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|  | **10th International Conference on Short and Medium Span Bridges**  **Quebec City, Quebec, Canada,**  **July 31 – August 3, 2018** |  |

**THE IMPACT OF THE EVOLUTION OF SIMPLIFIED METHODS OF ANALYSIS IN CANADIAN HIGHWAY BRIDGE DESIGN CODES ON THE EVALUATION OF TIMBER BRIDGES**

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**Abstract:** The design of bridge structures in Canada is currently undertaken according to the Canadian Standards Association S6-14 Canadian Highway Bridge Design Code. Historically, previous versions of this code have been used to design bridge structures along with provincial codes such as the Ontario Highway Bridge Design Code. The vast majority of bridge designs and evaluations undertaken using these codes employ a Simplified Method of Analysis (SMA). The evolving nature of design codes, including the SMA, has largely been governed by the analysis of larger bridges as opposed to the relatively short timber stringer bridges. The scope of the research reported in this paper was to develop a summary of the timber bridge inventory in Nova Scotia and investigate how the SMA has evolved over the course of the past 40 years with a specific focus on its applications to timber stringer bridges in that inventory. This work is part of a larger project, supported by Nova Scotia Transportation and Infrastructure Renewal to better understand the behavior of timber stringer bridges and develop a process for assessment of its existing inventory to better inform maintenance and rehabilitation decisions. Based on this research a categorization of the timber bridge inventory in Nova Scotia was completed and analyzed using the SMA from various codes. The results of this analysis suggest that there has been a major shift in how timber stringer bridges are considered between the modern bridge design codes.

1. **INTRODUCTION**

Over the course of the 20th century tremendous scientific strides were made which led to many technological advancements in infrastructure. As the decades continued, the availability of new construction methods and materials resulted in major shifts in the landscape of infrastructure in Canada. Broadly speaking, the prominence of timber and masonry as building materials was superseded by steel and concrete. The evolving nature of construction methods have been driven by new developments in construction technologies. As design methods change, so to do the design codes used to guide the design and evaluative methods. Bridge design codes have been increasingly driven by advancements in steel girder designs and concrete/prestressed concrete design. Timber stringer bridge construction is no longer as common as it once was however there are still a significant number of in-service timber structures in several provinces that require accurate evaluation and adequate maintenance.

Timber stringer bridges make up a significant part of the bridge inventory in Nova Scotia. Approximately 1500 timber stringer bridges are currently in service across Nova Scotia, mostly located on local and collector roads. To perform the required rehabilitation on any structure it is important to have a means of accurately evaluating the behaviour of the structure. When designing or evaluating most bridge structures, the initial analysis is undertaken using the Simplified Method of Analysis for Longitudinal Load Effects (SMA) as described in CSA S6-14 cl. 5.6. The SMA provides a method of describing the live load sharing behaviour of bridge structures provided that the structures meet a set of guidelines as described within the clause. Bridges are broken in to several categories by the SMA: slab bridges, voided slab bridges, slab-on-girder bridges, multi-spine box girder bridges and shear connected box girder bridges. Timber stringer bridges fall under the purview of slab-on-girder bridges, specifically cl. 5.6.7.5 and its accompanying tables.

This paper will explore the inventory of timber stringer bridges in Nova Scotia to better understand the nature of these bridges. The characteristic variables of the bridges will be broken down and studied. By characterising the structural elements, a representative bridge structure can be established and a series of parameters can be identified to describe the representative structure. In doing this the distribution of timber stringer bridges can be established and any discrepancies within can be identified.

Simplified methods of analysis have been present in Canadian bridge design codes for many decades in various forms. The modern SMA described in CSA S6-14 is the result of the evolution of previous Canadian bridge codes, namely previous versions of CSA S6 as well as the Ontario Highway Bridge Design Code. This paper will examine how both bridge codes have evolved and influenced each other since 1983 and as a result how the SMA used to analysis timber stringer bridges has changed. Six different Canadian bridge codes from this time period will be used in the analysis. Nova Scotia uses a computer database to catalogue its bridge inventory. The bridge database includes all the information required to conduct the SMA, provided the bridges have been fully catalogued. Using this database, the SMA from each of the six codes under consideration was run on each of the timber stringer bridges in the database. Based on this analysis, this paper will explore how the evolving nature of the SMA has affected how timber stringer bridges are designed and evaluated.

1. **TIMBER BRIDGE INVENTORY CHARACTERIZATION**

The current Nova Scotia Transportation Infrastructure Renewal database of timber bridges provides information on roughly 70 different criteria ranging from structural information to administrative qualities. Of these many criteria, six key parameters where established to best capture the structural state of the bridge inventory: year of construction, clear span length, stringer count, stringer spacing-on-centre, number of spans and the results of maintenance inspections. The database characterization began in mid-2016 and reflects the state of the database as of that time.

Figure 1: Decade of Construction of Timber Bridge Structures in Nova Scotia

Understanding the age of construction of the timber stringer bridge inventory is critical to discussions of infrastructure maintenance. As Canadian infrastructure ages the question of whether structures should be repaired, replaced or left as is becomes more and more salient. Accurate information on the age of the timber stringer bridges was available for roughly a third of the bridges listed in the database. Through discussions with representatives from Nova Scotia Transportation and Infrastructure Renewal, the bridges with no information available on their age are likely older structures. The age of original construction was mostly taken from original design drawings or as-built drawings and older bridges are more likely to have had their drawings misplaced. The database does not reflect any rehabilitation activities that may have occurred. As a result, the histogram shown in Figure 1 would likely skew further to the left if it reflected all bridges in the database. The newest timber stringer bridge was constructed in 2014 while the oldest structures date back the beginning of the 20th century. The majority of the structures were constructed between the 1950s and 1980s with 44% of the structures having been built in this era. Assuming that a design life of 50 years was used prior to the CSA S6 2000 version, roughly 50% of the structures in the database have exceed their design life.

Figure 2: Clear Span Length (in Meters) of Timber Bridge Structures in Nova Scotia

The clear span length of a bridge is critical to the SMA approaches used in CSA S6-14. In short, the longer the clear span, the larger the design moment that a stringer must be designed to resist. Figure 2 shows the distribution of clear span across the 92% of the structures in the database that have accurate information on their length. Three bridges listed in the database seem anomalous for sawn timber stringer bridges with clear span lengths of 30.5 m, 44.45 m and 105 m. The average clear span length of structures in the timber stringer database is 7.2 m placing them in the realm of short to medium span bridges.

Figure 3: Stringer Count of Timber Bridge Structures in Nova Scotia

Stringer count is an important parameter to consider especially as it relates to differentiating timber stringer bridges from other slab-on-girder type bridges. The median stringer count is 14 for two lanes of traffic which is at least double the number of girders that would normally be used in prestressed concrete girder bridges and composite steel girder bridges. There is also a wide distribution in the number of stringers within timber stringer bridge designs as shown in Figure 3.

Figure 4: Stringer Spacing of Timber Bridge Structures in Nova Scotia

Similar to stringer count, the stringer spacing is a design parameter that is drastically different for timber stringer bridges then it is for other slab-on-girder bridges. The average stringer spacing is approximately 550 mm. Stringer spacing in the database is defined as the spacing between the centers of adjacent stringers. Database entries may contain errors. Consider stringer spacing values or 50 mm or less; it is physically impossible that the center-on-center spacing between two adjacent stringers be less than the width of the stringer. In analyzing Figure 4 it can be seen that there is a sharp increase between bridges having a stringer spacing of 300 to 349 mm and bridges having a stringer spacing between 350 to 399 mm. While it is possible that some of these values may represent situations were construction or rehabilitation required stringers adjacent to each other, it was difficult to confirm from the database alone. Therefore, when conducting the SMA on the database bridges with a stringer spacing below the 350 mm threshold were ignored.

Figure 5: Multispan Timber Bridge Structures in Nova Scotia

Figure 5 shows that an overwhelmingly vast majority, 88%, of the timber stringer bridges in the database are single span, simply supported structures. Given that timber stringer bridges typically have a span less than 10 m and are found on local or collector roads, as previously discussed, then it follows that the majority of them would be single span structures. Two and three span structures make up 9% of the inventory in the database while bridges with upwards of three spans make up only 3% of the database.

Figure 6: Level 2 Rating of Timber Bridge Structures in Nova Scotia

Nova Scotia Transportation and Infrastructure Renewal conducts inspections of their timber bridges at three level: Level 1 inspections are general visual inspections carried out on an annual basis by trained field technicians. Level 2 inspections are conducted every five years by a regional bridge engineer and are broken down in to a number of different criteria, including structural criteria. Level 3 inspections are conducted when a specific issue has been noted about a structure and are conducted as needed. The criteria for the level 2 inspections are as described by the U.S. Department of Transportation Federal Highway Administration National Bridge Inventory guidelines whereby 1 to 4 is a bridge in poor condition, 5 to 6 is a bridge in fair condition and 7 to 9 is a bridge in good condition. Based on the level 2 inspection results of the database 83% of timber stringer bridges in Nova Scotia are in fair or good condition and so should be comparable to their original designs as shown in Figure 6.

Based on the analysis of the timber stringer bridge database, a representative structure can be delineated. A potential representative timber stringer bridge would be a single span, two lane structure, approximately 50 years old, with a length of 7.5 m to 9 m, having 14 to 16 stringers and stringer spacings ranging from 500 mm to 600 mm. Using these descriptive parameters it is possible to choose bridges from the database that best represent the entire database making them the best candidates for future modelling and case study.

1. **EVALUATION OF THE EVOLUTION OF CANADIAN BRIDGE CODES**

With a better understanding of the timber stringer bridge database in Nova Scotia it was possible to begin analysing the evolution of Canadian bridge codes. The six bridge codes considered within this study are as follows: CSA S6-88, CSA S6-00, CSA S6-06, CSA S6-14, OHBDC 83 and OHBDC 91. When preforming the SMA of these codes on the bridge database, no significant differences were found between the S6-00 and S6-06 codes and the OHBDC 83 and OHBDC 91 and so these codes were considered together. The SMA used by each of the codes vary however they all follow a similar trend. The method used by the SMA is to calculate the total load on the bridge caused by a design truck and distribute this load out to the individual stringers using a load distribution factor (LDF), which is influenced by configuration and geometry of the bridge, its stringer and deck components. Additional factors that influence the LDF are the design truck, lane loading, multilane loading effects, number of design lanes, dynamic load allowances, limit states and resistance factors. Of the initial database, 1158 structures had accurate information that allowed them to be fully analysed by the SMA and of these structures 413 were deemed applicable for analysis using the SMA guidelines of all codes. To unify the various SMA into one cohesive form, their output has been formatted such that:

[1]

Where Ms is the design moment of a stringer; fs is the load distribution factor; and MT is the total design moment applied to the bridge by one design truck.

For each version of the code, the respective values of Ms and Mt were determined using all relevant code parameters, the value of Fs was then determined from equation1. It is assumed that all decks are the same type, wood plank decks. There were no major differences noted by directly comparing the parameters that individually influence the SMA of the various codes. Significant differences were noted when comparing the LDF as analyzed across the six codes considered. The older CSA and OHBDC codes produced average LDF of 0.196 and 0.401 respectively. When the two older codes were combined in to CSA S6-00 the average LDF becomes 0.187 for one lane bridges and 0.209 for two lane bridges. The most recent iteration of CSA S6 produced an average LDF of 0.280 for one lane bridges and 0.261 for two lane bridges. There was a major restructuring of the SMA between CSA S6-06 and CSA S6-14 that resulted in a 50% average increase in the bending moment that a stringer must be designed for on one lane bridges and a 25% average increase for two lane bridges. To better understand this phenomenon, the calculated LDF from each code was compared against the factors that influence the LDF calculations. The comparisons from CSA S6-14 will be shown however the trend was similar across all codes.

Figure 7: LDF vs. Clear Span (m) CSA S6-14

Figure 8: LDF vs. Overall Bridge Width (m) CSA S6-14

When comparing the calculated LDF to stringer lengths and to the overall bridge width, there are no direct correlations as shown in Figure 7 and Figure 8. For each figure, the lower limit present is caused by the limited applicability of the SMA to structures with small stringer spacings.

Figure 9: LDF vs. Stringer Spacing on Center (mm) CSA S6-14

Figure 10: LDF vs. Stringer Count CSA S6-14

Figure 9 and Figure 10 show the variation in LDF versus stringer spacing and stringer count respectively. The LDF values are linearly correlated to the center-on-center stringer spacing. As the stringers become further apart, the bridge deck becomes less capable of laterally distributing the applied loads between the stringers. The correlation between the LDF and stringer count is more incidental as there is a correlation between stringer count and stringer spacing; as the number of stringers on a bridge increase, the spacing between them generally decreases. This finding is especially significant given that, as previously discussed, one of the key difference between timber stringer bridges and steel and concrete slab-on-girder bridges is the number of longitudinal bending members.

1. **SUMMARY AND CONCLUSION**

This research set out to better understand the recent evolution of the simplified design methods in Canadian bridge design codes particularly in reference to timber stringer bridges commonly used in Nova Scotia. Through studying the timber bridge inventory in Nova Scotia this paper sought to better categorize timber stringer bridges and determine the variability in structural parameters. Beyond this, six recent Canadian bridge codes were studied by examining the design parameters used in the SMA and tracking their changes through the codes. Of the many parameters considered, the LDF was found to differ significantly between codes and so the LDF was studied in further detail.

The conclusions of this study to date are as follows:

* The majority of the timber stringer bridge infrastructure in Nova Scotia is rapidly approaching the end of it its design life or has surpassed its design life;
* Timber stringer bridges in Nova Scotia can broadly be defined as short, single span structures with roughly 15 simply supported stringers which rarely exceed 10 m;
* The overall approach of the SMA in bridge design codes has changed three times since the early 1980s resulting in changes to the LDF as calculated across codes;
* Changes made to the SMA between 1980 to 2010 resulted in a gradual reduction of the LDF as applied to timber stringer bridges;
* Across all codes the greatest correlation to LDF has been the stringer spacing; and
* Changes made to the SMA in the most recent version of CSA S6 resulted in an approximate 25% to 50% increase to the LDF as calculated across the timber stringer inventory in Nova Scotia.

The work reported in the paper is directing further experimental and analytical work to establish the values of LDF that should be used in evaluation of the Nova Scotia bridges in the inventory. It is important to note that while much of the infrastructure is reaching or exceeding its design life, the useful service life may be much longer.

**ACKNOWLEDGEMENTS**

The Authors would like to thank Nova Scotia Transportation and Infrastructure Renewal for their funding and collaboration in conducting this research.

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