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Aluminum Structures

Structures en aluminium

Aluminum in Bridge Design and Construction

Michael Stacey, Michael Stacey Architects

Since the mid 1990s, architects have increasingly become involved in bridge design – linking the art and science of construction. Inventive fabricators are also generating innovation in the use of aluminum to form bridge structures. Typically bridges have a very clear identity and the design of bridges is like product design. Martin Heidegger poetically describes the role of bridges in human experience: “The bridge gathers to itself in its own way earth and sky, divinities and mortals.”¹

The Towards Sustainable Cities Research Programme conducted by Michael Stacey Architects with KieranTimebrlake has revealed a growing and worldwide take up of aluminum in bridge construction, from complete bridge structures to bridge deck systems, and standard and bespoke aluminum guarding systems.²

The first use of aluminum in bridge construction is the replacement of deteriorated timber and steel decks of the 1882 Smithfield Street Bridge in Pittsburgh with aluminum decking in 1933. This is almost 40 years later than the first use of aluminum in architecture.³ The deck was fabricated from 2014-T6 aluminum alloy and was in use until 1967, when the deck was replaced again with a 6061-T6 aluminum alloy deck. The earliest all aluminum bridge was built in Massena, New York State in 1946, the Grasse River Bridge had a 30.5m span fabricated from 2014-T6 alloy. It carried rail traffic serving an Alcoa smelter.⁴

The world's first two aluminum opening bascule bridges were built in the UK, serving the docks of Sunderland and Aberdeen. Hendon Dock aluminum bascule bridge, Sunderland, 1948, was built by Head, Wrightson & Co of Stockton who had started making mining engineering equipment out of aluminum alloys in the 1930s and they were awarded the contract by the River Wear Commissioners to build this bridge.⁵ The bridge was 37m long and 5.64m wide.

The second of these aluminum bascule bridges was assembled at Victoria Dock in Aberdeen, by Head, Wrightson & Co, to a similar specification, but it was only 30m long, it opened on 30 September 1953.⁶

Contemporary examples of bascule bridges built from aluminum include Helmond bridge built in 1999, Riekerhavenburg and Westdork Bridge both completed in 2003. These bridges in Amsterdam were fabricated by Bayards using extruded trapezoidal aluminum profiles.

Arvida Bridge is the oldest extant aluminum road bridge, it spans the Saguenay River at Saguenay–Lac-Saint-Jean in Québec built of aluminum between 1948 and 1950. It is 10.4m wide, 154m long and the primary arch spans 88.4m. This bridge, fabricated from 2024-T6 aluminum alloy, is still performing well having been refurbished during 2013 and 2014.

The primary advantages of using aluminum in the construction of bridges include:

- Lightweight, with a high strength to weight ratio, this is particularly important in opening bridges and the refurbishment of existing bridges;
- Durable, offering long-life with low maintenance, subject to appropriate alloy selection, detailing and finishing;
- Flexible in fabrication from the extrusion of large sections and highly developed welding techniques including friction stir welding;
- Rapidly installed, using large prefabricated components that can be readily transported and lifted in to place.

Aluminum performs very well in life cycle assessments (LCA), especially in regions of low carbon hydro electric smelting, furthermore, the total cost of ownership of all aluminum bridges can be beneficial, as evidenced by Canadian research undertaken by Deloitte (2012).⁷

A particularly delightful pedestrian bridge, with an aluminum structure, is the Bridge of Aspiration at the Royal Ballet School, London, UK, designed by architect WilkinsonEyre with engineers Flint & Neil.

It was fully prefabricated and installed in a single Sunday during 2003. The brief called for a bridge crossing Floral Street in Covent Garden, to link the Royal Ballet School with the E. M. Barry's Royal Opera House, and to provide direct access for the dancers to rehearsals and performances.



Bridge of Aspiration, London, UK, installation.

Credit: WilkinsonEyre

Two existing openings were identified, however, they were asymmetrically placed in terms of both plan and level above the street. Jim Eyre's initial sketch, sent to structural engineers Flint & Neill, was a series of rotating squares in space translating the geometry between the two buildings and resulting in a gently ramped walking plane.

The realised design is composed of 23 aluminum frames, each rotated in space by 3.91°. The frames are linked together by a twisting aluminum box beam, which is only apparent during assembly.

The bridge is articulated by the rotating aluminum frames and united by a glass skin that is translucent and clear. The translucent glass conceals the structure but more importantly provides privacy for the dancers from the street below. This gives way to clear glass that provides views out for those using the bridge. One way of reading this bridge is the interplay of two forms, each made of translucent and clear glass.

Internally the aluminum frames are partially clad in oak, to accommodate the glass that is not parallel with the mullions and to accentuate the reading of the twisting geometry.

The Bridge of Aspiration was totally prefabricated by GIG, an Austrian company, in its North London facility, which is more typically used for prefabricating unitised curtain walling. Thus, GIG has all the advantages of the controlled conditions of factory production, yet avoiding transporting large prefabricated assemblies across continental Europe and the Channel.

The bridge is literally a translation in space; however, it also serves as a metaphor of the movement of a dancer through space, an architectural overture of the performance in the Royal Opera House—just a few dance steps away across Floral Street.

The Equestrian Park Bridge, Blainville, Québec was designed for use by pedestrians, horses and riders by specialist fabricator MAADI Group and installed in 2012. It is an 18m single span aluminum bridge with a clear width of 3m and a self-weight of almost 7 tonnes or 380 kg/m.

It is an open truss with a gently curved profile fabricated from MIG welded square hollow section (SHS) aluminum extrusions in two sizes, 125mm and 150mm and was fully prefabricated. This mill finished single span aluminum bridge rests on simple concrete abutments. It has an Ipe hardwood deck and kick plates with aluminum guardrails.

During 2004 MAADI Group used similar technology to fabricate an all aluminum pedestrian bridge linking an oil-rig and its accommodation platform. It spans 46.3m and is a walk through box truss with a clear width of 1.2m. It has an aluminum grip span deck, aluminum kick plates and guardrails. The self-weight of the bridge is only 13.7 tonnes or 296 kg/m. The bridge is fabricated from welded 150mm and 200mm SHS aluminum extrusions, using a combination of 5083-H321 and 6061-T6 alloys. It will require very little maintenance, even in an exposed maritime location. It was fully prefabricated in Boucherville, Québec, using MIG and TIG welding.

A prototype of a rapidly deployable military bridge for the Canadian armed forces has been designed and fabricated by MAADI Group in 2016.⁸ Designed for pedestrian and light vehicles to overcome obstacles, such as rivers and ravines, in the battlefield and humanitarian disasters. This bridge has an overall length of 18.3m to be able to span a maximum 16m, with a clear width of 1.5m. Eight to 10 people can deploy the bridge in 80 minutes. The quick fit prefabricated assembly of aluminum components is locked off with stainless steel bolts, with reusable stainless steel split pins on stainless steel wire tethers.

This military bridge is a development of MAADI Group's patented weld free civic pedestrian bridge range Make-A-Bridge.⁹ The military



A rapidly deployable military bridge for the Canadian armed forces



Pedestrian bridge linking an oil-rig and its accommodation platform.



Equestrian Park Bridge, Blainville, Québec.

Credit: MAADI Group

Credit: MAADI Group

Credit: MAADI Group

version of MAADI Group Make-A-Bridge is an exemplar of Design for Assembly (DfA) and Design for Disassembly (DfD) as discussed in Aluminum Recyclability and Recycling.¹⁰ It is also an excellent example of the versatility of aluminum extrusions and casting, providing flexibility in design and realisation. Alexandre de la Chevrotière, CEO of MAADI Group, considers that 'this product would not be possible without capability of aluminum extrusions'.¹¹ ■

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¹M. Heidegger, *Building Dwelling Thinking*, in *Poetry, Language, Thought*, (1975) trans. by Albert Hofstadter, Harper Colophon Books, New York, p.153.

²Towards Sustainable Cities Research Programme is funded by the International Aluminium Institute and the reports can be down loaded via www.world-aluminium.org/publications/tagged/towards%20sustainable%20cities/

³The known example is an aluminium ceiling of Church of St Edmund, Fenny Bentely in 1895 see M. Stacey (2014), *Aluminium and Durability: Towards Sustainable Cities*, Cwningen Press, Llundain, second edition 2016, pp.30–31.

⁴Ibid.

⁵Martin Routledge, Keeper of History at Sunderland Museum and Winter Garden, recoded on Sunderland Council's website, [www.sun-](http://www.sun-derland.gov.uk/index.aspx?articleidMS =11139)

[derland.gov.uk/index.aspx?articleidMS =11139](http://www.sun-derland.gov.uk/index.aspx?articleidMS =11139) (accessed December 2015).

⁶Film available from British Pathe <http://www.britishpathe.com/video/aberdeen-queen-mother-opens-new-bridge> www.britishpathe.com/video/stills/aberdeen-queen-mother-opens-new-bridge (accessed December 2015).

⁷Deloitte (3 March 2012), *Life Cycle Analysis Aluminium vs. Steel*, 3 (accessed January 2016 via www.maadigroup.com/wp-content/uploads/2012/03/ID-Etude-manufacturiere_MAADI-EN-Web-2-.pdf).

⁸A. de la Chevrotière in conversation with the author February 2016.

⁹The prototype deployable bridge is part of a research project led by MAADI Group, Make-A-Bridge®, funded by Centre québécois de recherche et de développement de l'aluminium (CQRDA), Quebec Aluminium Research Center, with the Programme d'Innovation Construire au Canada (PICC), the Build in Canada Innovation Program (BCIP) and Programme d'aide à la recherche industrielle (PARI), Industrial Research Assistance Program (IRAP).

¹⁰M. Stacey (2015), *Aluminium Recyclability and Recycling: Towards Sustainable Cities*, Cwningen Press, Llundain, pp. 53–63.

¹¹A. de la Chevrotière in conversation with the author February 2016.



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Aluminum pedestrian bridges: recent developments and studies

Scott Walbridge and Alexandre de la Chevrotiere

While aluminum has a long history of successful performance in civil infrastructure applications, it largely remains a construction material that has yet to achieve its full potential, in comparison with more established structural materials, such as reinforced concrete, steel, and masonry.

Recent efforts by the Canadian aluminum industry to address knowledge gaps and a perceived reticence of structural designers to work with this relatively exotic structural material have led to tangible progress. This has manifested itself in the introduction of a new chapter in the Canadian Highway Bridge Design Code (CSA S6) in 2011 and a modernization of the Canadian code for Strength Design in Aluminum (CSA S157) in 2017.

These developments have come, thanks in large part to the support of industry organizations such as the Aluminum Association of Canada (AAC) and the Centre québécois de recherche et de développement de l'aluminium (CQRDA). Revisions of the Canadian code for Welded Aluminum Construction (CSA W59.2) for 2018 and CSA S6 for 2019 are well underway. The development and modernization of these standards has been undertaken with a philosophy of organizing these standards to resemble as closely as possible their steel counterparts, so that designers will become more comfortable with the design of aluminum structures.

New technologies, such as friction stir welding have been introduced, and code provisions have been revised where appropriate to acknowl-

edge modern analysis capabilities. For example, it is now recognized that second order analysis to assess the stability of structures is easier with current structural analysis software and therefore can be considered as a more routine element of any structural design.

Provisions on local approaches for fatigue design have also been improved, recognizing the capabilities of current finite element (FE) analysis software and the need for design methods that can accommodate the wide variations in design geometries made possible by the versatility of the extrusion process.

A recent report for the AAC (Walbridge and de la Chevrotiere, 2012) documented previous examples of the successful application of aluminum in vehicular bridges, and identified applications where aluminum could play a larger role in reducing the life-cycle costs of bridge construction and maintenance. The positive attributes of aluminum alloys are identified include: light weight, high corrosion resistance, and extrudability.

The best opportunities for aluminum use are identified as those that exploit one or several of these positive attributes. The most successful applications are identified as including: deck replacement retrofits, as well as temporary, lift, floating, and pedestrian bridges.

Aluminum Pedestrian Bridges

In the case of pedestrian bridges, aluminum—as a construction material—has a more established history. In the past, the most common applications have been those where corrosion resistance and light weight were critical, including: boat boarding ramps for marine applications, catwalks in industrial facilities, etc. Recently though, aluminum has become an increasingly popular choice in civil pedestrian bridge applications, in particular where transportation costs are high or corrosion resistance is deemed key. Figure 1 shows examples of several recent structures falling into this category, including several custom welded structures, as well as a bolted/modular pedestrian bridge system.

Research on Vibration Behaviour

In the design of aluminum pedestrian bridges, vibration issues present a significant challenge, due to the light weight and low stiffness of aluminum (density and elastic modulus roughly 1/3 that of steel) combined with its strength, which can approach that of mild steel.

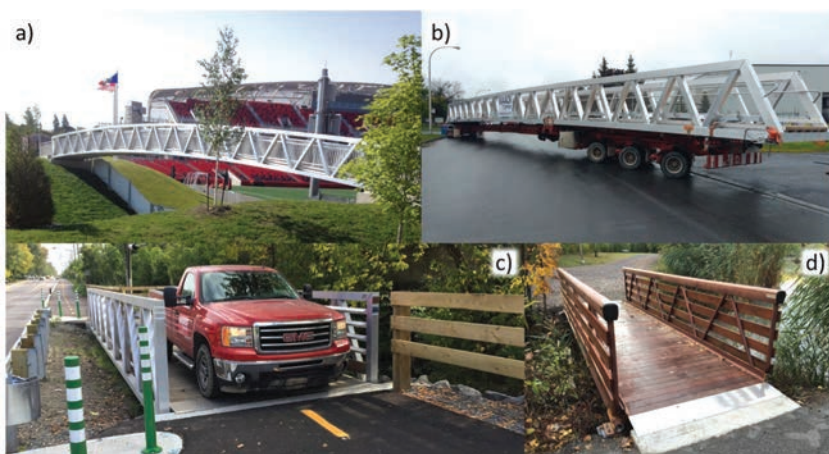


Figure 1: a) Pedestrian walkway at TD Place stadium in Ottawa. b) aluminum pedestrian bridge in transit. c) bridge with service vehicle. d) aluminum “Make-A-Bridge” with architectural finish.

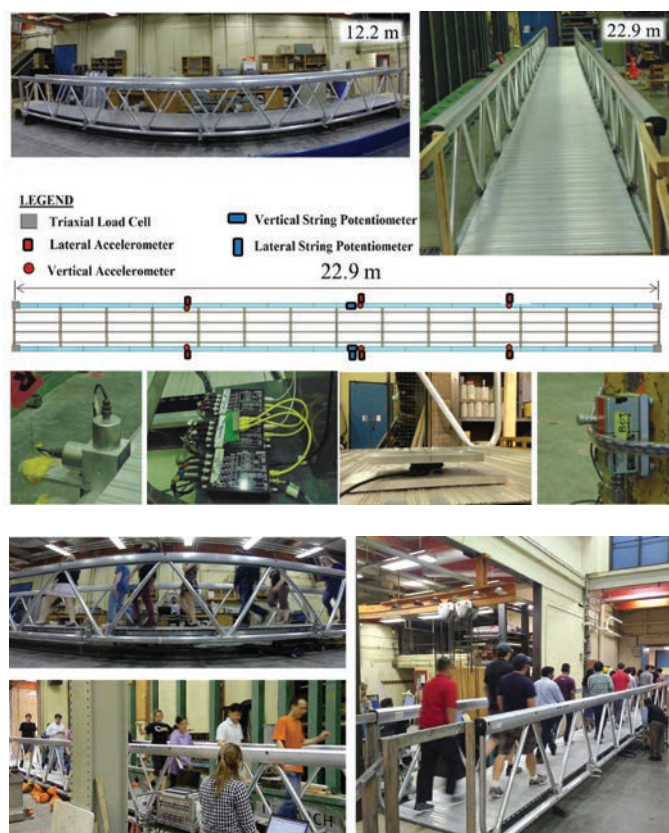


Figure 2: Test setup for laboratory testing of bridge.

Figure 3: Crowd loading tests.

In order to better understand the behaviour of aluminum pedestrian bridges subjected to crowd-induced vibrations, a research project was recently undertaken at the University of Waterloo, with financial support provided by the AAC and the Natural Sciences and Engineering Research Council of Canada (NSERC). The industry partner for this project, MAADI Group, supplied a 75ft-long modular aluminum pedestrian bridge “specimen”, which could be installed in the Waterloo Structural Testing Laboratory at any desired span between 10ft and 75ft. Figure 2 shows the test setup for this research, including accelerometers, displacement gauges, and load cells, along with the bridge constructed in its 40ft (12.2 m) and 75ft (22.9 m) configurations. Figure 3 shows examples of crowd loading tests conducted with assistance of undergraduate and graduate students, staff, and faculty members at Waterloo. The experimental setup offered a number of important benefits, which can be summarized as follows:

- In contrast with vibration studies performed on pedestrian bridges in the field, with the laboratory testing approach it was possible install load cells under each of the four support points to capture the dynamic reaction loads in the vertical, lateral, and longitudinal directions, as pedestrians walked across the bridge, individually or in groups.
- With the employed modular bridge system, it was easy to investigate otherwise identical bridges, with a wide range of spans and stiffness.
- With the employed bridge system, it was possible to add/remove elements (e.g. lateral cross-bracing) to alter the dynamic bridge response.

Results of Crowd Loading Tests

Figure 4 (next page) shows an example of the experimental results obtained from the pedestrian loading tests for the case of the 22.9m bridge, with no lateral x-bracing under the deck, under the loading induced by a crowd with a density of 0.7 pedestrians/m².

For each test type, acceleration and load cell data was collected. If possible, around 30 repetitions were recorded for each test type (specimen configuration, pedestrian volume, walking speed) to ensure statistical significance. Acceleration data was transformed into the frequency domain, so that critical frequencies could be identified. For further details on the full test program and data post-processing methods employed in this study, recently published journal papers by the research group can be referenced (e.g. Dey et al. 2016a, 2016b).

One of the main goals of this research has been to collect data for the purpose of assessing the suitability of the various available international pedestrian bridge design standards for application to aluminum structures. Results were compared with the measured data and the predicted accelerations and acceleration limits from several well-known standards (e.g. SÉTRA, ISO, Eurocode).

In reviewing these standards, common elements were apparent. For example, all of these standards follow a design approach which involves first estimating the natural frequency of the structure. If the calculated frequency is far enough away from the typical range of frequencies that could be excited by pedestrians, then no further analysis is required. If the natural frequency of the structure falls within a critical frequency range, then the design acceleration response is compared against the prescribed acceleration serviceability limit, to achieve a certain level of pedestrian comfort. If the acceleration is below the limit, then the design passes. Otherwise, mitigation measures (e.g. re-design, supplemental dampers) must be employed to satisfy serviceability requirements.

Results from a detailed study of the guidelines revealed that there is a wide discrepancy between the measured and predicted accelerations, as well as considerable breadth in the acceleration limits, suggesting a lack of consensus in what constitutes serviceability failure and the level of conservatism across the various standards.

Based on comparisons such as this, Waterloo researchers have made recommendations for improving the design provisions, which may result in future design code improvements—not just for aluminum bridges, but for the vibration design of pedestrian bridges in general.

These include, for example, such things as considering resonance with higher harmonics of walking, which are often ignored in design, but can be significant for stiff, lightweight structures. It has also been observed that the added mass due to the pedestrians on the bridge, which is not considered in a majority of design provisions, may have a significant impact on the design code predictions, suggesting (as has been suggested previously by others) that it should be considered, in particular in the design of bridges made of lightweight materials.

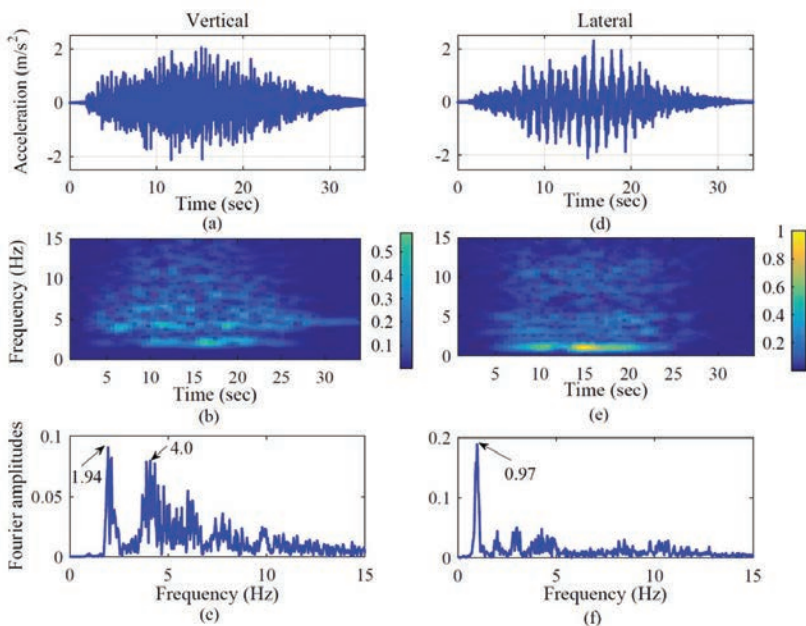


Figure 4: Results for 75' (22.9 m) bridge, no x-bracing, 0.7 pedestrians/m².

Future Research Directions

Work in this area is ongoing, thanks to a new collaborative project between the University of Waterloo and MAADI Group. Among other things, this work is taking a critical look at the design provisions for pedestrian bridges using a probabilistic framework, similar to the one structural engineers are more familiar with for the calibration of strength provisions in design codes.

While it must be recognized that there are many sources of uncertainty that come into play in predicting the vibration behaviour of a pedestrian bridge, this approach makes it possible to apply some degree of rigor to the process, and may provide a rationale for future design code modifications to ensure more consistent levels of safety against

serviceability failures due to poor vibration performance under crowd loads.

Conclusions

In conclusion, aluminum, with its light weight and good durability characteristics is finding its place in pedestrian bridge applications. The confidence that can be placed in its use is growing at an accelerated pace, thanks to research projects such as the one highlighted in this article. ■

Scott Walbridge, P.Eng., Associate Professor, University of Waterloo and Alexandre de la Chevrotiere, MAADI Group.

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