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Proceeding Paper

Optimal Extrusion Shape for Fabricating Aluminium Bridge Deck Using Assembly-Based Friction Stir Welding with Bobbin Tool †

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Abstract: This article presents an optimal extrusion geometry for fabricating a bridge deck. The profile of the extrusion enables the possibility of welding onto another extrusion through butt joints only. This type of welding joint is optimal in terms of both the ultimate resistance and the fatigue performance. Thus, the aluminium deck will be manufactured by welding these extrusions together through the bobbin tool friction stir welding process, resulting in a full-penetration weld, free of the kissing bond and the flash toe defects, and in which the thermal input and the stirring are symmetrical on both outer sides of the butt joint. Therefore, this geometry addresses the shortcomings of both the MIG and the conventional FSW processes and significantly increases the lifespan of the aluminium deck. This article will present the scientific and technical approach, based on the Canadian standard CSA S6:19, and will present an example of application on an aluminium/glued laminated timber bridge.

Keywords: welding; aluminum; bridge; extrusion; FEM; finite element analysis

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1. Introduction

The ageing of road network structures and bridge decks in particular demands substantial rehabilitation investment. In the province of Québec alone, no less than CAD 724.4 was devoted to maintaining the bridge structures within its road network in 2014 [1]. This ageing phenomenon is even more visible on concrete bridge decks due to the corrosive action of the de-icing salts typically used in cold environments [2]. These rehabilitation investments seek to find alternatives to the traditional concrete bridge decking and endow existing bridges with additional cantilever bikes and pedestrian lanes to increase the use of alternative commuting options [3].

In this regard, aluminium presents the advantages of being corrosion-resistant, requiring little to no maintenance, and being easily shaped into optimized and adapted forms by extruding the desired profiles. It also offers an excellent resistance-to-weight ratio and good resistance in low temperatures and harsher environments [4].

Ever since aluminium began to be used on bridge decking, metal inert gas (MIG) welding has been the main technique used to join together the extrusions making up the bridge deck [5]. This fusion welding technique, known for many decades, has been proven to significantly weaken the aluminium in the vicinity of the weld, known as the heat-affected zone (HAZ) [6]. In addition, it is not always possible for the extruded aluminium beams to be butt-welded together, as shown in Figure 1, which, according to many design codes, is the best type of weld in terms of fatigue performance [7]. To circumvent these flaws, designers need to create substantially wider and deeper welding joints, resulting in heavier decks, thicker welds prone to stress concentrations, and a significant build-up of residual welding stresses in the structures, leading to geometrical imperfections, which in turn do not allow a flat deck to be obtained [8].

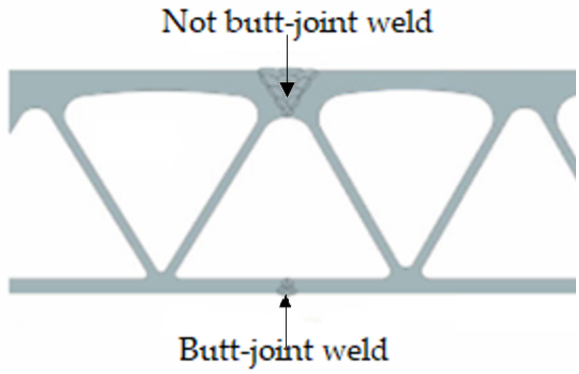

Figure 1. Presence of butt joint and other type of welding joints in the same extrusion [9].

One alternatively is friction stir welding (FSW), a solid-state welding technique where the parts to be joined are locally heated using friction and in which the softened material from either part is stirred into a welding joint all by the means of the vertical force of the stirring tool [10]. In addition, friction stir welding (FSW) involves a much smaller heat input compared to MIG welding, resulting in a narrower HAZ and making the fatigue performances of an FSW joint lie between those of an MIG joint and the base metal [11].

Although FSW welding addresses many of the shortcomings of MIG welding, its application to assemble hollow extruded sections together has proved to be challenging. In fact, a form of temporary backing is required to withstand the large vertical force from the stirring tool, especially in thin-walled profiles [12], as shown in Figure 2. This removable temporary backing adds to the complexity of the welding process and could ultimately govern the profile of the extrusion instead of it being shaped by mechanical and structural considerations. This was the case for the Saint-Ambroise bridge made from an aluminium deck on steel girders. The aluminium deck was made through the welding of extrusion using the standard FSW process of triangular aluminium extrusion [13].

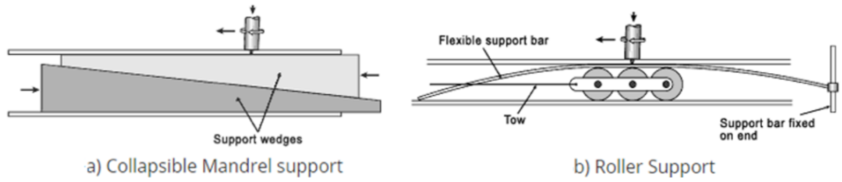

Figure 2. Extrusion and hollow section support for FSW [12].

A few projects attempted to include in the shape of the extrusion an inbuilt supporting feature to withstand the vertical force of the stirring tool and eliminate the need for a temporary backing, as shown in Figure 3a. However, due to the geometrical tolerances and discrepancies between two consecutive extrusions to be welded together, as shown in Figure 3b, a lack of penetration often happens, resulting in a kissing bond.

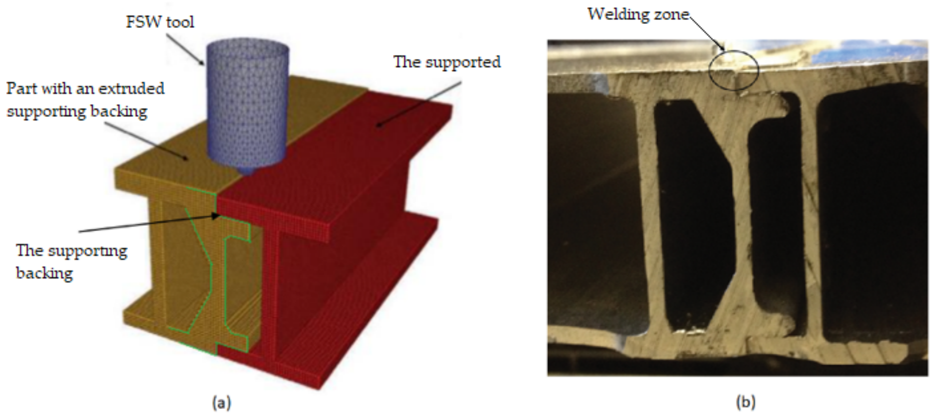

Figure 3. Inbuilt supporting feature. (**a**) Extruded profile with a supporting backing; (**b**) the actual shape after extrusion [14].

This kissing bond greatly reduces the fatigue performances of the welding joint to a level below that of a MIG butt joint weld [15]. Finally, the inherent vertical force in the FSW welding may create a toe flash and a loss of section, which negatively impacts the fatigue performance of the welding joint, even in simple butt joints free of any built-in supporting backing [15]. Figure 4 presents some examples of the toe flash defect. It can easily be observed that the loss of the cross-section and the sharp stress concentration due to the defect reduce the fatigue performance of the weld.

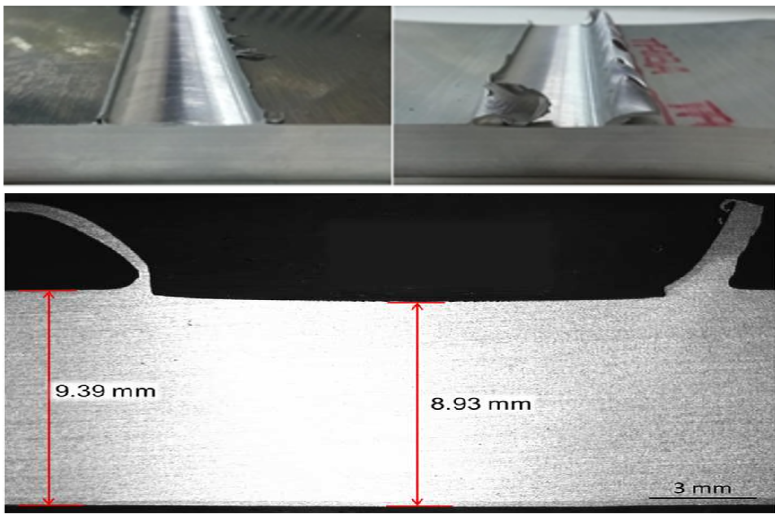

Figure 4. Toe flash in an FSW butt joint weld [15].

2. Design of the Bridge Deck

2.1. Material Proprieties

The design of the deck was carried out according to the aluminium alloy proprieties provided by the Canadian Highway Bridge Design Code (CHBDC) [8]. Amongst all these provided alloys, AA6005A-T61 offers the highest mechanical resistance, with good extrudability and weldability still. The CHBDC provides both the yield and the ultimate stress values for the base metal, respectively, F_y and F_u. However, the CHBDC, in its version referred to in this article, does not provide any yield (F_{wy}) nor ultimate (F_{wu}) value for the metal inside the HAZ nor the extent of this HAZ for the friction stir welding. In the absence of such information, a conservative approach will be taken and the values of the MIG welding will be used instead. The minimal resistance values are listed in Table 1.

Table 1. Minimal resistance according to CHBDC for AA6005-T61.

Alloy	Type	Thickness, mm		Minimal Resistance, MPa			
		>	<	F_u	F_y	F_{wu}	F_{wy}
AA6005-T61	Extrusion	--	25	260	240	165	90

Similarly, the CHBDC only provides fatigue resistance values for the base metal and the HAZ of the MIG-welded metal. As previously mentioned, the deck design only comprises flat butt joints welded together. The CHBDC refers to the base metal and the butt joint welds as "A" and "B" categories, respectively. To compute the fatigue resistance values of these two categories, the loading cycle's frequency is considered. In this regard, the deck is designed to be used on class-A highways, which is the highest class in terms of average daily truck traffic (ADTT), and for a lifespan of 75 years. Finally, the maximum values of the stress range for the loading conditions previously mentioned and for the detail categories "A" and "B", $f_{sr,max}$, are shown in Table 2. The value of $f_{sr,max}$ is the factored and standardized fatigue stress range due to the passage of a CL-625 truck that the CHBDC provides for the considered detail category.

Table 2. Fatigue resistance criteria, $f_{sr,max}$, for detail category "A" and "B".

	Detail Category A	Detail Category B
$F_{sr,max}$, MPa	60.9	29.0

2.2. Deck Configuration

In order to develop a fatigue-resistant deck configuration, it is initially sufficient to apply a wheel patch load on a 3 m by 3 m deck, as shown in Figure 5. Once this initial deck geometry is obtained, a validation with a full-scale bridge design is carried out using this geometry, where other limit states are to be checked.

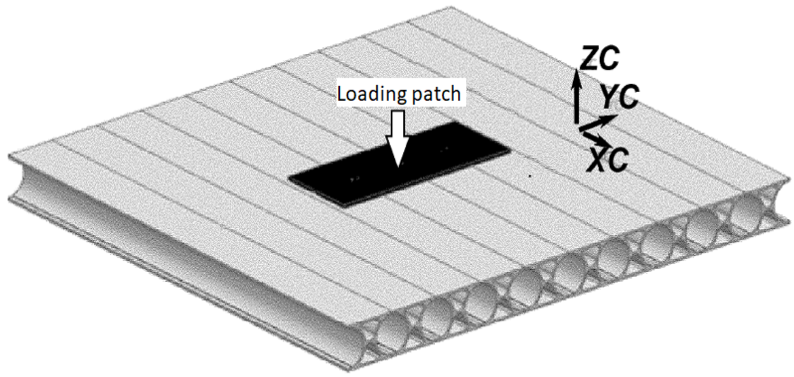

Figure 5. A 3 m by 3 m deck panel and the loading patch.

2.3. Design Loads and Criteria

According to the CHBDC, the live load to apply is based on a truck model called the CL-625. This 5-axle truck, with a total weight of 625 kN, is illustrated in Figure 6.

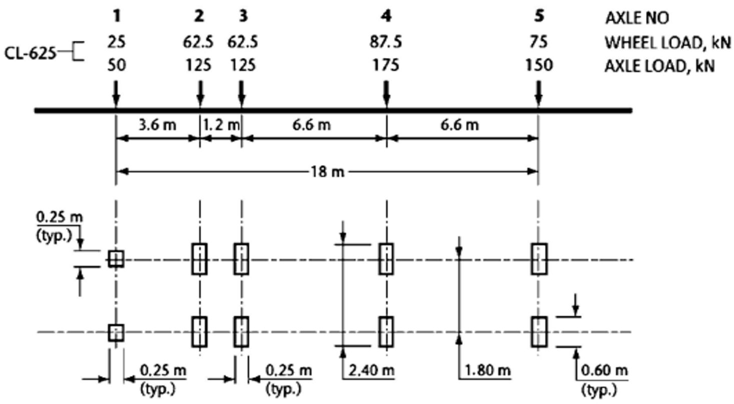

Figure 6. The CHBDC loading truck, CL-625.

Given that the fatigue limit state (FLS) controls the design [15,16], the geometry of the extrusions is developed using the loading and the criteria of this limit state, and then the obtained profile is validated in a full-scale service and ultimate limit state, SLS and ULS, respectively. The CHBDC states that for the fatigue limit state, only axles 2 and 3 are to be used. Also, given the size of the 3 m by 3 m panel used to develop the geometry of the extrusion, the most taxing flexural loading is obtained by placing one wheel only in the centre of the panel.

The extrusions to be developed need to allow bobbin tool friction stir welding (BTFSW) and MIG butt joint welds. To accommodate the bobbin tool, a minimum clearance of 26 mm is required in the extrusion, as shown in Figure 7. Note that the profile is for illustrative purposes only.

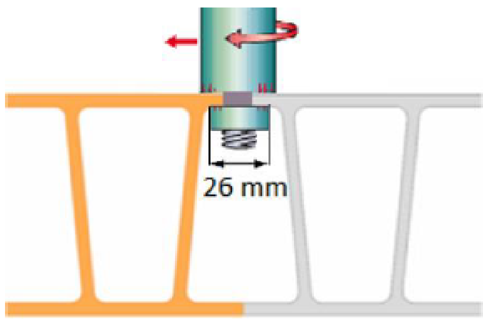

Figure 7. The clearance required to allow for the bobbin tool nut.

Lastly, the cross-sectional area of the developed extrusion needs to be below 9000 mm^2 so it can be manufactured on the extrusion presses available in the industry.

2.4. Design Method

Using the commercial finite element analysis (FEA) software NX/NASTAN, several geometries were simulated under the loading conditions and the design criteria previously mentioned.

The models to be analyzed were meshed with hexahedral quadratic solid elements, and the appropriate boundary conditions were applied, as illustrated in Figure 8, where one lower edge of the last extrusion of the panel is fully restrained while the opposite lower edge is only vertically restrained and free in all other directions. A gluing contact interaction was set between the extrusions that form a deck and between the loading patch and the deck. The loading patch material is rubber with a minimum thickness of 5 mm to avoid any local stiffening of the loaded area.

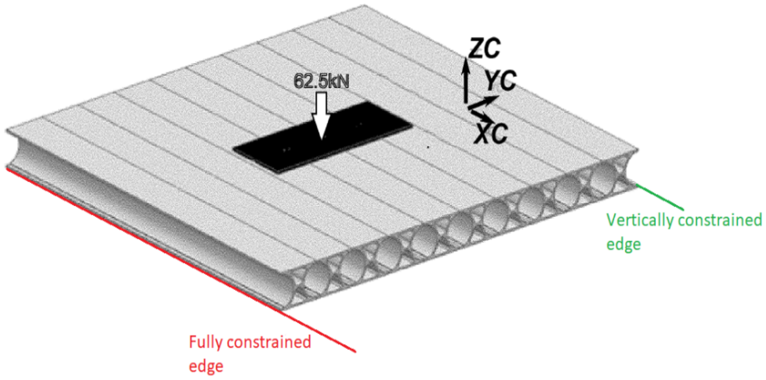

Figure 8. CAD model and boundary conditions.

3. Results

3.1. Simulation Results for Different Extrusion Shapes

Figure 9 presents the von Mises stress of one of the several extrusion profiles used to design the optimal deck panel extrusion. The von Mises stress scale is set from 0 to 30 MPa. The value of 30 MPa is slightly above 29.02 MPa, which is the fatigue limit for an MIG-welded butt joint. We can observe many red zones where the von Mises stress is higher than the maximum value of 30 MPa.

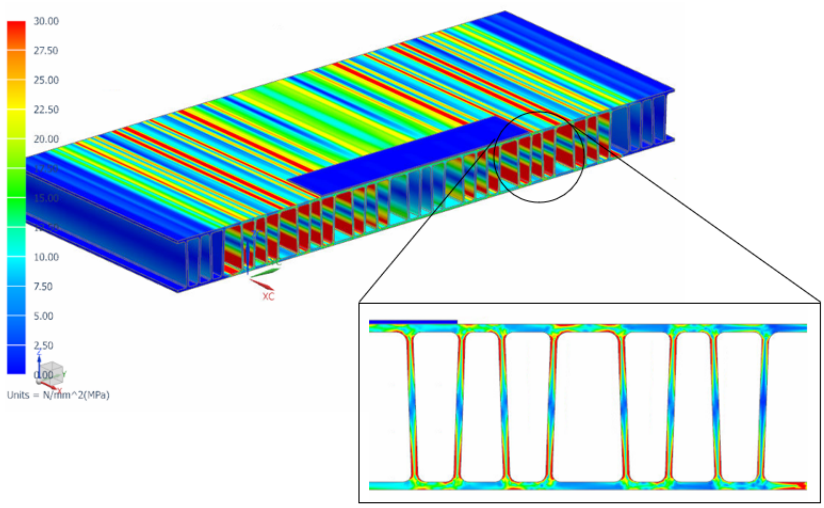

Figure 9. The von Mises stress distribution of a given extrusion profile.

The result for this geometry is not satisfactory, and many other extrusion profiles were simulated. Some of these profiles as well as their von Mises stress distributions are presented in Figure 10.

These geometries are again still not yet satisfactory, and a final geometry was tested based on a trial-and-error approach. The von Mises stress distribution of this geometry is presented in Figure 11, where the stress distribution is satisfactory based on the design criteria previously mentioned.

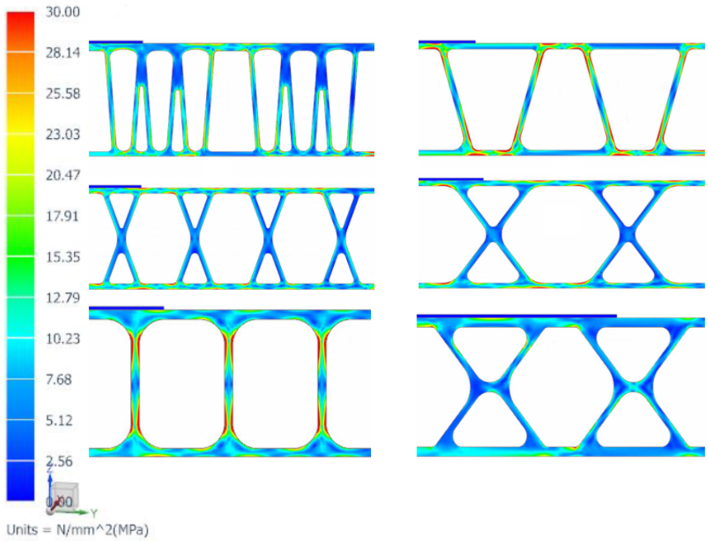

Figure 10. The von Mises stress distributions of some of the simulated profiles.

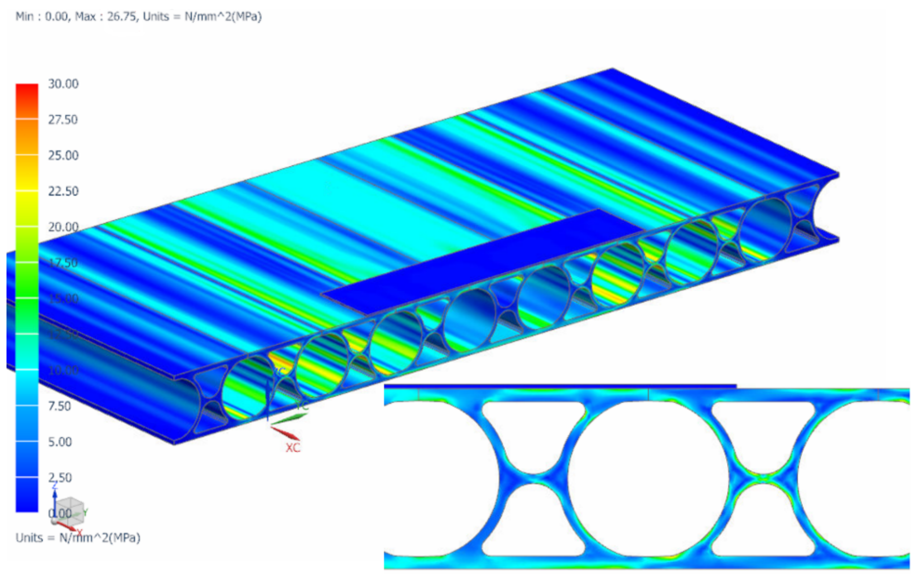

Figure 11. The von Mises stress distribution on the optimal extrusion shape.

3.2. Full-Scale Bridge Simulation Using the Optimal Extrusion Shape

A full-scale 20 m bridge case study (aluminium deck on glulam girders) was carried out using the geometry previously developed, where not only the fatigue limit state (FLS) but also the service (SLS) and the ultimate (ULS) limit states were checked [17]. In this full-scale bridge case study, the design was again controlled by the fatigue limit state (FLS). Hence, only the results of the FLS are presented in this article.

Figure 12 presents the von Mises stress of the entire bridge. It can be noted that the stress is mainly located in the close vicinity of axles 2 and 3, which are the only loaded ones in the FLS. Figure 13 presents the von Mises stress distribution in a transversal cut along the most stressed area of the bridge, whereas Figure 14 presents the distribution of the transversal stress to the welding joint, σ_{yy}.

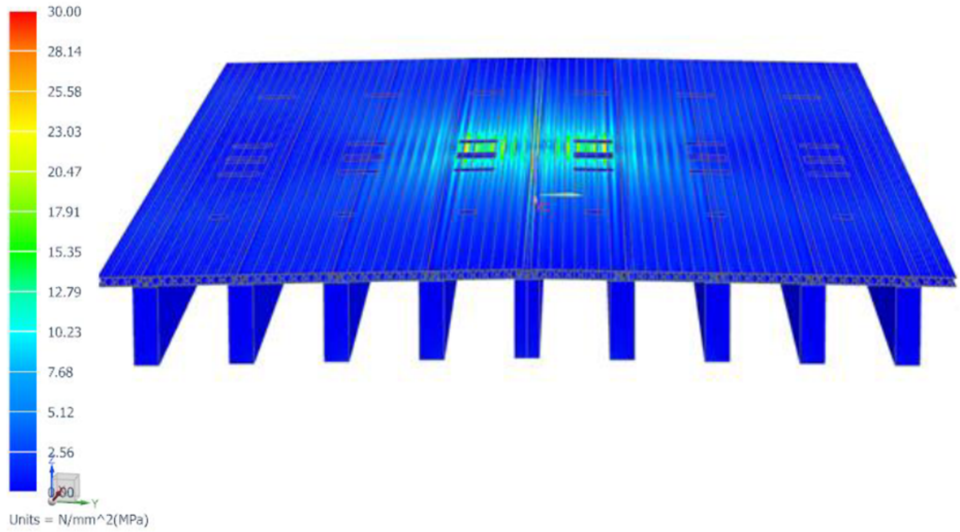

Figure 12. View of the full-scale 20 m bridge [17].

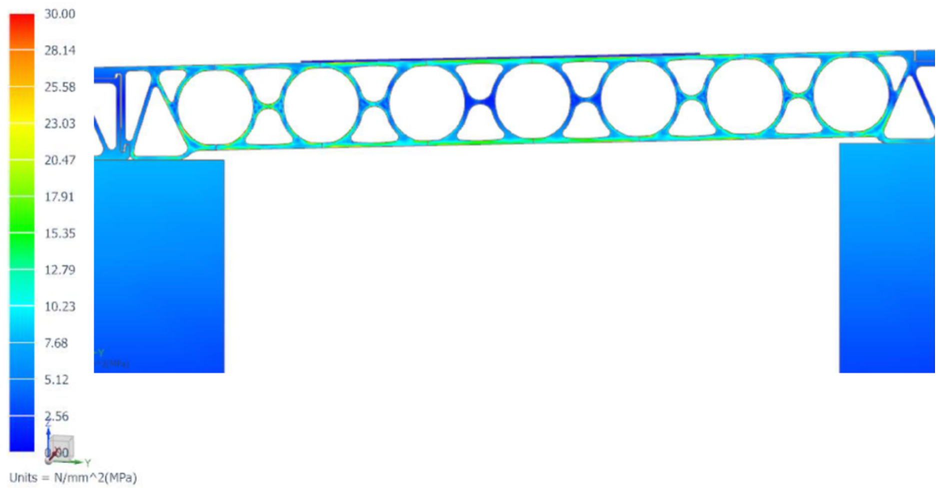

Figure 13. The von Mises stress distribution under the loaded axles.

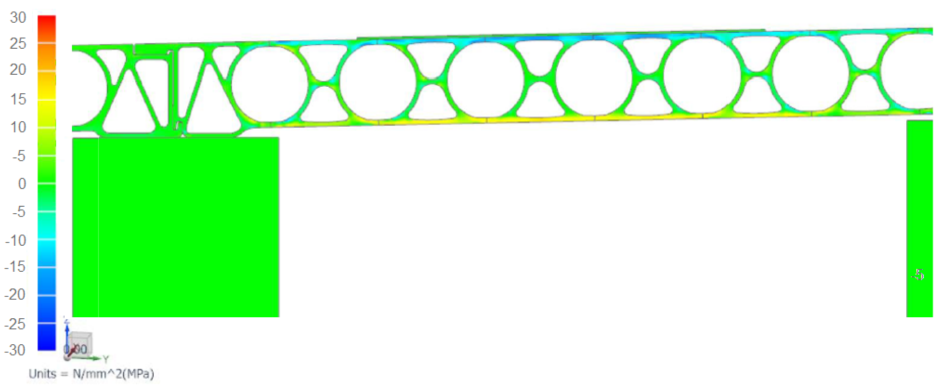

Figure 14. The transversal stress distribution, σ_{yy}, in the most stressed area of the bridge.

4. Fatigue Test

Instead of extruding the profile presented in this article, a more economical approach was preferred to test the weldability and fatigue performances of a BTFSW butt joint weld. In this regard, the upper and lower 8 mm thick flanges of two 6005-T6 H-beams were welded together using BTFSW, as shown in Figure 15. These H-beam profiles were chosen given the geometrical similarity they provide with the butt joint welds of extrusion geometry of this article. Samples from the welding joint were taken and tested in the laboratory both in fatigue and in static loading. The results were published in [18]. These show beyond any doubt that the fatigue resistance of this type of weld greatly exceeds the values prescribed by the CHBDC. Note also that the 2025 version of the CHBDC plans to add a new category of details for butt joints welded using FSW.

Figure 15. Set-up for the welding of 2 H-beams using BTFSW.

5. Conclusions

This paper presents the innovative solution of using the bobbin tool friction stir welding technique to join aluminium extrusions through butt joints only. This weld with good fatigue performance, coupled with the innovative geometry of the extrusion, allows the manufacturing of aluminium decks in which all the shortcomings of the MIG welding technique as well as the conventional friction stir welding technique have been addressed.

A finite element analysis of a full-scale bridge, using a deck made out of the extrusion geometry presented in this paper, was carried out. The satisfactory results of this simulation led to carrying out fatigue tests on bobbin-tool-butt-joint-welded H-beams. The results of these fatigue tests confirmed the high performance of the welding technique presented in this paper.

6. Patents

Extrusion profile for modular structural applications and corresponding method; Université Laval; Amar DJEDID and Mario FAFARD; V/Réf.: 02248; N/Réf.: 000819-043.

Author Contributions: Conceptualization, A.D. and M.F.; methodology, A.D. and M.F.; software, A.D.; validation, A.D., M.F. and M.O.; formal analysis, A.D.; investigation, A.D.; resources, A.D.; data curation, A.D. and M.F.; writing—original draft preparation, A.D.; writing—review and editing, A.D., M.F. and M.O.; supervision M.F. and M.O. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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