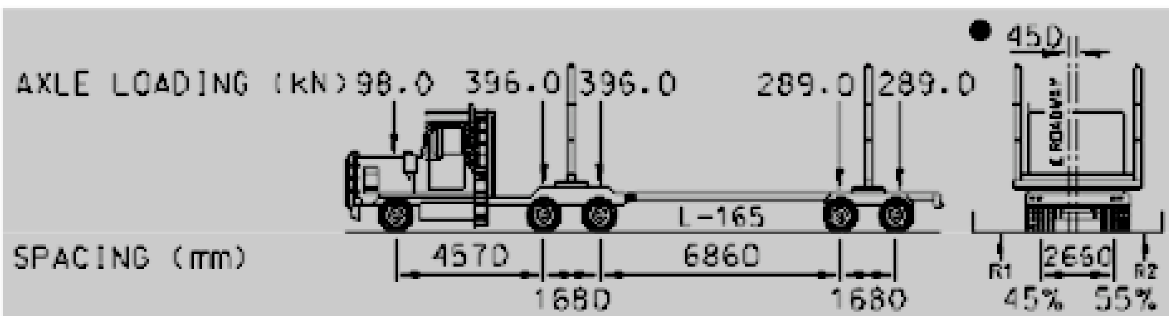

Figure 3: Axle Loading for L-165 Log Truck

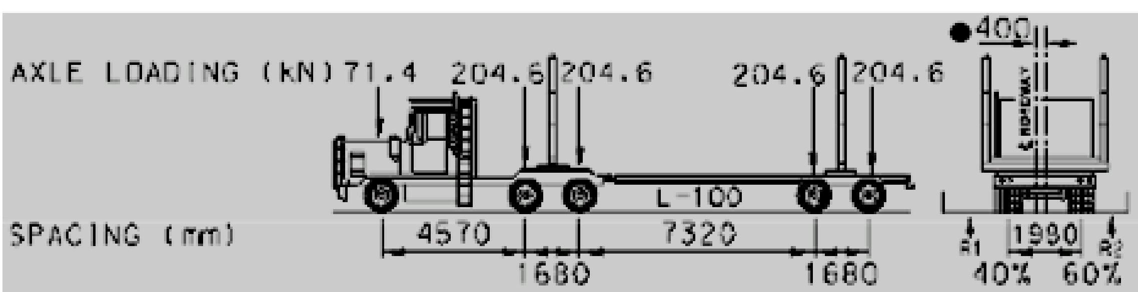

Figure 4: Axle Loading for L-100 Log Truck

Summary of Vehicles

The length of a vehicle relative to the length of the bridge determines what portion of the weight of the vehicle is supported by the bridge. On the 20m bridge, the full weight of all the vehicles is supported by the bridge, and not the ground. The BCL100 is 25cm longer than the 15m bridge, so only a very small portion of the load is supported by the ground on this bridge. The BCl165 is 21cm shorter than the 15m bridge, so the entire load is supported by the bridge. Both the Cat740 and the Madill 144 have a wheelbase length less than 10m, so the full weight of both vehicles is supported by the bridge for all lengths analyzed (Figure 6).

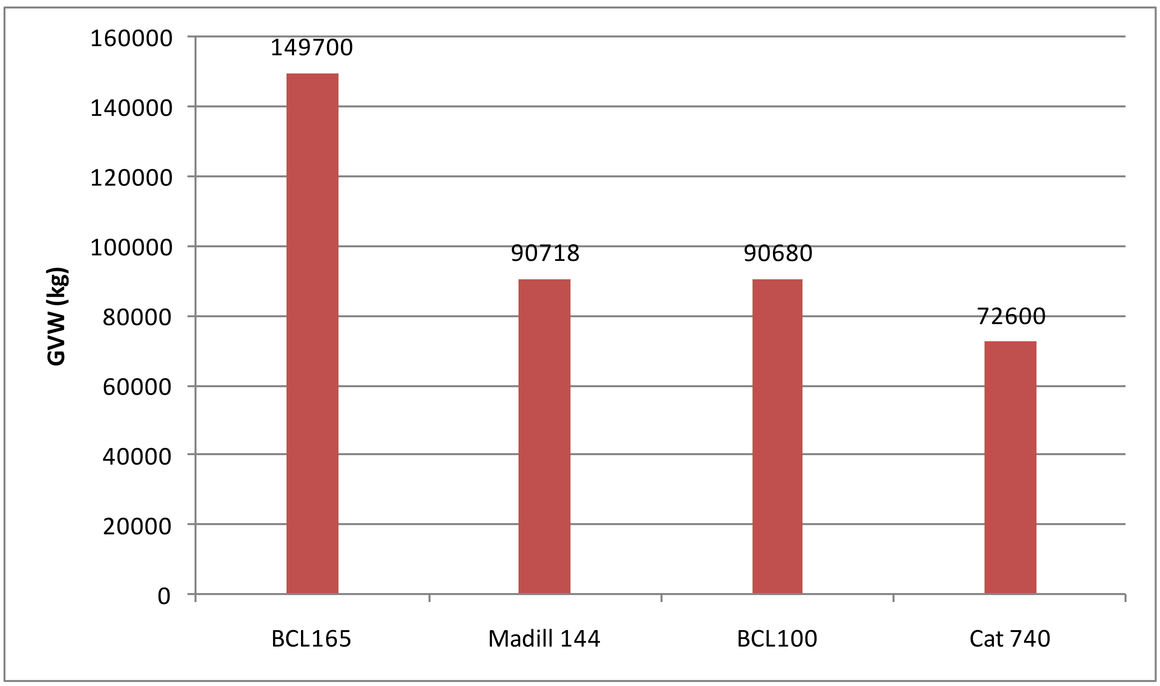

Figure 5: Comparison of GVW

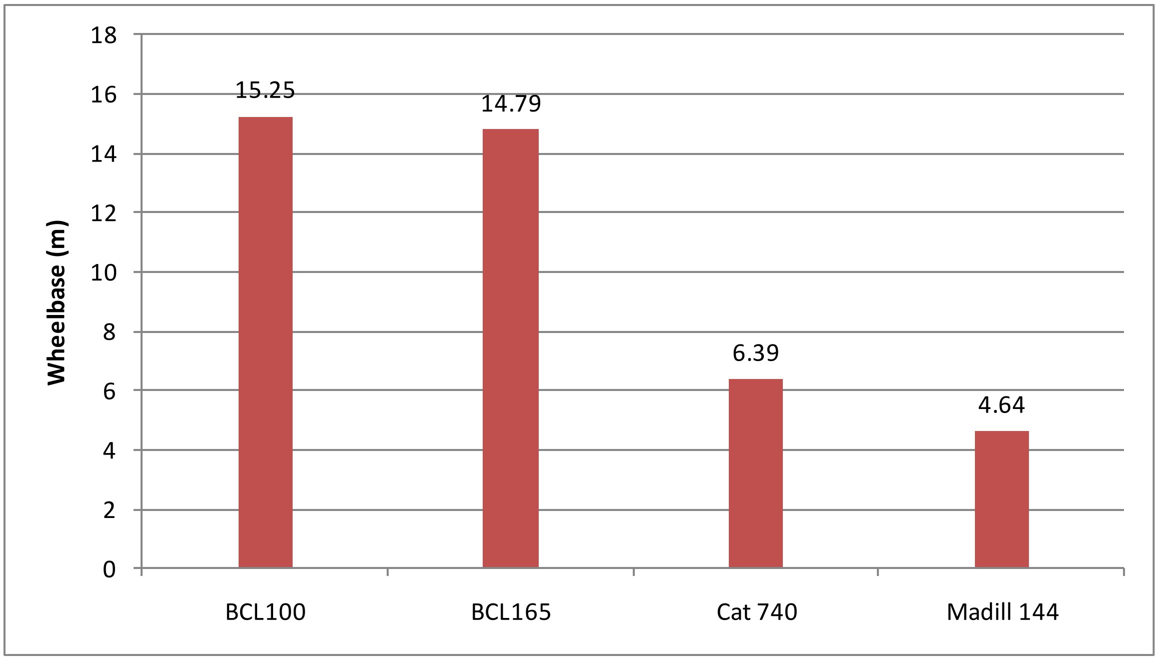

Figure 6: Comparison of Wheelbase Length

METHODS

All experiments were performed using the BRIDGframe program V5.0.2.3 running on Windows XP. BRIDGframe is a 2D bridge analysis software program designed by Simplified Bridge Solutions Inc., an Ontario based company founded by Vic Segula, C.E.T. and Jim Cantrell, P.ENG in 2006. Created to fill a gap in the market for engineers looking for a simple, yet effective program to design small and medium sized bridges, BRIDGframe uses a VBA input and an excel output. All parameters are entered into a tabbed window, and the program produces tables of results in excel. BRIDGframe provides bridge analysis that conforms to the Canadian Bridge Design Code CAN/CSA-S6-06.

The parameters for the example bridge design were maintained, except for the length and the vehicle loading. The sample bridge has a superstructure of type A, which represents steel beam or box systems with composite steel decks (Simplified Bridge Solutions Ltd., 2011). The bridge type, in accordance with CHBDC 5.5 specifications is type C, which represents concrete Deck-on-Girders. One design lane was used for the sample bridge, as most bridges on resource roads are only one lane. More detailed information concerning the sample bridge specifications can be found in Table 1.

Table 1: Sample Bridge Parameters

Girder Depth (cm)	59.8
Girder Area (cm^2)	115
Girder Moment of Inertia (cm^4)	65700
NA to Girder Bottom (cm)	29.9
Deck Modulus of Elasticity(E) (MPa)	200000
Transformed Superstructure 'E' (MPa)	200000
Composite Moment of Inertia (cm^4)	2033161.1
Area of all Girders (cm^2)	460
Non-transformed Area of Deck (cm^2)	23850
Transformed Superstructure Area (cm^2)	24310
Depth of Deck (cm)	22.5
Depth of Superstructure (cm)	82.3
Width of Deck as per A5.1.4 (cm)	1060
NA to Bottom of Comp. Girder (cm)	70.27
NA to Top of Comp. Girder (cm)	-10.47

Determining the axle loads to input into the program was the first step of analysis. The design vehicle configurations (L100 and L165) have specified axle loads and the Caterpillar specification brochures provide axle loads of the loaded Cat 740. BRIDGframe does not support distributed loads analysis, so the total operating weight of the Madill 144 was divided into 5 equal loads spaced evenly along the length of the tracks for analysis.

Analysis of truck loads can be done in two ways; either by advancing the vehicle across the bridge incrementally or using a fixed location. In order to determine the maximum bending moments and shear forces, analysis was done using advancement with an increment of 0.25m. Axle loads and axle spacing were entered for each vehicle with a dynamic load allowance of 1.3. Ten, fifteen and twenty metre bridge lengths were analyzed, and the results were reported in 0.25m increments. The BRIDGframe outputs used for this essay were: maximum positive bending moments and maximum positive shear forces for the superstructure. BRIDGframe provides the maximum force or moment at each analysis increment, the corresponding momentum or force at that point and the position of axle 1 where the maximum occurred.

RESULTS

Maximum bending moment and maximum shear force were plotted over 3 bridge lengths for the 4 test vehicles. The results are shown in Figure 7 and Figure 8.

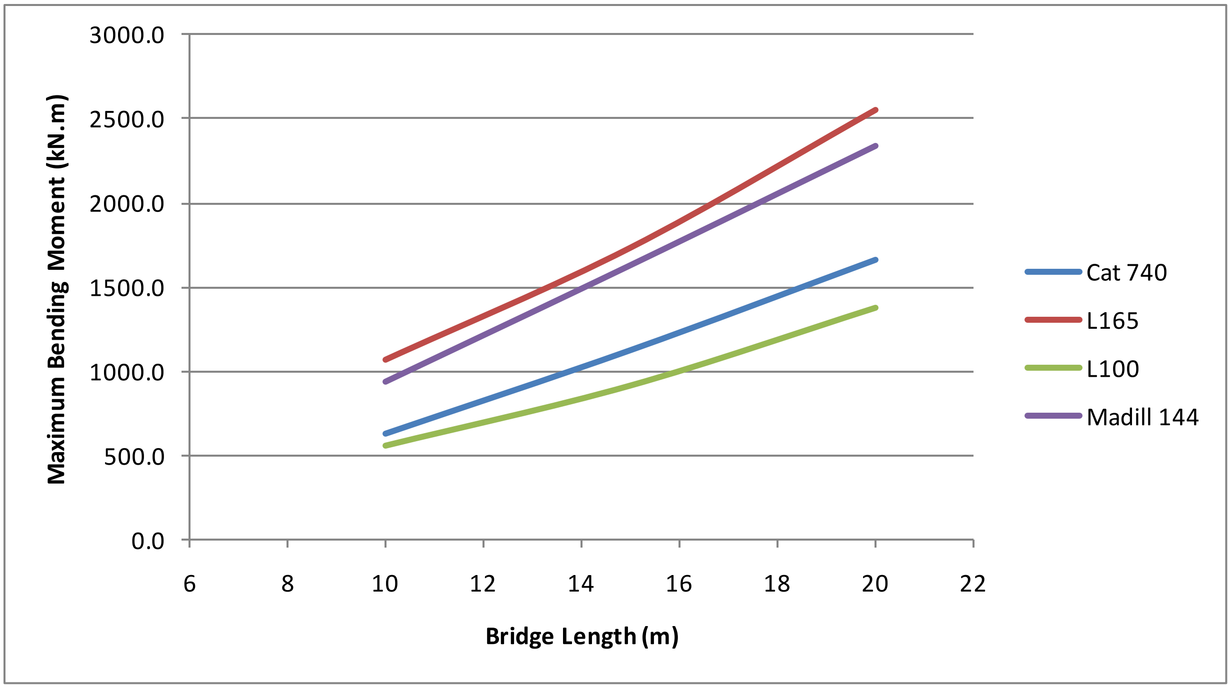

Figure 7: Maximum Bending Moment over 10, 15 and 20m Bridge Lengths for 4 Test Vehicles

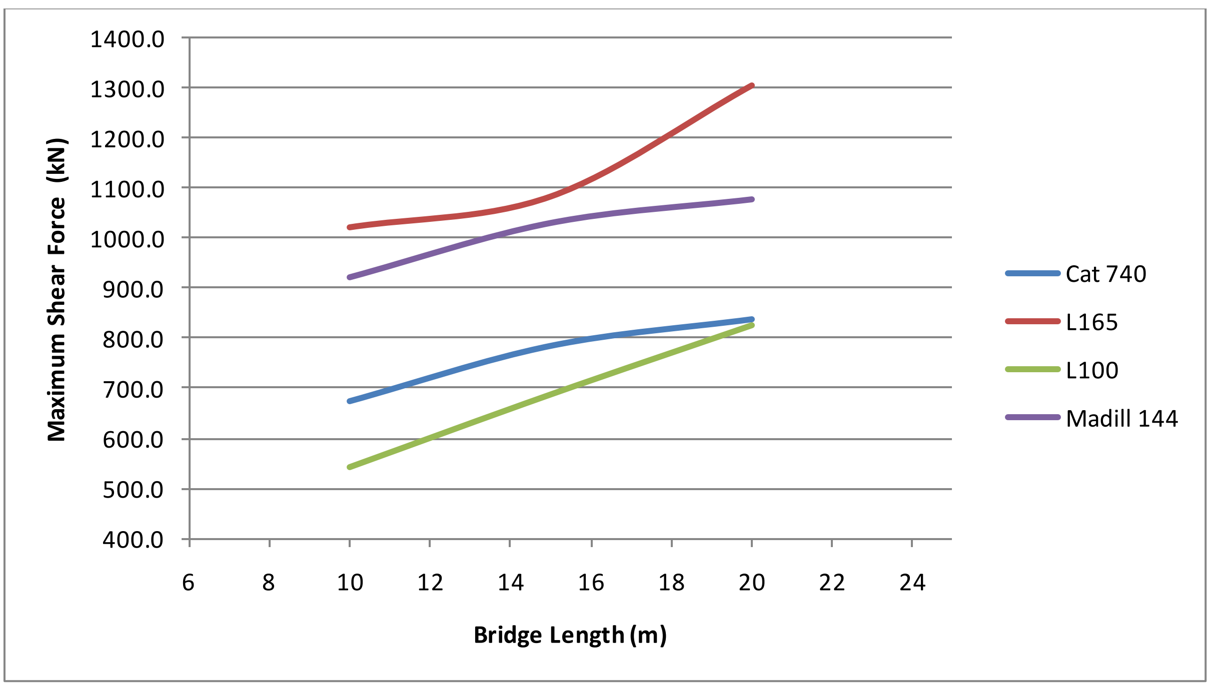

Figure 8: Maximum Shear Force over 10, 15 and 20m Bridge Lengths for 4 Test Vehicles

The Maximum bending moment produced by the L165 is highest, followed by the Madill 144, the Cat 740 and finally the L100. Maximum bending moment increases more or less linearly with increasing bridge length for all 4 vehicles, with a slope of approximately 148kN.m/m for the BC L165, 139 kN.m/m for the Madill 144, 102 kN.m/m for the Cat 740 and 82 kN.m/m for the BC L100.

The maximum shear force shows a different pattern than maximum bending moment. The Cat 740 and Madill 144 show the same pattern of increasing maximum shear force with increasing bridge length, with the curve leveling off as bridge length increases. The L100 shows a linear increase, while the BC L165 shows an irregular pattern, increasing sharply between the 15 and 20 m bridge lengths.

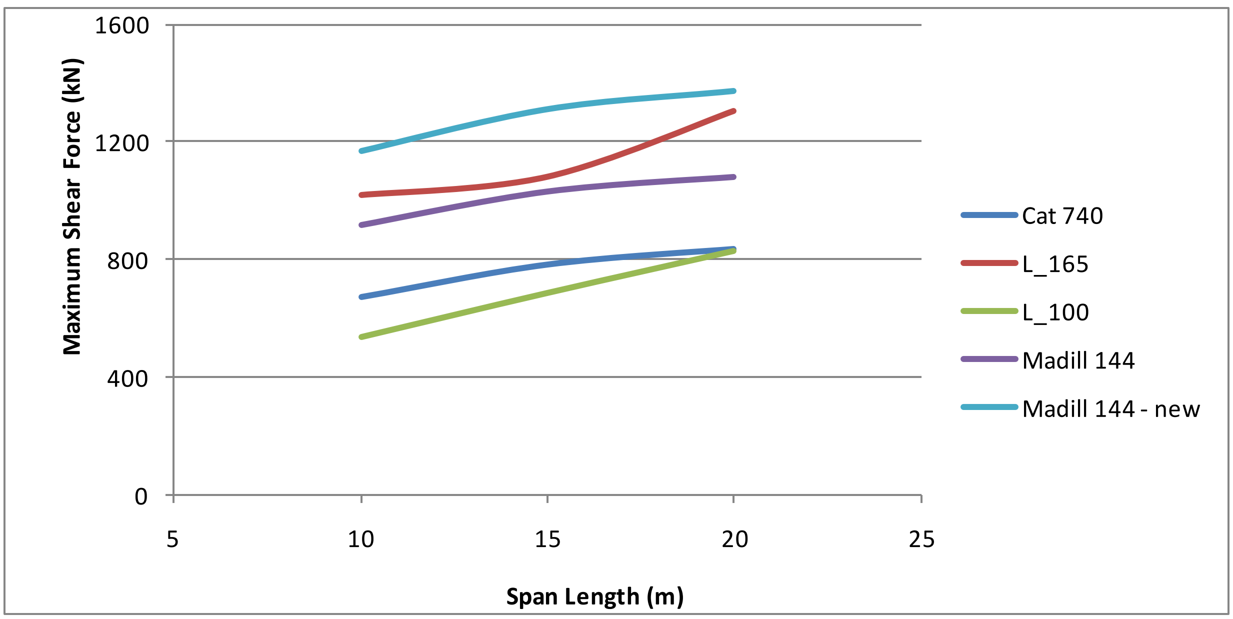

Figure 9: Maximum Shear Force over 10, 15 and 20m Bridge Lengths for 5 Test Vehicles

An engineering bulletin titled "Clarification of GVW as Applicable to Bridge Load Rating" was released in September 2009 by the British Columbia Ministry of Forests and Range. This bulletin shows the results of a similar experiment. The bending force effects of a Madill 144 were compared to the L165, over different shear bridge lengths. In their calculations, the GVW used for the Madill 144 was 115 260kg, 25 000kg more than the GVW used in my calculations. A second, more conservative run of the Madill 144 was done to determine the importance of the weight of the yarder.

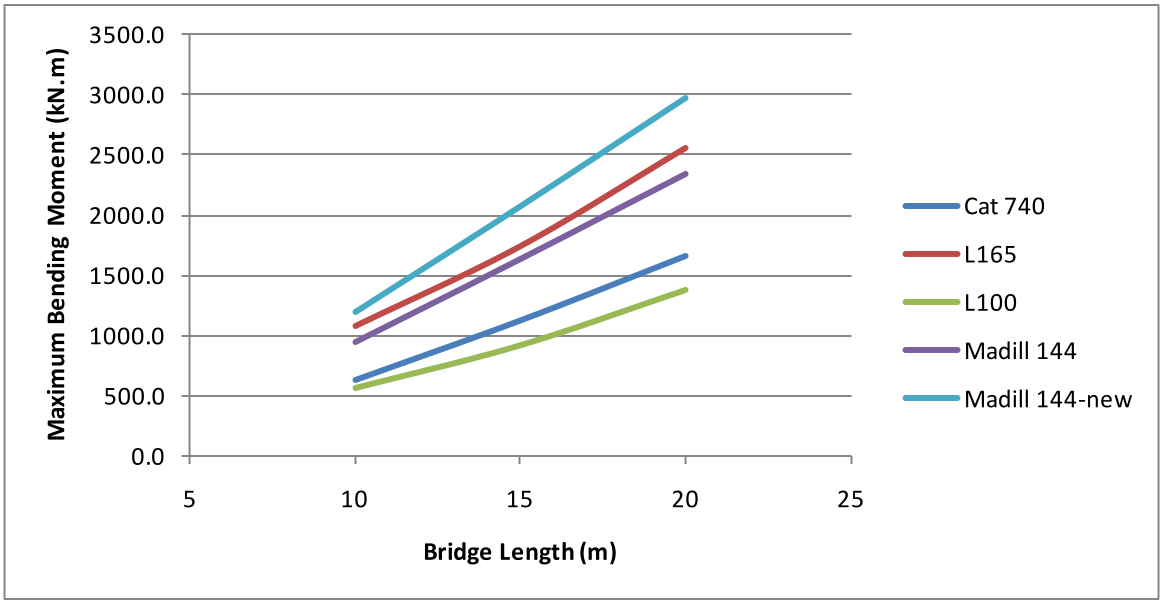

Figure 6: Maximum Bending Moment over 10, 15 and 20m Bridge Lengths for 5 Test Vehicles

As can be seen in Figure 9, an increase of 25000kg in GVW has a notable impact on the maximum shear force produced by the Madill 144. When using the GVW used by the Ministry of Forests, the maximum shear force generated by the new Madill 144 is greater than that of the L165 for all bridge lengths studied. The difference is smallest on the 20m bridge and largest on the 15m bridge. Figure 10 shows a corresponding increase in maximum bending moment, with a slope of 177 kN.m/m.

Discussion

The Madill 144 likely exerts a higher maximum bending moment and maximum shear force on the bridge than the L100 because of the length of the vehicle and the distribution of the load. Both vehicles have a GVW of approximately 90 000kg, but the Madill 144 has a track length of 4.64m, while the wheelbase of the L100 is 15.25m. This shorter wheelbase results in the load of the yarder being concentrated on a smaller portion of the bridge. On a bridge shorter than 15m, the full weight of the L100 will not be supported by the bridge, while the full weight of the Madill 144 will be supported by the bridge.

Vehicle length likely affects the relationship between the L100 and the Cat 740. The Cat 740 produces a higher maximum bending moment and a higher maximum shear force than the L100 on 10m and 15m bridges, even though the L100 has a GVW that is 18 080kg higher. All of the wheels of the L100 are on the 20m bridge and the maximum bending moment produced by the Cat 740 is larger than the maximum bending moment produced by the L100. This is due to the concentration of the load over a smaller area.

On the 20m bridge, the maximum shear force exerted by the two vehicles is almost equal. The L100 has a higher GVW, but the load is distributed over 5 axles. As a result, the Cat 740 has higher individual axle weights than the L100. The reduced axle weights lower the maximum shear force that the L100 exerts on the bridge, despite its higher GVW, even though the entire vehicle is on the bridge. The force is distributed over a larger part of the bridge, and as a result, the maximum force effect is lower.

Maximum bending moment exerted by each vehicle increases with increasing span length. The L165 exerts the highest force because of its high GVW. The Madill 144 has a higher maximum bending moment than the other vehicles with similar GVWs due to the concentration of the load on the bridge due to its short tracks. As previously discussed, the Cat 740 produces a higher maximum bending moment than the L100 due to its short length and high axle loads. Maximum shear force also increases with increasing span length. The Cat 740 and Madill 144 show the same pattern of increase as span length increases. Both of these vehicles are shorter than the bridges and have concentrated loads. The L165 and L100 also share a similar pattern because of their identical dimensions and similar load distributions.

The slope of maximum bending moment to bridge length is higher for vehicles with high absolute maximum bending moment. The maximum bending moment increases at a higher rate with increasing bridge length for these vehicles. This is likely due to the fact that bending moment is magnified by longer bridge lengths. A bending moment that is already high will show a greater increase when the length of the bridge is increased because the rate of increase is proportional to the initial value.

Increasing the GVW of the Madill 144 by 25000kg, to 115260kg increases the maximum shear force extorted on the bridge to a level greater than the BC L165, which is approximately 34000kg heavier than the Madill 144. The length of the Madill 144 causes the load to be concentrated on a smaller part of the bridge, resulting in a higher shear force despite the lower GVW. This effect is most pronounced on shorter bridges and decreases with increasing bridge length. Increasing the GVW of the Madill 144 also has an impact on Maximum bending moment. Both the actual values and the rate of increase are higher for the heavier yarder.

The MOF report shows that the L165 produces a larger shear force than the Madill 144 on longer bridge lengths, without specifying actual numbers. Their report states that it is the effect of additional axles coming onto the bridge that causes the L165 to surpass the Madill 144. The results in Figure 9 do not show this, as all the axles of the L165 are on the 15m bridge. A different bridge was likely used for the MOF calculations, though they do not provide any information on the specifications of the bridge used in their calculations.

Significance of Results

Bridges built to L100 specifications could not be expected to support the weight of the Madill 144. The L100 has a GVW of 90600kg and the Madill 144 has a GVW between 90718kg and 115 260kg, depending on fuel and cable loads. Under the best circumstances, the Madill 144 has a GVW that is higher than the load limit of the bridge.

The Cat 740, however has a GVW of 72600kg, which is 80% of the GVW of the L100, and the load limit of a bridge designed using this load configuration. On all bridge lengths, the Cat 740 produces a maximum bending moment that is greater than the L100. Maximum shear force produced by the Cat 740 is greater than the L100 on the 10m and 15m bridges, and equal to the L100 on the 20m bridge . A bridge built to L100 specifications would be subject to bending moments and shear forces greater than the design load if a Cat 740 or other vehicle with similar weight distribution were to drive over it. The consequences of these forces depend on the actual bridge and its design and condition.

A bridge designed to L165 standards could safely support the Cat 740 as the maximum bending moments and shear forces are substantially lower than the maximums produced by the L165. A bridge built to L165 standards could not, however, safely support the weight of a Madill 144 yarder. The BC165 has a GVW that is 34440kg greater than the heaviest GVW for the Madill 144, yet due to the concentrated load produced by the relatively short tracks, the Madill 144 produces a higher maximum bending moment and higher maximum shear force. The worst case scenario for the Madill 144 of 115 260kg, which is only 77% of the GVW of the L165, produces maximum shear forces and bending moments that are well above those produced by the L165 on all bridge lengths. The best case scenario of 90718kg, which is 60% of the GVW of the L165, could generate higher loads if the weight distribution over the tracks is not even, as assumed. Sudden acceleration or deceleration could cause a shift in weight that would increase the maximum bending moment and shear force. Rocks or other abnormalities on the deck of the bridge could also concentrate the load of the yarder, resulting in a higher maximum bending moment and shear force.

Implications for Forest Professionals

Several examples of bridge failures have been noted by the Association of British Columbia Forest Professionals (ABCFP). One notable example is the Jovo Creek bridge collapse in 2007. A contractor was operating on TFL 25, and the purchase agreement required the contractor to provide a crossing assurance statement for a 9m log bridge built to BC L165 standards. The purchase agreement holder subcontracted the oversight of the bridge to a Registered Professional Forester (RPF). The RPF was the coordinating registered professional (CRP) overseeing the bridge but British Columbia Timber Sales (BCTS) assigned an engineering implementation contractor to the project. The engineer expressed concerns about the size of the stringers, which were not addressed before the RPF signed off on the bridge.

The bridge failed as a Madill 144 yarder was crossing it for the third time, after active log hauling on the bridge. No one was hurt, but the yarder dropped into the S5 stream 2m below, introducing shot rock into the fish stream. An investigation revealed that undersized stringers for the length and load limit of the bridge were used. This was determined to be the primary cause of the accident, but improper lashing patterns and the load distribution from the grapple yarder were determined to be contributing factors (Association of BC Forest Professionals, 2008).

In this case, the Professional Forester did not properly evaluate whether they were qualified for the task and did not seek the help of a qualified individual when it was necessary. A summary presentation of this incident by the Ministry of Forests suggests that at minimum, a Ministry of Forests Bridge engineer should be used to provide guidance, and that the design should be reviewed by Ministry Bridge Engineer before starting the project if a Ministry engineer cannot be used as the CRP for the structure (Johnson, 2010). Their recommendations cover bridges within BCTS jurisdiction only, and the presentation does not address the issue of non-Ministry engineers being used.

The engineering implementation contractor failed to adequately document their opinion that the stringers were undersized and did not appear to have acted on this information. The theory behind the Ministry recommendations of using Ministry of Forests Engineers is that the Ministry of Forests retains control over the oversight of these structures, and Ministry engineers are more likely to make their concerns more widely known. However, since the APEGBC is a professional association, this should not be an issue. It also leads to questions about the role of the engineering implementation contractor in this incident, and whether they fulfilled their professional obligations. No documentation on this subject could be found.

In addition to issues that occur during the construction and design stage, many problems occur with bridges during the maintenance stage. A 2001 report by the Forest Practices Code found that over half of the bridges audited in the two years prior to the report were not in compliance with the forest practices code. Three audits identified instances of non-compliance with bridge maintenance programs. 50% of the instances of non-compliance were due to a lack of signage, which poses a relatively low risk. However, 15% were due to a lack of repair and 4% were due load limits (Forest Practices Code, 2001).

Under Forest Practices Code Forest Road Regulations, which are now outdated, signs showing the actual capacity of the bridge should be implemented if a professional engineer determines that the bridge is unable to safely support its design load. There are potentially bridges that are unable to safely handle their design load without proper signage, creating a potentially unsafe condition, which is magnified by vehicles with load configurations that exert more force and a higher bending moment that the design load.

Recommendations

The results from this experiment should be used for illustrative purposes only. The bridge used for analysis does not represent any actual structure and may not be representative of structures used on resource roads. The implications of maximum shear force and maximum bending moment observed have not been considered, therefore the suggestion is not that the bridge will break if a different vehicle configuration is used, just that it is experiencing more stress. The load distribution calculated for the

Madill 144 grapple yarder is an approximation and due to the limitations of the program, was not considered as a distributed load, but rather as a series of point loads. The width of the vehicles and the positions of the stringers were also not considered. This being said, conclusions about the safe passage of machinery over resource road bridges can made.

When a bridge is used in, or between settings where a large grapple yarder is used, designing the bridge using a standard log truck design configurations is not adequate. The load distribution of the grapple yarder results in higher maximum shear force and maximum bending moments than the standard log truck design configuration. When combined with other compounding factors, such as improper construction methods, a lack of repair, or a reduction in load limit that is not clearly identified, this effect can have serious consequences, as illustrated in the Jovo bridge collapse. A bridge that is to be used for large grapple yarders should be designed by a professional engineer for that purpose.

Secondly, when moving equipment that is substantially different from a standard log truck design configuration, such as a tracked machine over a bridge, caution must be used, especially if the vehicle has a GVW that is more than 60% of the load limit of the bridge. A critical eye must be used to ensure the safety of the crossing, considering the GVW of the vehicle, and how the load distribution differs from the design vehicle configuration. The number of axles, the overall wheelbase of the vehicle compared to the length of the bridge, the GVW and the approximate center of gravity should be considered. If there is any doubt that the vehicle can pass safely over the bridge, a professional engineer should be consulted or a lowbed should be used to distribute the load over more axles and a larger portion of the bridge. Bridges which are frequently used for transporting vehicles other than log trucks should be assessed by a professional engineer to determine which vehicles can safely pass over the bridge. Clear signage should be installed and operators should be made aware of the restrictions.

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