engineering proceedings

Proceeding Paper

Modern Applications and Construction Details for Aluminium Bridges †

Benoit Cusson

WSP, Montreal, QC H3H 1P9, Canada; benoit.cusson@wsp.com

† Presented at the 15th International Aluminium Conference, Québec, QC, Canada, 11–13 October 2023.

Abstract: Canada's bridge industry is witnessing a momentum for the use of aluminium in pedestrian and vehicular bridges. This paper describes the results of six years of developing tangible innovative aluminium details and structural arrangements. Various projects of different scales, which are presented, include two architectural pony truss pedestrian bridges, the first GMAW welded aluminium deck on steel girders vehicular bridge in Canada and a signature pedestrian bridge where an 80 m long through truss connects to a curved girder structure. The development of a simple aluminium girder pedestrian bridge concept also inspired an innovative composite structural system involving a friction stir welding (FSW)-welded aluminium deck connected to longitudinal girders. These various projects generated code-update propositions for the aluminium section of the CSA S6 standard. Featured topics in this paper relate to bolted connections for decks, barriers and truss chords, welded straight and curved girders, expansion joints and designs for fatigue and fabrication. The context is ideal to reflect the roadmap towards 100% aluminium vehicular bridges.

Keywords: aluminium; FSW; welding; connections; stability; HAZ; curved girders; Vierendeel

check for updates

Citation: Cusson, B. Modern Applications and Construction Details for Aluminium Bridges. *Eng. Proc.* **2023**, *43*, 13. https://doi.org/10.3390/engproc2023043013

Academic Editor: Nicolas Boissonnade

Published: 13 September 2023

1. Introduction

Bridge design and construction methods continue to evolve, leading to safer and more sustainable infrastructures. Steel and concrete bridges have been thoroughly studied and optimised. They are well known to structural designers and are regulated by recognised standards. However, cold weather in Canada and other northern countries triggers the usage of de-icing salts, which is a major issue for bridges' sustainability [1]. Furthermore, the COVID-19 pandemic demonstrated the importance of the local procurement of materials to benefit from sustainable development principles.

Canada is the fourth largest primary aluminium producer in the world. A total of 90% of this production is generated in Québec and represents an important part of the province's economy. For these reasons, Canada's and Québec's bridge industries are witnessing a momentum for the use of aluminium in pedestrian and vehicular bridges. With its non-corroding and lightness properties, this material is worth considering, especially when the total cost of ownership and the environmental life cycle are considered [2]. More than 45 aluminium pedestrian bridges are inventoried in the province by Alu-Québec in their corresponding public directory [3]. Québec is also home to the world renowned Arvida Bridge, which was the first all-aluminium long-span bridge at the time of its opening in 1950 [4].

Over the last several years, WSP has developed a particular interest for the design of pedestrian and vehicular aluminium bridges. With the use of this material being relatively new, such structures require analysis methods, design procedures and assembly detailing that are frequently non-conventional. Research, development, partnerships with universities and mandates from owners have recently led to the design and construction of innovative structural arrangements.

This paper presents various projects that have shaped the expertise of the Canadian division of WSP in this field. The firm acted as the designer on all of the presented projects. The aim is to share the most up-to-date applications, construction details and normative content to propel the use of aluminium in bridges.

2. Hall and Wellington Pedestrian Bridges

Built in 2018, Parcs Canada's Hall and Wellington pedestrian bridges, shown in Figure 1, are twin pony truss bridges. The 27 × 4.5 m structures are completely welded, thus requiring no assembly on-site. The patrimonial truss geometry, the accelerated bridge construction (ABC) approach, the compressed top chord stability and the fabrication highlights are amongst the topics reported for these bridges [5,6].

(**a**) (**b**)

Figure 1. (**a**) Hall pedestrian bridge installation; (**b**) Wellington pedestrian bridge crane lift.

Elastomeric bearings for bridges are usually delivered with a top plate that is welded to the superstructure on-site. This allows for final positioning with regard to the built foundations. Aluminium's welding challenges and bearings' locations under the trusses' chords led to a different positioning strategy, requiring no welding on-site. The bearing's top plate shown in Figure 2a is already welded to the superstructure. The anchoring rods shown in Figure 2b are grouted in oversized holes that were drilled based on the precise surveys of the backfilled foundations and the fabricated superstructure.

(**a**) (**b**) (**c**)

Figure 2. (**a**) Bearing device's sliding surface; (**b**) anchoring rods; (**c**) expansion joint cover plate.

Figure 2c shows how the expansion joints were designed to maximise the comfort and safety of cyclists. The cover plate is fixed to both the wood deck and the angle embedded in the concrete foundation. It contains slotted holes that allow for thermal expansion and field adjustment. In collaboration with welding consultant GCES, welded connection details were established so that the connection's resistance is at least 75% of the member's resistance in accordance with the CSA S6-19 requirements [7]. Welding details included filet welds, full-penetration groove welds with backing bars left in place as well as partial penetration welds for the face of diagonals on the acute side. Upcoming CSA S6-25 and CSA S7-23 propose new provisions to clarify when partial penetration welds and backings left in place can be acceptable for aluminium bridges [8,9].

At the time of the design, Sétra's provisions were considered the state of the art for pedestrian-induced vibrations design [10]. Hall and Wellington bridges' dead load, stiffness and natural frequencies were optimised to qualify for maximum comfort for Class III loading and minimum comfort for Class II loading. CSA S7-23 provisions on the same topic were partly calibrated with the Hall and Wellington bridges [9].

3. Montmorency Forest's GMAW Aluminium Deck on Steel Girders

Currently under construction, Laval University's gas metal arc welded (GMAW) aluminium deck on steel girders bridge for highway loads, shown in Figure 3, is the first of its kind in Canada. The 15 m long × 8 m wide deck made of hollow 6005A-T61 aluminium extrusions welded longitudinally sits on three steel girders. Various aspects of the design of this bridge have been reported [11]. This project inspired new provisions for aluminium decks in the upcoming CSA S6-25 [8].

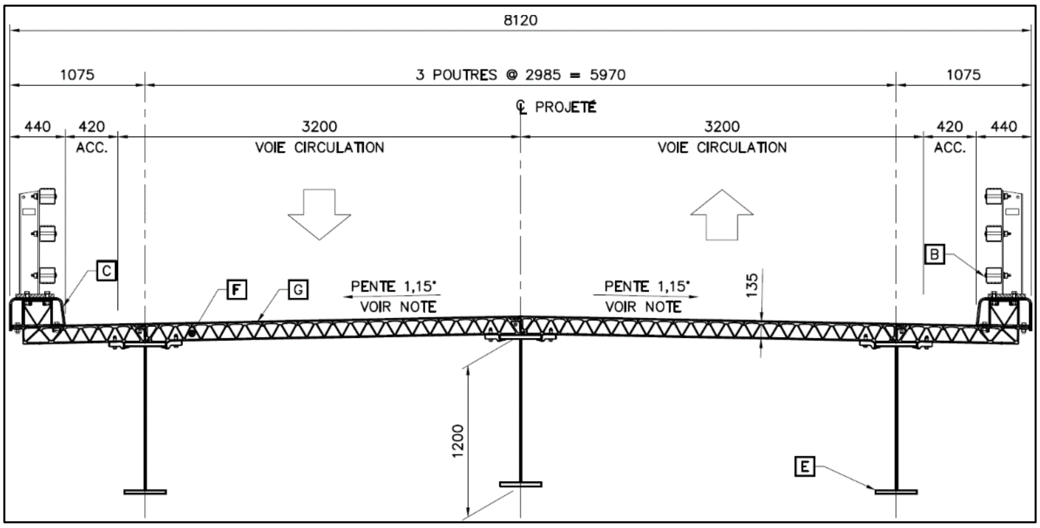
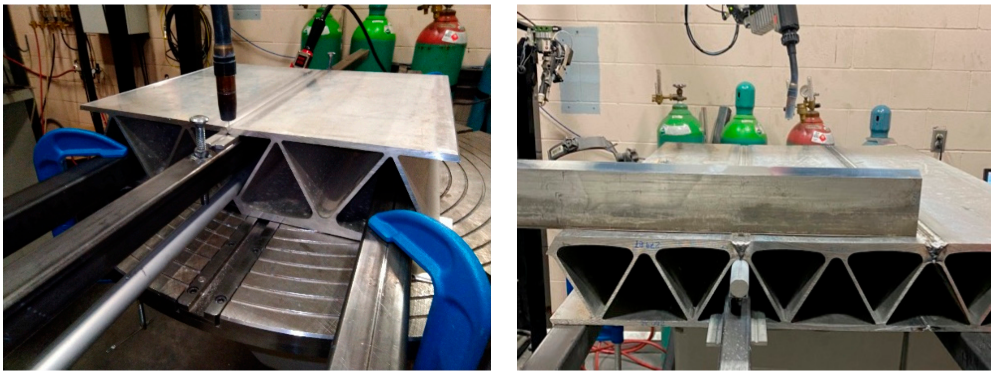


Figure 3. Montmorency Forest's bridge cross-section.

The research project that frames the construction of the aluminium deck requires the use of the GMAW technique. The heat generated by such a procedure can cause significant undesirable deck deformation, which has to be limited to strict specified tolerances. For fatigue purposes, the design requires that the backing bars be removed after welding, leading to a higher fatigue detail class. In the construction contract terms, it was specified that the owner would provide extrusions to the contractor at the beginning of the project to allow its aluminium fabricator to test various welding strategies.

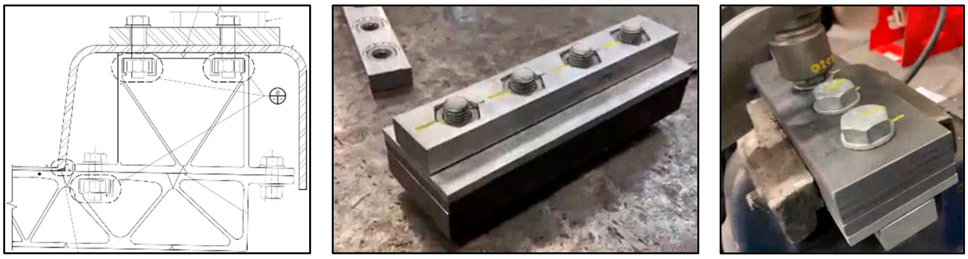
Figure 4 presents the welding trials that were taking place at the time of the writing of this paper. Preliminary removable backing bar setup was successfully achieved by the fabricator. Figure 4b shows the angular measurement of the welded extrusions after the welding and grinding of the top skin. The fabricator tried several initial angular deviations for extrusion pairs. Tables presenting final deviation as a function of initial configuration are currently being studied. Based on the preliminary results, the project team is confident that specified tolerances are achievable.



(**a**) (**b**)

Figure 4. (**a**) Welding of the bottom skin of the extrusions; (**b**) top skin deformation measurements.

WSP introduced the "bolting plate" technique to solve an important issue relative to hollow extruded aluminium decks. By their long and hollow nature, connecting extrusion panels to one another or anchoring barriers to the deck cannot be achieved with traditional bridge details as seen in Figure 5a. In the proposed solution, A325 galvanised nuts are embedded in an aluminium plate, as seen in Figure 5b, that is inserted inside the deck and guided by small flanges that are part of the extrusion. Bolts are then inserted by the top surface and turn-of-the-nut tightening can be achieved since the nut is stuck in place. Physical tests shown in Figure 5c have confirmed the performance of this technique and are reported in a companion paper [12].



(**a**) (**b**) (**c**)

Figure 5. (**a**) Barrier's anchoring system; (**b**) bolting plate technique; (**c**) physical tests.

An innovative expansion joint was developed during this project. The goal was to obtain a waterproof joint connecting the aluminium deck to the concrete foundation. The joint details are shown in Figure 6. The right-hand part of the device is the traditional concrete embedded joint detail. The left-hand side shows how the deck is transversely machined to leave room to weld an internal transverse capping designed to receive the strip seal. The important movements between summer and winter seasons generated by the aluminium deck's high thermal expansion coefficient are accommodated by this joint.

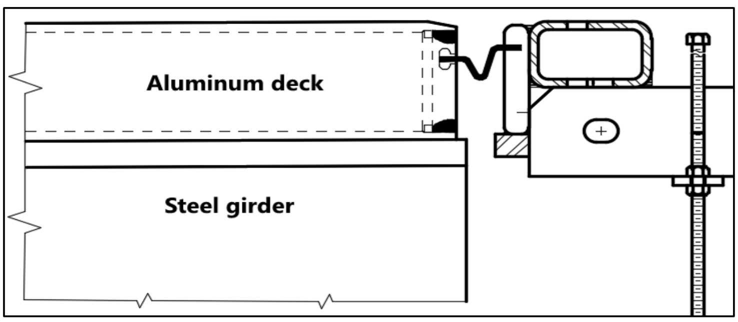
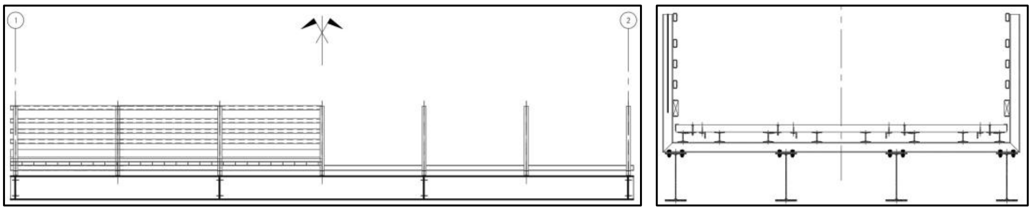


Figure 6. Montmorency Forest's expansion joint.

As described further in this paper, replacing the steel girders by aluminium girders would be a natural extension of this structural system. Composite action could then be considered because of the thermal compatibility of the two structural layers. Also, friction stir welding (FSW) has the potential to surpass GMAW for the deck. Application of the bolting plate technique to connect deck panels together is another interesting avenue.

4. Aluminium Girders for Bridges

Alu-Québec's directory shows the growing popularity of the truss structural system for aluminium pedestrian bridges [3]. A preliminary design project for Alu-Québec aimed to determine if a simpler solution consisting of aluminium girders could be competitive. The lateral elevation and the cross-section of the single-span concept are shown in Figure 7. U-shape aluminium frames support the barriers and act as floor beams. Decking is composed of transverse wood planks sitting on aluminium longitudinal stringers.



(**a**) (**b**)

Figure 7. (**a**) Lateral elevation of the aluminium girder bridge; (**b**) cross-section of the bridge.

The project confirmed that the procurement of large aluminium plates is possible for North American projects. Such a structural system requires the bracing of the girders for lateral stability. Welding stiffeners to the flanges and the web of the girders generate a heat-affected zone across nearly the entire girder cross-section. This section is weakened by welds for the sectional flexural resistance. But, for the global flexural stability, the transverse welds are advantageously considered to be located at the end of the member because they coincide with the location of the bracing. As far as flanges and web plates welded splices are concerned, the previous ascertainment shows that it is preferable that they be located closer to the bracing to regroup the heat-affected zones "at the ends" (i.e., the bracing locations) of the girder.

The preliminary design led to the conclusion that a girder system could be more cost-efficient than a truss system for spans shorter than 20 m. The girder bridge would require a larger aluminium mass because of the reduced depth of the flexural component. That extra procurement cost is, however, counterbalanced by the highly reduced cost of welding, which is simpler for girders than for trusses.

The project led to an extension mandate to clarify the calculation procedure for aluminium girders. As seen in Figure 8, an aluminium girder bridge can exhibit multiple welding scenarios. Each scenario requires a specific calculation approach to account for weld effects. The method to account for slender webs was clarified by the provisions of Eurocode where the web thickness is reduced according to post-buckling resistance [13].

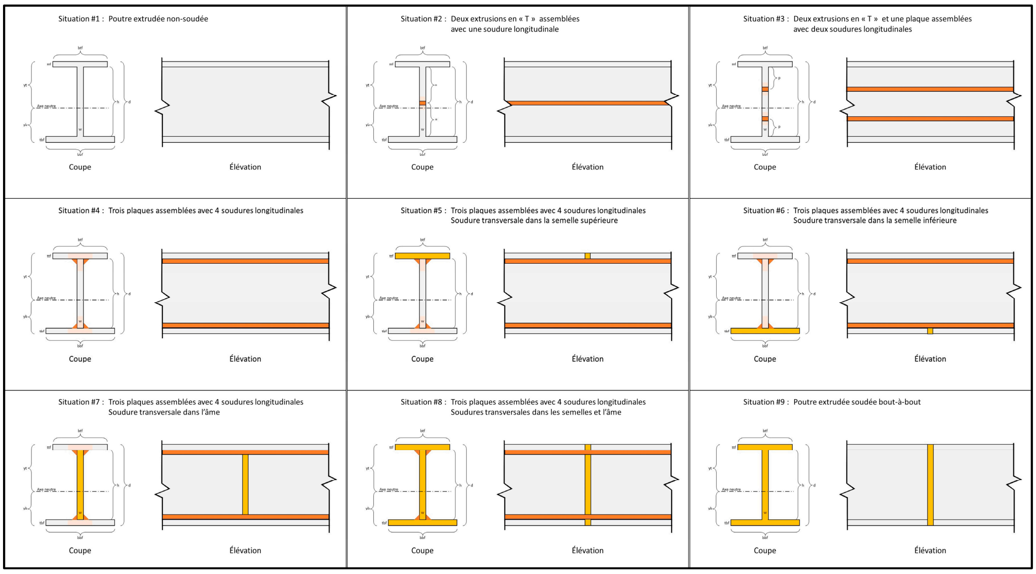


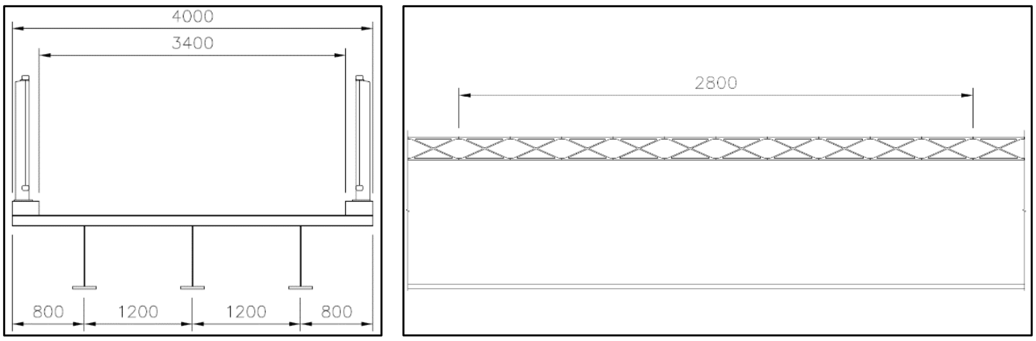
Figure 8. Various welding scenarios for aluminium girders.

A main difference between the calculation of steel and aluminium girders is the requirement for the latter to calculate elastic and plastic effective section properties based on welding and slenderness effects. A calculation tool based on a parametric section using three segments for each flange and six segments for the web was developed. The tool available through the Alu-Compétences' platform explicitly details the bending and shear resistance for the nine scenarios presented in Figure 8 [14].

It is believed that aluminium girders' potential is currently underestimated. This project inspired new provisions for aluminium flexural members in the upcoming CSA S6-25 that will hopefully help to facilitate their design [8].

5. Aluminium Deck and Girders Composite System

Various features from the three previous projects were merged into an innovative structural concept presented in Figure 9. To respect the confidentiality aspect of the specific project, a generic layout of the structural arrangement, which could be applicable to multiple situations, is presented in this paper. The upper part of the structure is a deck composed of transverse aluminium extrusions welded together by FSW. The lower part consists of a web and a lower flange assembled by GMAW. The whole forms a fully prefabricated composite-effect aluminium structure. The guardrail is bolted to the deck using the bolting plate technique presented previously. An epoxy-aggregate layer is used as an anti-skid wearing surface.



(**a**) (**b**)

Figure 9. (**a**) Composite aluminium deck and girder cross section; (**b**) side elevation of a deck panel.

This structural arrangement was developed in the context of adding a multiuse path on various long-length vehicular bridges. Such bridges' decks would rely on the presence of floor beams spaced between 5 and 15 m apart, which would define the aluminium structure's span. The pedestrian bridge is continuous in bending and shear across the length of each of the vehicular bridge spans as described further. The material's lightness allows us to reduce the cost of reinforcements of the vehicular bridge. Moreover, the targeted spans are easily accommodated by adjusting the depth of the aluminium girders, which is an important advantage when compared to an orthotropic steel deck system.

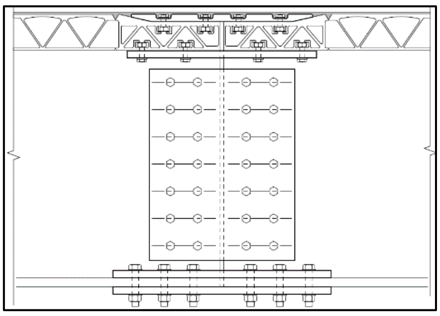
The deck extrusions are proportioned for pedestrian bridge loads. Deck sub-panels are welded using FSW, for which new provisions for fatigue based on recent research are currently considered for the upcoming CSA S6-25 [8,15]. Then, these sub-panels are assembled to one another in factory using the GMAW technique similarly to how it is used in the Montmorency Forest project. The final assembled deck can be as long as transportation limits allow.

Orienting the deck extrusions on the transverse direction has many advantages:

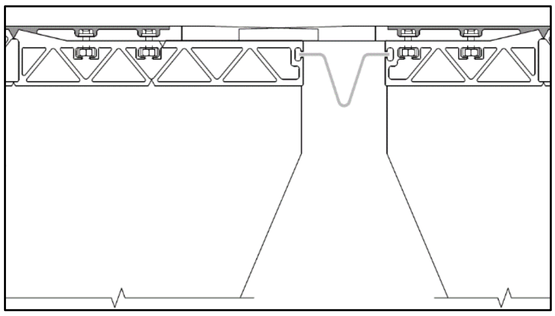
- Deck sub-panel's width can be adapted to fit in various FSW gantries.
- Specific extrusions can be designed for: barrier anchorage locations; bolted joints locations as show in Figure 10a; expansion joint and end of deck details as show in Figure 10b.
- Fabrication is repetitive and can be optimised.
- Complex transverse butt joint splicing of extrusions is avoided.

Aluminium plates are welded together to reach the assembled deck length. Web and bottom flanges are welded to the deck using GMAW. Stiffeners, bracings, barriers and wearing surface can be installed in factory. Aluminium's lightness allows for this complete prefabrication. For a hypothetic 80 m vehicular bridge span, three segments of 25, 30 and 25 m could be sufficient, making the installation quite efficient.

Two critical details have been developed for this concept. First, the aim is for the segments to be continuous along one vehicular bridge span. Specific bolted joints presented in Figure 10a are capable of transmitting moment and shear between segments. The web and bottom flanges are spliced in a traditional manner. Custom transverse extrusions allow for the insertion of the bolted plates described in the Montmorency Forest Project. Top and bottom cover plates transfer the longitudinal forces across the deck connection. The top plate is hidden below the wearing surface so that the splice does not affect cyclists' comfort.



(a)



(b)

Figure 10. (**a**) Composite structure bolted connections detail; (**b**) large amplitude expansion joint.

At the end of each vehicular bridge span, an aluminium expansion joint presented in Figure 10b allows for larger displacements than the Montmorency Forest project joint in Figure 6. This is required because of the more important structure length and aluminium's high thermal expansion coefficient. Finger joints are precisely machined in an aluminium plate according to cyclist comfort requirements. They are bolted to custom transverse extrusions using the bolting plate technique and hidden under the wearing surface. These plates could easily be replaced if required (e.g., following wear caused by snow removal vehicles).

This structural arrangement introduced in Figures 9 and 10 could advantageously be geometrically scaled up to accommodate vehicular traffic loads for innovative 100% aluminium vehicular bridges.

6. Signature Multi-Span Pedestrian Bridge with a Curved Segment

Alu-Québec mandated WSP to demonstrate that in addition to popular single span truss pedestrian bridges, it is also possible to design complex aluminium structures. The aim of this project was to redo the design of a steel architectural pedestrian bridge concept, but with aluminium as the structural material. Figure 11 presents the general layout of the proposed structure.

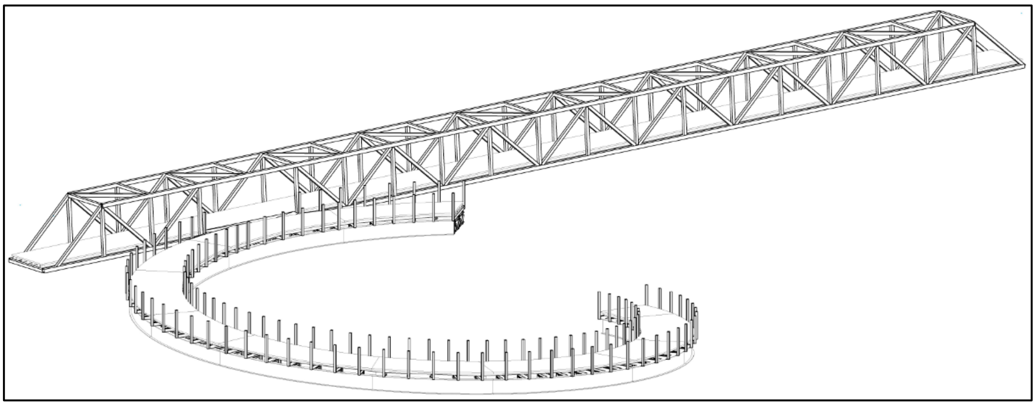


Figure 11. Isometric view of the aluminium signature pedestrian bridge.

The 80 m long linear portion is a 3.6 m deep by 3.9 m wide through truss. The longest span is about 47 m long. The truss is divided in four fully prefabricated segments, which have been optimised to fit into roadway transportation geometrical limits. Slip-critical bolted connections of truss chords have been developed for this project and are presented in Figure 12. This configuration includes a bulky internal extrusion on which high compression forces from the turn-of-the-nut tightened A325 steel bolts can be applied.

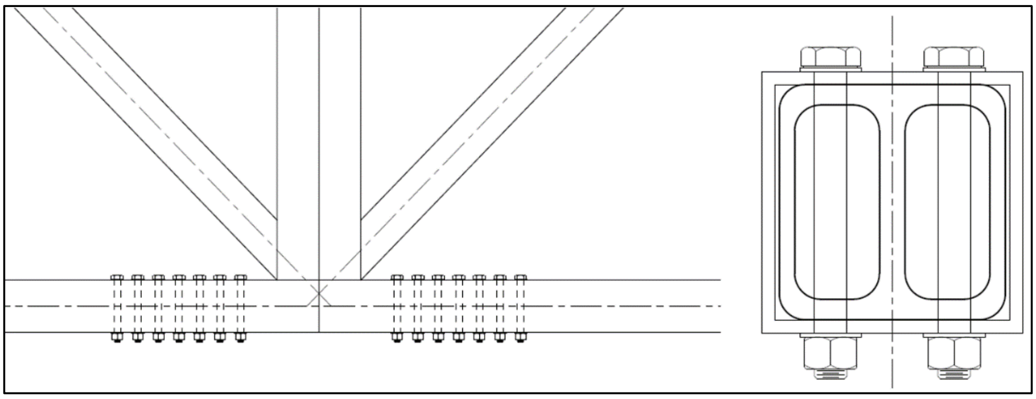


Figure 12. Truss chords slip-critical bolted connections plan view.

As seen in Figure 11a, Vierendeel opening in the truss allows users to travel between the straight and curved portions of the bridge. To reduce the bending moments in the truss, this opening is performed at an inflexion point of the straight structure. Welded reinforcement plates are added to the chords to increase their bending resistance. Articulated bearings fixing displacements but which allow for rotations are located under the verticals at each end of the Vierendeel opening.

The curved segment represents an important structural challenge. Since curved aluminium girders lack explicit design provisions, the CSA S6 approach for curved steel girders is adapted accordingly [7]. A direct consequence of the low radius of the curvature of the bridge is a narrow five degrees spacing between each set of transverse bracings. Finite element modelling shows that this close spacing is beneficial to reduce the warping stresses in the aluminium girders' flanges. At each bracing location, the vertical stiffeners welded to the girders lead to a completely heat-affected zone section. The unrestrained bending moment resistance in between the bracings is around the same magnitude, leading to demand over capacity ratios that are well balanced along the girders. Similar as the straight portion, the curved structure is designed as 11 fully prefabricated segments that are bolted on-site for quicker installation.

7. Conclusions

This paper has presented various structural arrangements and details that hopefully will inspire more vehicular and pedestrian aluminium bridge projects. The following non-exhaustive list presents topics that would help to propel the use of aluminium in bridges:

- The owners of bridges choosing structural main material based on total cost of ownership and environmental life cycle analysis [2];
- Continued research on the anchoring of barriers to aluminium decks [16];
- Advancements in the field of FSW technique applications;
- Extrusion industry mobilisation to standardise large structural sections such as square tubes and to publicise maximum geometrical capacities;
- Continued research on the galvanic corrosion of A325 steel bolts for aluminium bolted connections [1].

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The author would like to express his gratitude to Alu-Québec for the various opportunities to develop an aluminium industry network and to deepen technical challenges. Owners such as Parcs Canada and Laval University are thanked for their continued collaboration at each step of recent aluminium bridge projects. CSA S6 Technical Subcommittee on Section 17—Aluminium structures is acknowledged for the team efforts towards recent provision improvements.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Zhang, J.; Ebrahimi, N. *Galvanic Corrosion in Steel and Aluminum Bridges*; CSA: Mississauga, ON, Canada, 2022.
2. Pedneault, J.; Bayan, C.; Sorelli, L.; Margni, M.; Conciatori, D.; Desjardins, V.; Fafard, M. *Analyse du Coût Total de Possession sur le Cycle de vie d'un Pont Routier à Platelage en Aluminium*; Laval University: Québec City, QC, Canada, 2019.
3. Répertoire des Passerelles Conçues et/ou Fabriquées au Québec. Available online: https://aluquebec.com/repertoires/passerelles/ (accessed on 4 April 2023).
4. Arvida Aluminium Bridge. Available online: https://csce.ca/en/historic-site/arvida-aluminium-bridge/ (accessed on 4 April 2023).
5. Cusson, B. Two Outstanding Aluminum Pedestrian Bridges in a National Historic Site. In Proceedings of the IABSE Conference, New York City, NY, USA, 4–6 September 2019.
6. Cusson, B.; Toupin, J.D. Innovative Aluminium Pedestrian Bridges Case Study. In Proceedings of the CSCE Annual Conference, Laval, QC, Canada, 12–15 June 2019.
7. *CSA S6:19*; Canadian Highway Bridge Design Code, 12th ed. Canadian Standards Association: Mississauga, ON, Canada, 2019.
8. *CSA S6:25*; Canadian Highway Bridge Design Code. Canadian Standards Association: Mississauga, ON, Canada, *Currently under development*.
9. *CSA S7:23*; Pedestrian, Cycling and Multiuse Bridge Design Standard. Canadian Standards Association: Mississauga, ON, Canada, 2023.

10. Service d'Étude Technique des Routes et Autoroutes. *Footbridges—Assessment of Vibrational Behavior of Footbridges under Pedestrian Loading*; Association Française de Génie Civil: Bagneux Cedex, France, 2006.
11. Cusson, B. Designing and Detailing a GMAW Welded Aluminium Deck on Steel Girders for CSA S6:19 Traffic Loads. In Proceedings of the 11th International Conference on Short and Medium Span Bridges, Toronto, ON, Canada, 19–22 July 2022.
12. Buzatu, P.; Erian, J.; Cusson, B. Bolting Plate Technique for Aluminium Deck Connections. In Proceedings of the 15th International Aluminium Conference, Québec City, QC, Canada, 11–13 October 2023.
13. *EN 1999-1-1:2007*; Eurocode 9: Design of Aluminium Structures—Part 1-1: General Structural Rules. European Committee for Standardization: Brussels, Belgium, 2007.
14. Portail Alu-Compétences. Available online: https://aluquebec.com/alu-competences/ (accessed on 17 April 2023).
15. Oliviera Miranda, A.C.; Gerlich, A.; Walbridge, S. Aluminum friction stir welds: Review of fatigue parameter data and probabilistic fracture mechanics analysis. *Eng. Fract. Mech.* **2015**, *147*, 243–260. [CrossRef]
16. Cormier, M. *Développement D'assemblages de Dispositif de Retenue Pour Les Ponts à Platelage en Aluminium*; Laval University: Québec City, QC, Canada, 2019.