Building Tomorrow's Society

Bâtir la Société de Demain

Fredericton, Canada

June 13 – June 16, 2018 / *13 Juin – 16 Juin, 2018*

EFFECTS OF THERMAL LOADING ON A COMPOSITE ALUMINIUM DECK – ON-STEEL GIRDER BRIDGE SYSTEM

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Abstract: This article discusses the use of an extruded aluminium multi-cell section as an alternate decking solution to the traditional concrete slab-on-steel girder system in highway bridge application. It is proposed to connect the aluminium deck panel to steel girders using ASTM F3125 / F3125M-15A galvanized steel M20 diameter bolts, grade A325, in a slip-critical connection. The goal is to develop a total composite action between the deck and the girders for an enhanced flexural capacity of the composite beam. However, considering that the thermal expansion coefficient of aluminium is twice that of steel, differential movements between the aluminium deck and steel girders are possible due to temperature variations. This study uses the finite element method to examine the behaviour of the aluminium deck-steel girder assembly under the combination of thermal and mechanical loads at the serviceability limit state (SLS), as well as at the ultimate limit state (ULS). These loads are determined from specifications of the Canadian Highway Bridge Design Code (CAN / CSA S6-14). The results show that it is possible to develop full composite action between the aluminium deck panels and the supporting steel girders. The study also prescribes a recommendation to prevent slippage under thermal loads and to ensure that no slip takes place under service conditions.

1 INTRODUCTION

Aluminium's superior strength-to-weight ratio and durability properties, such as its resistance to atmospheric corrosion, compared with the traditional construction materials mean that a bridge solution using this material could offer tremendous potential for building new modern vehicular bridges and for rehabilitating old existing slab-on-girder bridges for an extended service life, increased traffic load capacity and rapidity of construction. Moreover, the material's extrudability properties provide designers with the flexibility to optimise the rigidity of sections to control deformations and vibrations under service conditions.

In new slab-on-girder bridge construction, the development of composite action between the deck and the supporting girders is preferred as the flexural resistance of the composite beam is optimised. Similarly, in the rehabilitation of an old existing slab-on-steel girder bridge involving the replacement of the concrete slab, composite action between the new deck and the steel girders must be maintained. If an aluminium deck is selected as the replacement deck, a composite connection must be developed between the aluminium deck panel and the steel girders. Since the thermal expansion coefficient for aluminium is about twice that of steel (23.6×10^{-6} mm/(mm°C) and 11.7×10^{-6} mm/(mm°C) respectively), high level of stresses and stress concentration could result from the composite connection between the aluminium deck and steel girders under significant temperature variations.

This study aims at investigating the effects of thermal loading, due to temperature variations, on the bolted connection between the aluminium deck and steel girders in a composite bridge construction. The aluminium deck is made of multi-cell extrusions which are welded together to form the deck panels. The selected aluminium material for the deck is the 6063-T6 alloy, which is one of the four alloys recommended for use for extruded bridge sections by the Canadian Highway Bridge Design Code, CAN/CSA S6-14 (CSA, 2014). The design of the deck and the girders will not be discussed in this paper. The aluminium deck design has been presented in an accompanying paper submitted to this conference, details of which can be found in Burgelin (2017). The deck and the steel girders are assumed to be joined together using slip-critical bolted connections with ASTM F3125 grade A325 high strength bolts. Other types of bolts, such as ASTM F468 aluminium bolts and ASTM F593 stainless steel bolts are allowed by the standards for slip-critical connections in bridges. However, ASTM F3125 grade A325 bolts were chosen because they are less expensive than the others. A number of bridge configurations are selected for investigation using the finite element method. The applied live loads and thermal loads are determined from the specifications of the Canadian standard CAN/CSA S6-14. The structural behaviour of the deck is analyzed and a recommendation is presented on how to maintain composite action between the deck and girders.

2 REVIEW OF THE THERMAL EFFECTS IN BRIDGES

Bridges are subjected to three types of thermal loading: effective temperature, vertical gradient and horizontal gradient. The effective temperature is the ambient temperature at the location of the construction site, which varies depending on the weather and the geographical location. The vertical gradient is the distribution of the temperature in the deck and the girders, between the top of the deck and the bottom of the girder; it depends mostly on the bridge configuration and material properties. The horizontal gradient is the temperature distribution between two points located at the same height of the bridge system. Figure Error**! No text of specified style in document.**-1 illustrates the phenomena responsible for heat exchange in a typical bridge section.

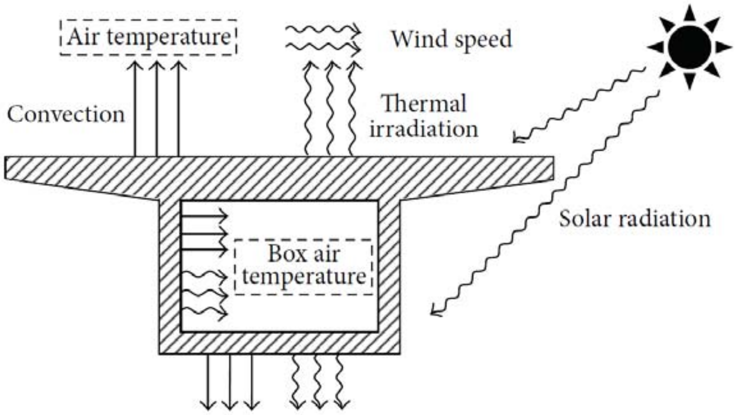

Figure **Error! No text of specified style in document.**-1 : Heat exchange between the boundary of a bridge and the environment (Zhou et al., 2013).

The CAN/CSA S6-14 standard provides requirements for thermal loads. The effective temperature range derives from the identified location of the bridge in Canada. The bridge shall be associated with one of the following superstructure types:

- type A: steel or aluminium beam, box or deck truss systems with steel decks, and truss systems that are above the deck;
- type B: steel or aluminium beam, box, or deck truss systems with concrete decks;
- type C: concrete systems with concrete decks.

This classification aims to characterize the thermal conduction behaviour of the bridge. For each superstructure type, the temperature range is broaden (table 3.8 of CAN/CSA S6-14) in order to take into account the phenomena (Figure **Error! No text of specified style in document.**-1) that can increase or decrease the effective temperature of a bridge. The temperature range shall also be broaden (figure 3.5 and figure 3.6 of CAN/CSA S6-14) in order to take into account the vertical gradient of temperature in the bridge.

3 FINITE ELEMENT ANALYSIS

3.1 Bridge configurations

Four configurations of bridges were selected for studies, covering a range of small to medium span application: a 15 m span with 8.9 m width, a 25 m span with 8.9 m width, a 15 m span with 11.6 m width and 25 m span with 11.6 m width. Figure **Error! No text of specified style in document.**-2 shows the two different width configurations. Only the 15 m span with 8.9 m width will be presented in this paper as the other configurations yielded similar conclusions.

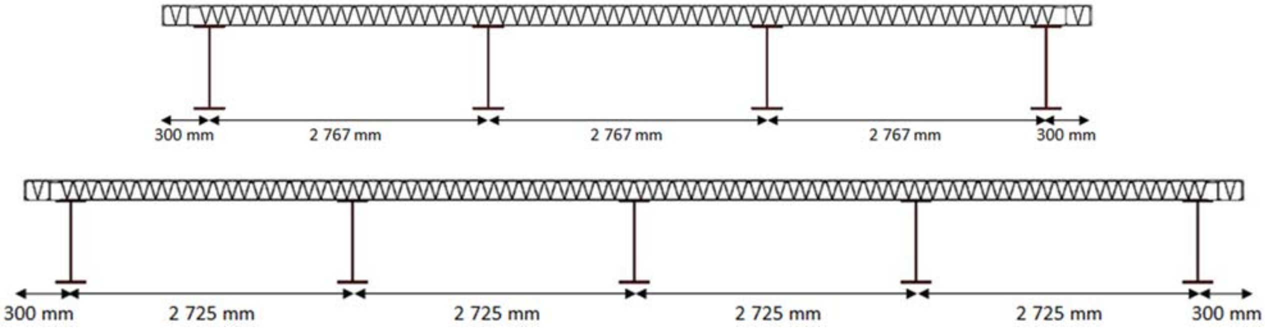

Figure **Error! No text of specified style in document.**-2 : Cross-section of the studied bridges: 8.9 m width (top) and 11.5 m width (bottom)

3.2 Generalities on finite element models

The FE analysis were carried out using the commercial software Abaqus 6.14.1 (Dassault Systèmes, 2014). The study was made for an intermediate girder and the part of the deck connected to the girder, using the beam analogy method for longitudinal stress, as formulated in article 5.6 of CAN/CSA S6-14. Considering the symmetry planes of the beam, only a quarter of the composite girder was modelled, as pictured in Figure **Error! No text of specified style in document.**-3, in order to reduce computational time. Symmetry boundary conditions were used for the two symmetry planes of the model.

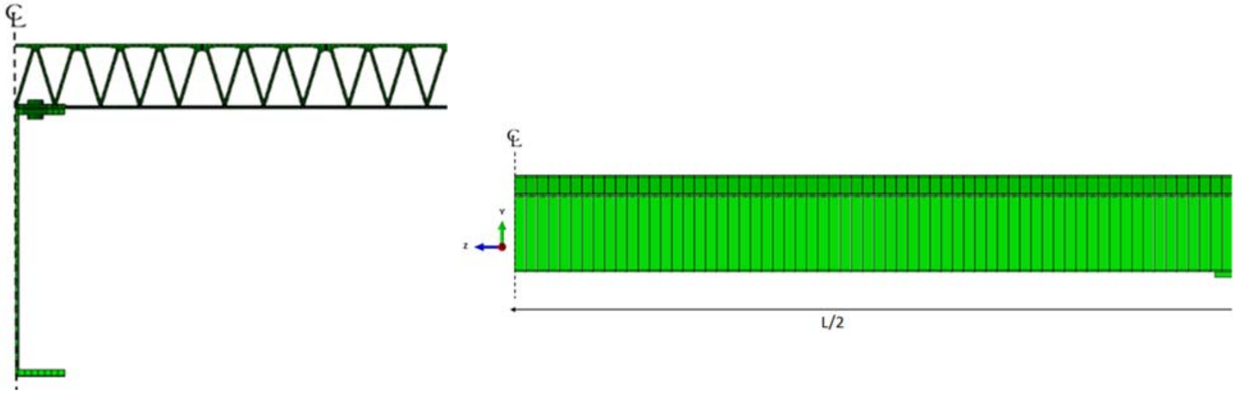

Figure **Error! No text of specified style in document.**-3 : Finite element model used for this research: transverse view (left) and longitudinal view (right).

The analysis procedure was divided in four steps. The first two steps were under general static conditions to impose the preload in the bolts. At the first step, a load is applied to the bolts at the level required by the CAN/CSA S6-14. At the second step, the length of the shank of the bolt is set as the length it reached at the end the first step. This method is specific to bolts modelling in Abaqus. Thereafter, the thermomechanical study can begin. The third step is the thermal loading and the fourth step is the mechanical loading. The thermal and mechanical loading stages are discussed below.

3.3 Interaction, boundary conditions and loads

Contact modelling is a major aspect of the study, in order to accurately describe the behaviour of the connection between the deck and the girder. Every contacts are simulated using *surface-to-surface* discretization, which is an efficient method where high contact pressures are involved, as expected in this study. Behaviour in the normal direction to the surfaces is represented by *hard contact* type, to prevent penetration of one surface to the other. Behaviour in the tangential direction is *penalty* type, using a slip coefficient of 0.3, which is the generic design slip coefficient between surfaces involving aluminium (aluminium-aluminium as well as aluminium-steel), as prescribed by CAN/CSA S6-14.

A thermal conductance model is used in order to represent the heat transfer between the different parts of the model (Heistermann, 2011). It is assumed that the heat transfer vary linearly with the applied pressure normal to the surfaces.

The bridge bearing is modelled by an elastomeric slab under the flange of the girder. The elastomer slab model serves to represent satisfactorily the controlled degrees of freedom without over-restraining the girder, which would have resulted in stress concentration near the bearings and consequently led to spurious results at these locations.

Thermal loads were modelled by temperature boundary conditions at the top fibers of the deck and at the bottom fibers of the girder, using the temperature range determined from the CAN/CSA S6-14 guidelines (see section 2). It was assumed that the aluminium-steel bridges is a type A structure (see section 2), because, due to material properties, an aluminium deck has a higher heat conductivity than a concrete slab. Two scenarios were investigated:

- Summer scenario, which covers a temperature range from the erection temperature (15 °C, as specified by CAN/CSA S6-14) to a maximum temperature (30°C, in Montréal) ;
- Winter scenario, which covers a temperature range from the erection temperature to a minimum temperature (-35 °C, in Montréal).

The bolt preload was modelled as described in section 3.2.

The mechanical load was applied as a pressure on the surface of the deck. The pressure is computed to give the same bending moment as the moment induced by the serviceability limit state (SLS) and ultimate limit state (ULS). This method is chosen instead of applying the actual wheel pressure, in order to maintain the same symmetry planes for loading as for the geometric symmetry planes.

3.4 Meshing

Elements of the mesh were made of first order hexahedrons. They have four degrees of freedom: displacement in the three translational directions (X, Y and Z), and temperature (T). Solid elements were chosen for their high accuracy as far as local contact pressure is involved.

4 RESULTS AND ANALYSIS

4.1 Results for the 15 m span bridge model

Results showed that slip occurs at locations up to 978 mm from the bearing location in winter conditions, and up to 633 mm at summer. Figure **Error! No text of specified style in document.**-4 illustrates the shear strength versus the slip at different positions along the model, in the longitudinal length. For the winter scenario, the live load lowers the shear stress, because the deck tends to shrink from the effect of temperature decrease, which causes stresses in the opposite direction to the ones caused by the mechanical loading.

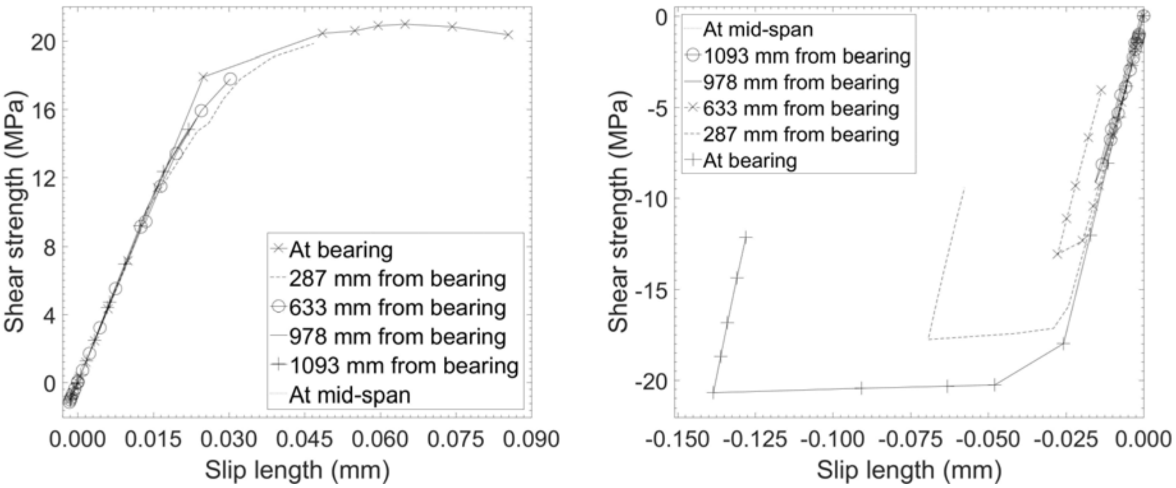

Figure **Error! No text of specified style in document.**-4 : Shear stress versus slip at different locations under SLS loads, for summer scenario (left) and winter scenario (right).

The study of axial strain on the section of the model can be used to determine whether or not the composite action between the deck and the girder is effective. A drop of axial strain was observed up to a distance of 920 mm from the bearing location. It can thus be concluded that total composite action is lost from this point to the bearing. The axial strain distribution in the section is similar to the one in Figure **Error! No text of specified style in document.**-5 up to 920 mm from the bearing, which is the longitudinal position from where there is no gap of axial strain at the deck-girder interface.

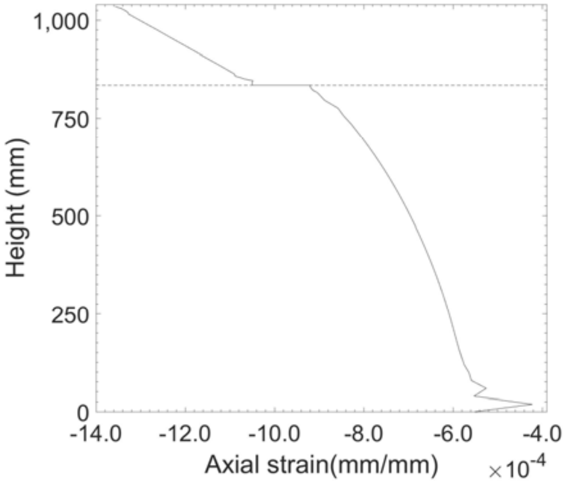

Figure **Error! No text of specified style in document.**-5 : Axial strain at 403 mm from the bearing, winter scenario, under thermal and mechanical loads.

At ultimate limit states, stresses locally exceeding the weighted yielding strength of aluminium are observed around the bolt holes. However, it does not reach the weighted ultimate strength. Stresses exceeding the weighted ultimate stress resistance are observed in the shank of the bolts near the bearing (Figure **Error! No text of specified style in document.**-6), due to shear stresses between the deck and the girder. Bolt failure is therefore anticipated near the bearing. Section 4.3 provides a recommendation for preventing bolt failure.

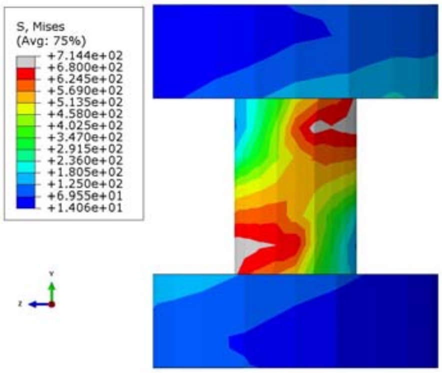

Figure **Error! No text of specified style in document.**-6 : Von Mises stress (MPa) of a bolt under ULS loading (areas in grey are where weighted ultimate resistance of the bolt is exceeded).

4.2 Effect of thermal cycles

Neither of the two temperature scenarios described above takes into count the cycling effect of temperature variation. As seen in section 4.1, slip occurs at bolted joints near the bridge bearings. An analysis with two complete temperature cycles was carried out to determine whether or not bolt slippage could result in bearing type connection after several temperature loadings, consisting of two complete thermomechanical cycles. As shown by Figure **Error! No text of specified style in document.**-7, the thermal loading leads to a hysteresis curve on the slippage which could lead to a premature failure of the bolted connection.

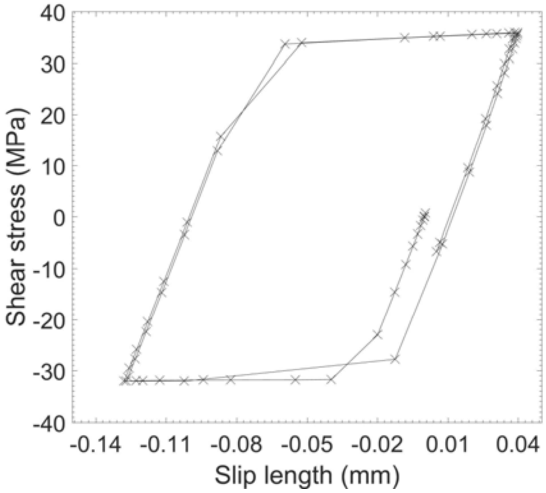

Figure **Error! No text of specified style in document.**-7 : Shear stress versus slip at a bolt near the bearing, for two complete temperature cycles.

4.3 Method for slippage prevention

In order to reduce slippage, two methods are proposed: the first method suggests using a surface treatment on the aluminium deck to increase the slip coefficient, while the second proposed solution involves a change in the bolt layout.

Previous studies have shown that a slip coefficient of 0.4 or higher between aluminium and galvanized steel can be achieved by sandblasting the aluminium surface to obtain a roughness of 1,5 mils (0,038 mm) (Fortin, 2001). As illustrated in Figure **Error! No text of specified style in document.**-8, the shear strength of a bolted connection increases from about 21 MPa to about 27 MPa when slip coefficient is increased from 0.3 to 0.4.

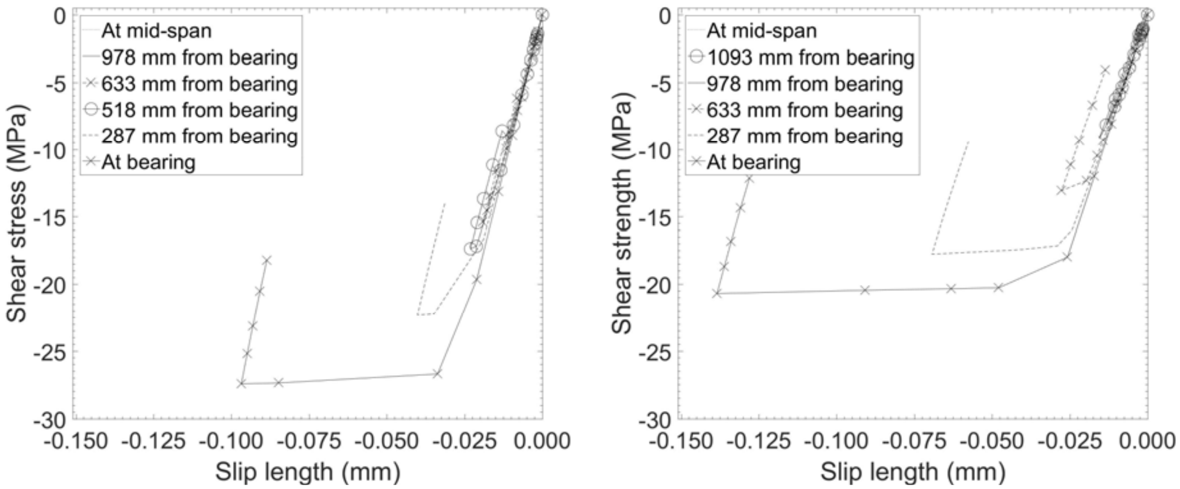

Figure **Error! No text of specified style in document.**-8 : Shear stress versus slip with a slip coefficient of 0.4 (left) and 0.3 (right), for winter scenario

Most of the strain in the deck and in the girder occurs near the bearing, which means the shear stress is higher at this location. The layout of the bolts should therefore be adjusted. The layout illustrated in Figure **Error! No text of specified style in document.**-9 was simulated with a 0.4 slip coefficient between the deck and the girder. This layout uses the same number of bolts as the ones used earlier.

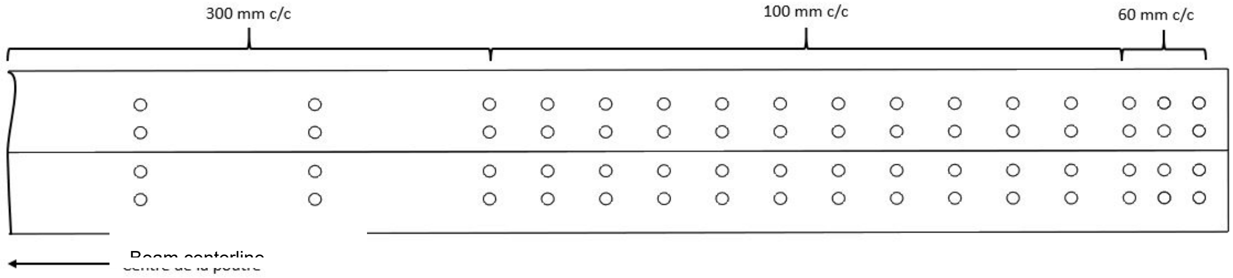

Figure **Error! No text of specified style in document.**-9 : Closer spacing of the bolts near the bearing location prevents slippage and bolt failure.

The results (shown in Figure **ERROR! NO TEXT OF SPECIFIED STYLE IN DOCUMENT.**-10 and Figure **Error! No text of specified style in document.**-11) demonstrated that slip was prevented in the entire model at SLS and composite action was therefore preserved. Moreover, stress in the bolt shanks was lowered under the weighted resistance of the material at ULS, as shown in Figure **Error! No text of specified style in document.**-11.

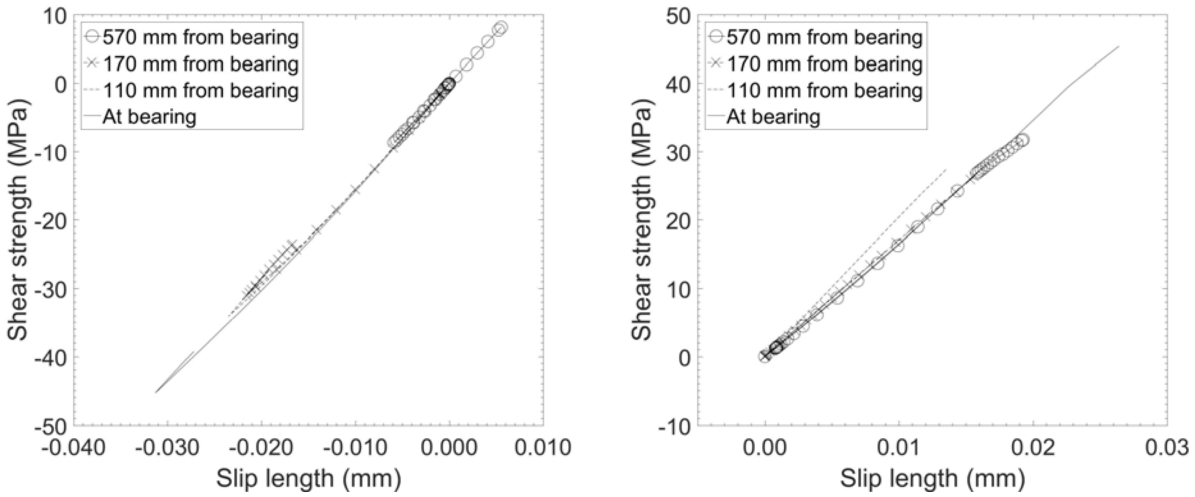

Figure **ERROR! NO TEXT OF SPECIFIED STYLE IN DOCUMENT.**-10 : Shear stress versus slip using the adjusted bolt layout : winter scenario (left) and summer scenario (right)

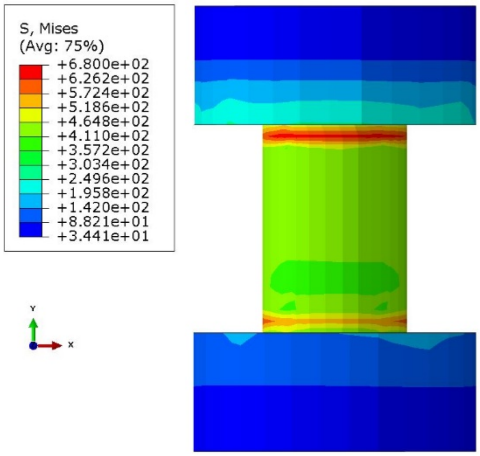

Figure **Error! No text of specified style in document.**-11 : Von Mises stress (MPa) of a bolt under ULS loading using the adjusted bolt layout

5 CONCLUSION

Thermal loads may induce severe stresses at the interface between a bridge deck panel and the supporting steel girders, which can result in the loss of composite action or even bolt failure. This effect may be aggravated if the materials of the deck and the girders are incompatible in terms of their responses to thermal load effects, as in the case of aluminium deck supported by steel girders. However, this can be prevented by using an appropriate surface condition for the aluminium to guarantee a higher slip coefficient, or by arranging the bolts in an appropriate pattern to optimise the distribution of shear stresses.

Acknowledgements

This project was supported by Ministère des transports, de la Mobilité durable et de l'Électrification des transports (MTMDET) and by the Aluminium Research Centre – REGAL. The authors acknowledge this two supporting organisations. A special thanks to Dominic Fortin, from MTMDET, for his technical support provided throughout this R&D project.

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