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# A NEW SIMPLE-SPAN BRIDGE CONCEPT IN ALUMINIUM

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**Abstract:** In this paper, a new highway bridge concept made of an aluminium deck and supported on aluminium girders is developed as an alternative to the traditional bridge solutions, namely the slab-on-girder and wood-deck-on-girder bridges. The all-aluminium bridge system is conceived as a modular solution, to be fabricated under controlled environment and transported in two parts to be installed on-site. The modular solution ensures higher quality control and rapid on-site construction. The aluminium deck is made from extrusions, 200 mm deep and 370 mm wide, which would be welded together using the friction stir welding (FSW) or by the traditional MIG (metal inert gas) welding technique. The aluminium girder is an inverted T-shape, and the top of its web is welded to the extrusion deck panels by means of a specially designed extrusion which eliminates the need for a top girder flange. The proposed design respects the requirements of the Canadian Highway Bridge Design Code (CAN/CSA S6-14). The aluminium deck is designed to be waterproof and requires minimal maintenance if care is taken to eliminate the risk of galvanic corrosion or accumulation of debris.

## 1 INTRODUCTION

According to a survey reported by Viami International Inc. and The Technology Strategies Group (2014), over 40% of bridges in Canada are 50 years or older. Many of these bridge structures need to be redecked or replaced. In this context, aluminium could offer a promising solution for building modern and durable bridges. Aluminium is inherently corrosion-resistant, with an excellent resistance-to-weight ratio and a good resistance at low temperatures. This recyclable material can also offer a flexible and optimized solution through the technique of extrusion, which allows the production of complex geometries/sections under controlled manufacturing conditions.

For structural application, aluminium has been used sparsely for bridges, either in the deck or the superstructure, or both. Since 1990, a number of bridges have been built from aluminium decks, produced by companies such as SAPA and AlumaBridge (Siwowsky, 2006). These decks are typically made from extrusions welded together by MIG or FSW into panels. Figure Error**! No text of specified style in document.**-1 shows an aluminium deck panel, designed and produced by AlumaBridge. This deck type was used recently for the construction of an experimental bridge at St-Ambroise, in the province of Québec, Canada. It is worth mentioning that the existing deck solutions in aluminium are largely proprietary, and existing design specifications for the construction of bridges in aluminium are not as comprehensive as those for the traditional materials such as steel, concrete and wood.

The present research aims to establish a proof of concept for a short span, all-aluminium bridge, to be produced under controlled manufacturing conditions, shipped and rapidly erected at its permanent construction site.

Figure **Error! No text of specified style in document.**-1 : AlumaBridge aluminium deck used for the construction of a short span bridge at St-Ambroise, QC, Canada; July 2015 (From the photo archive of the Aluminium Research Centre – REGAL).

The study bridge is intended to meet the following specifications or requirements:

- a 15 m single span, representing short span bridges that can readily be shipped by means of a truck;
- factory off-site built, to ensure high quality control of critical elements, such as welds;
- rapid installation on the construction site, to minimize downtime in case of road closure for rehabilitation;
- modular solution: the deck will consist of panels to be connected mechanically. Each panel will correspond to a traffic lane. Panel width of 5 m is dictated by truck and shipping limits;
- girders and deck to act compositely to enhance the longitudinal flexural rigidity.
- bridge design for low traffic (average daily traffic per lane < 500), and in accordance with the Canadian standard CAN/CSA S6-14 standard

## 2 DESIGN PREREQUISITES

### 2.1 Introduction

In the following subsections, certain basic but important prerequisites will be addressed prior to the presentation of the design. These are the properties of aluminium as a construction material, the extrusion process, the different types of connection between members, and some preliminary design choices linked to the geometry of the bridge.

### 2.2 Material Properties

The aluminium alloy chosen for the study bridge is the 6063-T6, which has a satisfactory balance between mechanical strength, cost, availability and extrudability. Extrudability describes the ability of a metal to be extruded. AA 6063-T6 has the following design strength: $F_y = 170$ MPa, $F_u = 205$ MPa, $F_{wy} = 55$ MPa and $F_{wu} = 115$ MPa. $F_{wy}$ and $F_{wu}$ respectively refer to the yield strength and the ultimate strength of the heat affected zones (HAZ) caused by welding. They are significantly lower than the strength of the parent material, because the high input of heat generated by the welding process changes the microstructure of the metal within the HAZ.

### 2.3 Extrusion process

The extrusion process consists of forcing a billet of aluminium through a die, as illustrated in Figure **Error! No text of specified style in document.**-2, to produce the desired extruded geometry. Aluminium is preliminarily heated to 430 – 500 °C (Develay, 1997). The extrusion presses are characterized by their pushing force, usually between 500 to 10000 tonnes (Guillot, 2013). The geometric properties (width, height, length, cross-sectional area and wall thickness) are limited by the size and the power of the press. For this study, it was assumed that the extrusions would be made by a 6000 tonne press, with a diameter of 457 mm (18 inches) and a maximum billet weight capacity of 560 kg. The resulting extrusion would be characterized by the following limitation: the extrusion profile cannot be wider than 370 mm and deeper than 200 mm. The total area of the extrusion is also limited by the maximum billet weight.

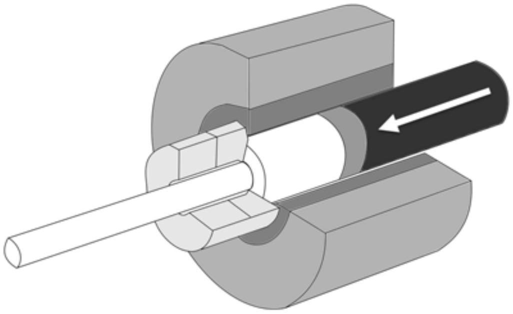

Figure **Error! No text of specified style in document.**-2 : Extrusion press: the pressing stern (in black) push the billet (in white) through a die (in light grey).

### 2.4 Assembly method

There are different ways to assemble aluminium members. Welding ensure material continuity, but weakens the metal near the weld area (heat affected zone). The most common method for welding aluminium is MIG. Friction-stir welding produce welds with higher quality than MIG; however this technology is currently not available in Québec at an industrial scale, thus it was not taken into account for joining the extrusions. Elements can also be assembled by mechanical means, such as bolting or riveting. This, however, results in local stress concentration, due to the holes created and the pressure of contact between the head of the connectors and the members to be joined. In this project, the MIG welding is selected to connect different parts of the bridge.

### 2.5 Bridge configuration

As far as the overall bridge configuration is concerned, there are two options for placing the aluminium deck on the girders. The extrusions can be placed parallel to the girders or direction of traffic (longitudinal deck), which maximizes the longitudinal flexural rigidity of the deck, facilitates the development of composite action with the girders, and allows a better adaptation to the shape of the roadway, because of the possibility of using special extrusions between the deck and the girders as described in section 3. The extrusions can also be placed transversely to the girders or direction of traffic (transversal deck). The latter is currently the most used configuration for placing extruded aluminium deck panels on girders. In this research, the deck will be designed to be longitudinal, in order to take advantage of the composite connection between the deck and girders.

## 3 PROPOSED DESIGN

### 3.1 Introduction

The design proposed in this section is the result of an iterative process. Several initial designs of hollow sections were created, then refined by the finite element analysis FEA (section 4) in order to meet the specifications of the selected extrusion press, the requirements of the CAN/CSA S6-14 standard, as well as to resolve the design of joints between deck panels and between different elements of the bridge structure. This section presents the final design.

The cross-section of the global bridge configuration is illustrated in Figure Error**! No text of specified style in document.**-3. It consists of two panels, each made from welded extrusions. MIG welding is selected for joining the extrusions. The panels are mechanically connected at the centre of the roadway by a joint designed to give the deck a 2% transversal slope for drainage purposes. Each panel is supported on three aluminium girders made of extrusions. The bridge is 15 000 mm long, 9 340 mm large and weigh 19.8 tonnes.

The bridge features the following elements:

- standard deck extrusions (Figure Error**! No text of specified style in document.**-4) between girders;
- connexion extrusions at girder locations (Figure Error**! No text of specified style in document.**-5);
- girder extrusions;.
- special extrusions to allow a mechanical joint between the two panels (Figure Error**! No text of specified style in document.**-6).

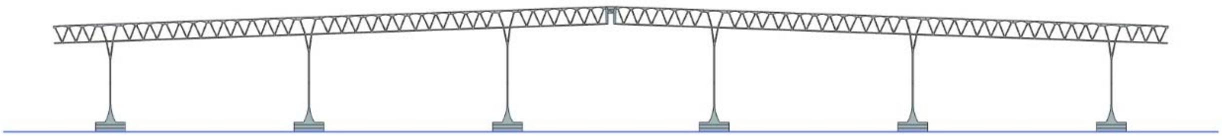

Figure **Error! No text of specified style in document.**-3 : Cross-section of the bridge.

### 3.2 Extrusion geometries

A schematic of the standard extrusion is shown in Figure Error**! No text of specified style in document.**-4. It has a truss-like profile. The top flange has a varying thickness with a greater thickness at the ends of the extrusion, to compensate for the loss of strength caused by the MIG welding between extrusions.

The connexion extrusion (Figure Error**! No text of specified style in document.**-5) is designed to transfer forces from the deck to the girders. The top flange has a greater thickness than the standard extrusion because it has to resist transverse moments due to wheel loads. The “V” shape of the connexion extrusion has a wider angle than the “V” shape of the standard extrusion, in order to decrease the extrusion transverse rigidity, and to avoid stress concentration in the girder.

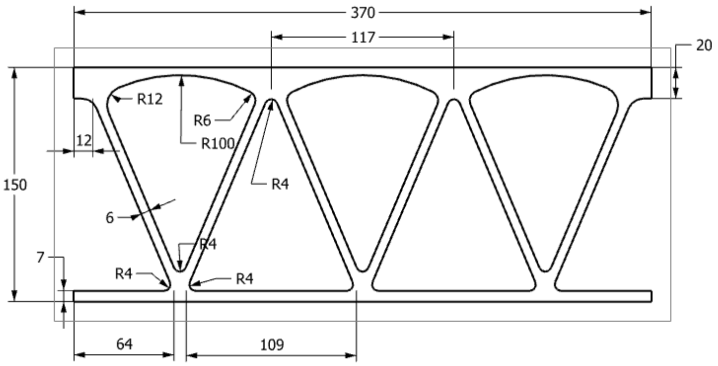

Figure **Error! No text of specified style in document.**-4 : Deck extrusion (dimensions are in mm).

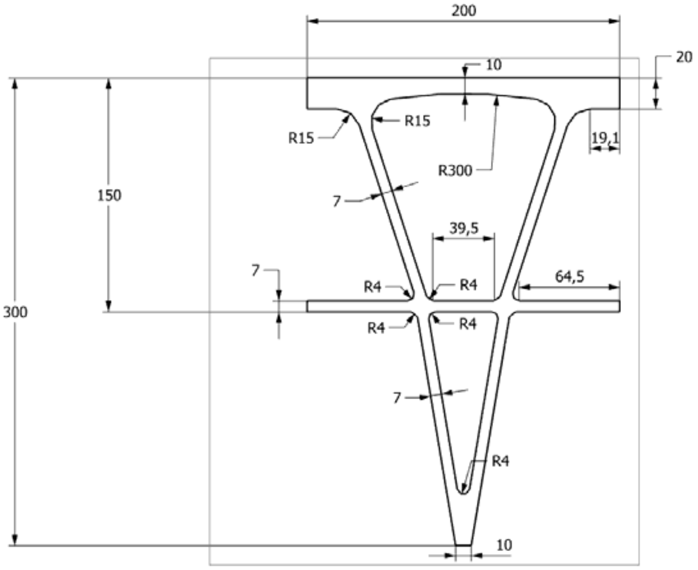

Figure **Error! No text of specified style in document.**-5 : Connexion extrusion (dimensions are in mm).

The girders are made of plate-type extrusions, which are welded together. As illustrated by Figure Error**! No text of specified style in document.**-3, the girders have a significant depth and their bottom flanges have a substantial thickness, to compensate for the relatively low rigidity of aluminium.

The design of the joint between panels (Figure **Error! No text of specified style in document.**-6) is critical, from a structural as well as from a functional point of view. Indeed, it must transfer forces from one panel to the other, it must be assembled on the construction site, and it must be waterproof to prevent water gaining access to the underside of the deck. A special extrusion is designed to create a “clip-type” connection that can transfer shear forces. The upper part of the joint (in blue on Figure **Error! No text of specified style in document.**-6) acts as a gasket, to prevent water intrusion. The mechanical connection shall be secured by bolts.

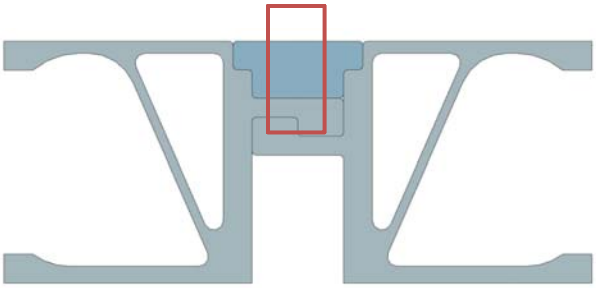

Figure **Error! No text of specified style in document.**-6 : Mechanical joint between panels; red rectangle is the location of bolts.

## 4 METHOD OF CONCEPTION

### 4.1 CAN/CSA S6-14 requirements

Only the dead load of the structure and the live load from the design CL-625 truck were considered for the design of the bridge. Thus, the evaluated limit states were: the ultimate limit state, combination 1 (ULS 1) and the fatigue limit state, combination 1 (FLS 1).

For the ULS, the live load consists of the axles of the CL-625 truck that produce the maximum bending moment in the structure. The loads applied to each wheel were weighted by the appropriate factors: live load factor, $\alpha_L = 1.7$, the multi-lane modification factor, $R_L = 0.9$ (for two lanes loaded) and the dynamic load amplification factor $DLA = 0.25$ (four axles). The dead load was computed as the total weight of the structure, multiplied by the dead load factor for factory-produced components: $\alpha_D = 1{,}1$. Von Mises stresses obtained by the FEA were compared to the factored resistance of the alloy AA 6063-T6: $\phi_u \times F_u = 153.75$ MPa for plain metal and $\phi_u \times F_{wu} = 86.25$ MPa for the heat affected metal.

For the FLS, the bridge was designed for infinite life; which implies that for each identified detail, the fatigue stress must be less that the endurance limit of the relevant detail category. Welds were considered as class C detail, with an infinite life resistance of 21.3 MPa. Plain material (i.e. not affected by welding heat) was considered as class A detail, with an infinite life resistance of 46.6 MPa. The applied load is the tandem of 125 kN axles of the CL-625 truck, and was centred on a traffic lane. Loading coefficients applied were: $\alpha_D = 1.0$, $\alpha_L = 1.0$, $R_L = 1.0$ and the DLA was 0.4. Von Mises stress and transverse stress, $\sigma_{XX}$, were compared to the calculated fatigue resistance of the plain material and welds.

## 4.2 Finite element models

The bridge was modelled using the commercial FEA software NX NASTRAN.

For each limit state, the loads were applied in accordance with the wheel load and the axle configuration of the studied limit states (ULS 1 and FLS 1). Bridges bearing were simulated with boundary conditions on the edges at the lower flange of the beam. One edge was restricted for the three translation degrees of freedom. The other edge was restricted for only the ascending degree of freedom. When applicable, a symmetry condition was imposed at the centreline of the bridge to reduce computation.

The model was meshed with solid elements, which were hexagon with 20 nodes (HEX20). According to Maljaars et al. (2008), geometries such as the one used in this study cannot be modelled using shell elements with sufficient accuracy, as the use of shell elements could lead to spurious results.

For the ULS, the von Mises equivalent stress was compared to the admissible stress values (see section 4.1). For the FLS, the stress transverse to the weld beads, represented by $\sigma_{XX}$, was compared to the fatigue admissible stress for each detail category. Figure **Error! No text of specified style in document.**-7 and Figure **Error! No text of specified style in document.**-8 are examples of fatigue post-processing results: the $\sigma_{XX}$ stresses are shown, and it is verified that the resistances of 21.3 MPa in heat affected zones and 46.6 MPa elsewhere were not exceeded.

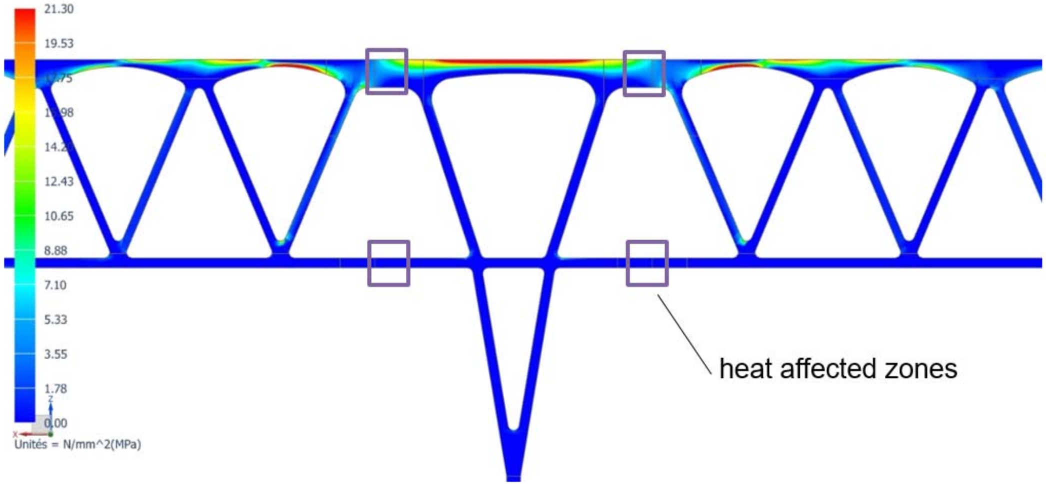

Figure **Error! No text of specified style in document.**-7 : Transverse stress ($\sigma_{XX}$) at FLS for the connexion extrusion.

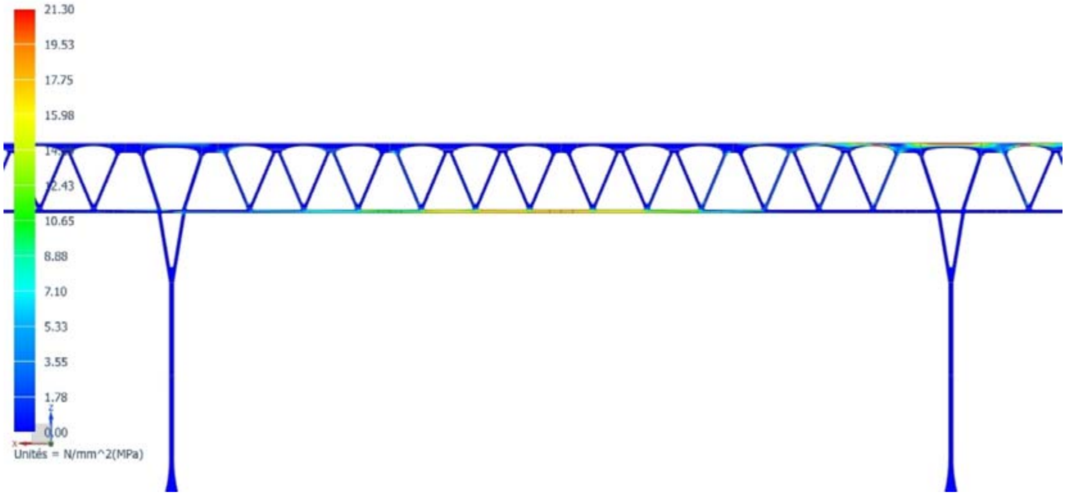

Figure **Error! No text of specified style in document.**-8 : Transverse stress ($\sigma_{XX}$) at FLS at a loaded part of the deck between two girders

## 5 DESIGN CHALLENGES USING CAN/CSA S6-14

During the design process, two principal challenges were faced with the use of the Chapter 17 (*Aluminium Structures*) of the Canadian standard CAN/CSA S6-14, which is the relevant section in the standard for the design of aluminium bridges. Firstly, it appears that the calculation of the truck load fraction, $F_T$, used by the prescribed simplified analysis method to represent the fraction of the truck load taken up by a given girder under the most critical loading configuration is based on the specified value of the truck load distribution width, $D_T$, for wood plank decks. This specification might lead to an over-conservative design for hollow extruded aluminium decks, as the specified low $D_T$ value may overestimate the truck load fraction and consequently lead to an increased girder dimensions and cost. For design purposes, the truck load fraction is multiplied by the longitudinal load effects to obtain the transverse distribution across the bridge width. In general, the truck load fraction depends on many factors, including the deck type, the girder spacing, the lane width, the span, and the location of the girder (interior or exterior).

The second challenge is the determination of the effective width in composite deck-on-girder bridge systems for the type of hollow extruded deck sections under study. The prescribed methodology in the Canadian standard cannot be applied for this type of deck profile. The effective width corresponds to the equivalent width of the deck section considered to contribute to the flexural resistance of the composite girder, assuming a uniform longitudinal stress distribution over the flange. In general, the effective width is influenced by factors such as the span, the girder spacing, the loading type, and the type of the deck section.

## 6 CONCLUSION

This study has presented a proof of concept for a complete highway bridge solution in aluminium, in a single span, 15 m bridge, which can be produced in modules under a controlled manufacturing environment and shipped to site for rapid erection. The new aluminium bridge concept meets the requirements of the Canadian standard for the design of highway bridges, CSA S6-14. It is worth noting that the current edition of the code is either not explicit or completely silent on a number of important design decisions, especially relating to the use of extruded multi-cell aluminium deck profiles for bridge systems. This proof of concept can be refined to further investigate its applicability to wider design requirements, and may also be adapted to other bridge applications, such as aluminium deck-on-steel girder systems.

## Acknowledgements

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