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Opportunities for the use of Aluminum in Vehicular Bridge Construction

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1. Introduction

Highway authorities across North America are currently being faced with significant and pressing bridge maintenance costs, as documented in several recent reports [A1,A2,C1-C3]. Reports published in the US estimate a need for $140 billion to be spent to upgrade the 600,000 existing US bridges – around 25% of which have been deemed to be either “structurally deficient” or “functionally obsolete” [C1]. In 2007, the total value of the bridges and roads in Canada was estimated to be $23.9 billion and $170.1 billion respectively [C2]. In 2005, the cost of upgrading and renewing our existing urban roads and bridges in Canada was estimated to be $66 billion [C3]. Recent bridge failures have drawn public attention to this concern (e.g. the Laval and Minnesota bridge collapses in 2006 and 2007). Less readily apparent than the high owner costs of bridge maintenance and the immediate and serious impacts of these recent bridge collapses, but arguably just as important, are the significant costs to the users and general public (e.g. user delay costs, environmental impacts) associated with the gradual deterioration of our bridge infrastructure and the continued use of functionally obsolete bridge infrastructure that is in need of upgrade or replacement (e.g. periodic lane closures for structural reinforcement of the Honoré-Mercier and Champlain Bridges in Montreal). Within this context, the current report focuses on the opportunities for increased aluminum use in vehicular bridge construction and the potential role that aluminum can play in addressing the maintenance challenges currently facing this industry.

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Historically, the use of aluminum in roadway bridges has been limited for the following reasons [A10,A16,A18]:

- the relatively high initial cost of aluminum, in comparison with concrete and steel,
- the relatively low stiffness of aluminum, in comparison with steel,
- the lack of familiarity that most bridge engineers have with aluminum, and
- the historical lack of codes and standards for the design of aluminum vehicular bridges.

Despite these issues, aluminum offers a number of advantages over the materials conventionally used in bridge construction (i.e. concrete, steel, wood) and has been used successfully on a number of vehicular bridge projects over the years. The current report, which was prepared at the request of the Aluminum Association of Canada (AAC), starts with a brief history of aluminum use in bridges. The positive attributes of aluminum that are of relevance to bridge applications are then discussed, and opportunities are identified for most effectively exploiting these attributes in the maintenance and construction of vehicular bridges.

2. Past use of Aluminum in Vehicular Bridges

2.1. 1970s and Prior

The history of aluminum use in vehicular bridges in the 1970s and prior is documented in a number of references [A3,A5,A7,A10,A14,A16,A18]. It is generally acknowledged that this history began with the replacement of the existing heavy steel and wood deck of the Smithfield Street Bridge in Pittsburgh with an aluminum deck in 1933. The resulting reduction of the bridge self weight allowed the load carrying capacity of the bridge to be significantly increased. The 2014-T6 alloy replacement deck served until 1967, when it was replaced by a more corrosion resistant 6061-T6 aluminum alloy deck, which remained in service until 1995.

The first use of aluminum to construct an entire bridge span was the Grasse River Bridge, in Massena, New York, constructed in 1946. This bridge, which had a span of 30.5 m, carried rail traffic serving an ALCOA smelter. The constructed span was part of a multi-span structure, the remainder of which was constructed out of steel. The aluminum span had a weight that was 43% that of a comparable steel span [A10]. A number of important aluminum bridges followed in the late 1940s and early 1950s, including the Sunderland and Aberdeen Bridges in England and Scotland, commissioned in 1949 and 1953, respectively, and the Arvida Bridge, constructed in Saguenay, Quebec in 1950 by ALCAN (see Figure 1). The Arvida Bridge in Saguenay remains the longest aluminum bridge in the world today, with a central span of 88.4 m.

In 1956, the first aluminum vehicular bridge on continental Europe was constructed – the Schwansbell Bridge in Germany [A14]. This bridge consisted of a 44.2 m single span truss. Due to the light weight, the structure was fabricated and then floated on a barge to the construction site. The parts were joined with aluminum rivets, made out of the same material as the members. A coating was applied between overlapping plates to prevent crevice corrosion. A recent report on the condition of this bridge indicated that minimal deterioration can be observed after more than 50 years of service over a waterway, in a highly corrosive, industrial environment.

In the period between 1958 and 1963, seven aluminum vehicular bridges were constructed in the US. These projects were motivated by the high price of structural steel during this period. Of these, the Route 86 overpass in Des Moines, Idaho is notable for being the first example of a welded aluminum bridge [A3,A10]. This four span continuous bridge was prefabricated in four pieces (two 21 m spans weighing 9.5 tonnes and two 12 m spans weighing 7.3 tonnes), which were erected on site with a crane. A concrete deck was then cast in place, with a zinc-based primer coating provided between the aluminum and the concrete for corrosion protection. This bridge performed well, until it was decommissioned in 1993, to make way for a larger replacement structure. A number of the other US bridges built during this period employed a concrete slab on triangular box girder design. Table 1 summarizes these and a number of additional examples of early aluminum vehicular bridges.

The first use of aluminum to construct an entire bridge span was the Grasse River Bridge, in Massena, New York, constructed in 1946.

#	Location	Bridge Type	Use	No. of Lanes	Span(s) (m)	Year	Alloy
1	Smithfield Street Bridge Pittsburgh, PA, USA	Steel truss bridge w/ orthotropic aluminum deck	Vehicular/ Trolly	2+2 Tracks	2@111	1933, 1967	2014-T6 (1933) 6061-T6 (1967)
2	Grasse River Bridge Massena, NY, USA	Riveted plate girders	Railway	1 Track	30.5	1946	2014-T6
3	Sunderland Bridge England	Riveted double leaf bascule	Vehicular/ Railway	1+1 Track	37	1949	2014-T6 6151-T6
4	Arvida Bridge Saguenay, QC, Canada	Riveted arch bridge	Vehicular	2	5@6.1, 88.4, 5@6.1	1950	2014-T6
5	Aberdeen Bridge Scotland	Riveted double leaf bascule	Vehicular/ Railway	1+1 Track	30.5	1953	2014-T6 6151-T6
6	Schwansbell Bridge Germany	Riveted Warren Truss	Vehicular	1	44	1956	6351-T6
7	Route 86 over I-80 Des Moines, IA, USA	Concrete slab on welded aluminum plate girders	Vehicular	2	12, 21, 21, 12	1958	5083-H113
8	Banbury Bridge England	Riveted bascule	Vehicular	1	3	1959	6351-T6
9	I-495 above the Jerico exchange Jerico, NY, USA	Concrete slab on riveted aluminum plate girders	Vehicular	4 (2 Bridges)	23	1960	6061-T6
10	Route 36 (Appomattox River) Petersburg, VA, USA	Concrete slab on aluminum bolted triangular box girder	Vehicular	2	30	1961	6061-T6
11	Gloucester Bridge England	Riveted bascule	Vehicular	1	12	1962	6351-T6
12	Route 110 above Sunrise Hwy Amityville, NY, USA	Concrete slab on aluminum riveted triangular box girder	Vehicular	6 (2 Bridges)	9, 23, 23, 9	1963	6061-T6
13	Route 32 (Patapsco River) Sykesville, MD, USA	Concrete slab on aluminum riveted triangular box girder	Vehicular	2	28, 29, 32	1963	6061-T6
14	Saone River Bridge Montmerle, France	All-aluminum truss	Vehicular	N/A	79.9, 79.9	1973	A-SGMT 6
15	Rodan River Bridge Groslee, France	Concrete slab on aluminum truss	Vehicular	N/A	174	1977	6082-R31
16	Chamalieres Bridge Chamalieres, France	Aluminum girder	Vehicular	4	N/A	1978	N/A

Table 1. Examples of aluminum use in vehicular bridges – 1970s and prior (adapted from [B2]).

2.2. Modern Applications

The Forsmo bridge, constructed in Norway in 1996, is a relatively well known example of a modern all aluminum vehicular bridge. This bridge has a span of 39 m, and consists of two aluminum box girders and an aluminum deck. Strong and durable 5xxx and 6xxx alloys were used in the construction of this bridge. The entire structure was transported to site on the back of a flatbed truck and installed with a single crane operation [A16]. Other examples of modern all aluminum vehicular bridges have tended to be for more specialized applications, where light weight has been particularly critical for achieving a successful design. These have included lift (or bascule) bridges (e.g. the Helmond and Riekerhavenburg bridges built in the Netherlands in 1999 and 2003), floating bridges, and movable bridges for emergency and military applications [A10,A13].

Much of the recent effort to introduce aluminum in vehicular bridge construction has focused on the development of replacement deck products [A4,A13,A17,A19]. The main reason for using aluminum in deck replacement applications is to increase the capacity of older bridges to carry modern truck loads by removing the heavy concrete deck and replacing it with a much lighter one. Severe deterioration of our existing reinforced concrete decks due to heavy road salt use is another reason for employing this retrofitting approach.

Aluminum deck has also been used recently in rapid bridge replacement projects, such as the Sandisfield, MA bridge replacement, completed in the spring of 2012 [C7]. This structure consisted of an extruded and friction stir welded aluminum deck on four galvanized steel girders. It had a span of 17.7 m, a width of 4.2 m, and was fabricated in its entirety offsite. It was then transported to site on a flatbed truck and erected with a crane. The rapid construction was enabled by the aluminum deck, which had 1/5th the weight of a concrete deck.

Aside from vehicular bridges, aluminum has also been used extensively for pedestrian and residential area bridge applications, in Europe, Japan, and North America [A7,A10] (see Figure 1). In these applications, the reasons for choosing aluminum are the light weight and the aesthetic qualities and durability of the unpainted metal. Aluminum walkways are particularly popular in highly corrosive environments such as marine docks and industry plants, due to the high corrosion resistance offered by this material [A8,A18].

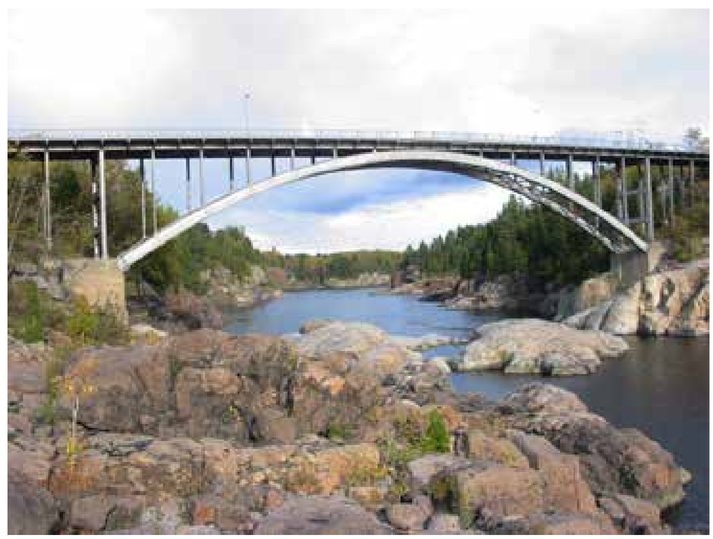


Figure 1. Arvida bridge in Saguenay, Quebec

Figure 1. Aluminum pedestrian bridge installation

3. Codes and Standards for Aluminum Bridge Design

One often cited reason for the limited use of aluminum in vehicular bridges is the lack of familiarity that most bridge engineers have with aluminum structure design and the historical lack of suitable codes and standards providing guidance on the design of aluminum bridges. In this section, the most important codes and standards are identified and recent developments to improve and add to these standards are discussed.

3.1. Codes for Aluminum Structure Design

The CSA-S157 standard has been in available for quite some time [D1] for the design of aluminum structures in Canada. Although it was recently renewed in 2005, it has been a while since the code has been thoroughly reviewed and updated. This standard is most applicable in Canada for the design of aluminum building structures. However, the design procedures in this code enable determination of the ultimate resistances of members and connections. Thus, CSA-S157 has general validity and has been applied to all types of load- bearing aluminum assemblies for which there is no separate design code. This includes such applications as: lattice towers, cranes, vehicles, rolling stock, and (until recently) pedestrian and vehicular bridges. Aircraft design, pressure vessel design, and other well-established fields have their own bodies of rules.

A much more recently updated example of an international standard for aluminum structure design is the Eurocode 9 standard “Design of Aluminum Structures” [D2]. This code applies to aluminum structures in general (i.e. not only building structures), and could be used in conjunction with the related Eurocode 1 standard for “Actions on Structures” to design aluminum pedestrian and vehicular bridges.

In the US, the Aluminum Association regularly updates and maintains the Aluminum Design Manual [D3]. The focus of this manual is on the determination of the resistance of members and structures. However, this manual also contains a wealth of information concerning material and section properties.

For the design of aluminum bridge structures using one of these general standards for aluminum structure design, engineers might consider using a general standard for calculating structural resistance, along with appropriate bridge design code provisions for calculation the loads and load effects. One problem with this approach is that modern building and bridge codes contain load and resistance factors, which are calibrated to ensure acceptably small probabilities of failure. The different factors are linked, so if you take load factors from one code and resistance factors from another, then there is a risk that the safety objectives of one code or the other will not be achieved. This approach should therefore be avoided, where possible.

3.2. Aluminum in Bridge Design Codes

In the US, the American Association of State Highways and Transportation Officials (AASHTO) specification for highway bridge design [D4] has included a chapter for aluminum structures for many years. This chapter shares many common elements with the Aluminum Design Manual [D3]. Importantly, this code contains both resistance and load provisions for aluminum highway bridges, resulting in a level of safety for aluminum bridge structures consistent with the level of safety specified for concrete and steel bridges.

In Canada, it was recently recognized by the aluminum industry and the Canadian Standards Association that information was needed in a single code for designing aluminum bridges. This led to the formation of a new technical committee for the Canadian Highway Bridge Design Code (CAN/CSA-S6), Chaired by Prof. Beaulieu from Université Laval [D5]. This committee completed its work on the new Chapter 17 for “Aluminum Structures”, which was recently published in a 2nd supplement to the 2006 code in the fall of 2011.

In developing the new code chapter for CAN/CSA-S6, a conscious decision was made to organize the chapter in the same way as the current steel chapter, so that bridge designers more familiar with structural steel design would have minimal difficulties applying the new code provisions. Provisions from the CSA-S157 aluminum structures code were used as a starting point. However, where these provisions were deemed to be outdated, the existing American and European standards were looked to for guidance.

Figure 2. Codes and standards for the design of aluminum structures.

4. Properties of Aluminum Alloys

In highway bridge applications, it is expected that wrought alloys will be of most interest for primary structural elements such as girders, bracing, and decks. In general, it is recommended that 5xxx and 6xxx alloys be used, due to their favourable strength properties and corrosion resistance [A11,A18].

The new CAN/CSA-S6 Chapter 17 makes particular reference to the following wrought aluminum alloys as being suitable for bridge applications: 5052, 5083, 5086, 6005A, 6061, 6063, and 6082. Cast alloys may be of interest for secondary bridge components, such as: connections and base plates of luminaries and sign support structures, connections in sidewalk and bike path support structures and posts for bridge rails and railings. The new CAN/CSA-S6 Chapter 17 makes reference to the following cast aluminum alloys/tempers as being suitable for pedestrian bridge applications: 356.0-T6, A356.0-T61, and A357.0-T61.

4.1. Strength and Stiffness

Table 2 summarizes the strength properties for common 5xxx and 6xxx aluminum alloys/tempers most likely to be used in highway bridge applications. Looking at this table, it can be seen that the yield and ultimate strengths, Fy and Fu, for common aluminum alloys, although somewhat lower than mild structural steel, are still considerable, given the significant differences in the densities of the two materials (aluminum alloys have a nominal density, $\rho = 2700$ kg/m^3, which is approximately 1/3 that of steel). Also apparent is the considerable local strength loss that can result from conventional welding processes (e.g. arc welding). This is a significant difference between aluminum and steel, which must be accounted for in the design. The effects of this strength loss can be minimized by smart detailing (e.g. using longitudinal, rather than transverse welds) [A18]. More recently (in 1991), a promising welding process called Friction Stir Welding (FSW), which is a olid state process that produces welds of high quality with low energy input, has been developed and found to produce very high strength welds. FSW has been successfully employed to join aluminum bridge deck sections. Applying FSW to other components of vehicular bridges is an area warranting further study.

Table 2. Strength properties for common alloys (adapted from [D5]).

Alloy-temper	Product	Thickness Range (mm)		Minimum Strengths (MPa)			
				As-Received		In Welded Regions	
		Min.	Max.	F_u	F_y	F_{wu}	F_{wy}
5052-H32	Sheet, plate	0.4	50	215	160	170	65
5083-H116	Sheet, plate	1.6	40	305	215	270	115
5086-H116	Sheet, plate	1.6	50	275	195	240	95
5086-H321	Sheet, plate	1.6	8	275	195	240	95
6005A-T61	Extrusion	–	25	260	240	165	90
6063-T5	Extrusion	–	12.5	150	110	115	55
6063-T6	Extrusion	–	25	205	170	115	55
6061-T6, -T6510, -T6511	Extrusion	All	–	260	240	165	80*/105**
6061-T6	Sheet	0.15	6.3	290	240	165	105
6061-T651	Sheet, plate	6.3	100	290	240	165	80*/105**
6082-T6, -T6511	Extrusion	5	150	310	260	190	110

* When welded with 4043 filler in parts thicker than 9.5 mm.
** When welded with 5356 filler, or welded with 4043 filler in parts 9.5 mm or less in thickness.

For design purposes, an elastic modulus for aluminum alloys of E = 70,000 MPa is assumed [D5]. This is approximately 1/3 of the design elastic modulus typically assumed for steel. Since the strength-to-stiffness ratio is generally higher for aluminum alloys, deflection or vibration limits often govern the design of primary structural elements in aluminum bridges, such as girders and deck panels. Despite this restriction, it is possible to achieve aluminum I-girder cross sections with the same flexural stiffness and half of the weight of a comparable steel section, if all dimensions except the flange width are increased by a factor of 1.4. Even greater weight savings can be achieved if the overall I-girder depth is not constrained [A11].

One ramification of the reduced elastic modulus is that local buckling of plate elements becomes more of an issue. This potential problem can be mitigated, however, by using stockier plates and extruding structural shapes with built in bulbs or stiffeners, in order to reduce the risk of local buckling [A18].

Aluminum alloys, and in particular in the 5xxx and 6xxx series, are known to be much more corrosion resistant than plain carbon or atmospheric corrosion resistant (ACR) structural steel.

4.2. Thermal, Corrosion, and Fatigue

Aluminum has a thermal expansion coefficient, $\alpha = 24 \cdot 10^{-6}$ / °C, which is approximately double that of concrete or steel. This means that care must be taken when designing aluminum bridges to ensure that the additional thermal expansion or contraction due to ambient temperature changes can be accommodated through the provision of expansions joints or by other means. Extra care must also be taken when designing concrete-aluminum composite structures, since thermal effects for the two materials will not be the same.

Aluminum alloys, and in particular in the 5xxx and 6xxx series, are known to be much more corrosion resistant than plain carbon or atmospheric corrosion resistant (ACR) structural steel. This is of particularly interest in Canadian vehicular bridge applications, where heavy road salt use in the winters is prevalent. Although there is much in the way of anecdotal evidence of the good corrosion performance of aluminum in marine and highly corrosive industrial environments, further research to quantify this benefit would be beneficial. In one study where this benefit was quantified, the results for aluminum were highly favourable. In an environment with high salt exposure and medium exposure to pollutants, an annual thickness loss of 0.0194 mm/year was reported for aluminum, versus 0.81 mm/year for weathering steel and 2.19 mm/year for carbon steel [C5].

In highway bridge applications, several of the older structures still in service provide evidence of strong corrosion performance for service periods now exceeding 45 years [A3,A14,A6]. Evidence of poor corrosion performance of aluminum structures has also been reported. However, this can generally be attributed to the use of older aluminum alloys, which are less corrosion resistant (e.g. 2xxx alloys) or poor detailing, which resulted in direct contact between aluminum and concrete or locations on the structure where water could sit in close proximity to lap joints, thus creating conducive conditions for crevice corrosion to occur.

Early fatigue design provisions for aluminum were established by taking the design stress ranges for steel and multiplying them by 1/3. Although this may have been a reasonable assumption to start with, over time, these provisions have been considerably refined. Stress versus life (S-N) design curves with different slopes are now assumed for the different detail categories, and much larger fatigue test databases are now available, to increase our confidence in these curves. Only limited fatigue testing of aluminum welds has been performed to date under in-service variable amplitude loading conditions [A21]. However, conservative assumptions are made to facilitate fatigue design of bridges in the North American standards [D4,D5]. Based in the state-of- the-art in research in this area, it is apparent that fatigue is somewhat more critical for welded aluminum structures than for mild steel ones, since the ratio between the "fatigue strength" and static strength is lower. That having been said, there are opportunities to mitigate fatigue problems in aluminum that are not available for steel. An example of this is the elimination of welds in aluminum bridge decks by extruding them in their entirety, rather than fabricating them out of welded plates. In general, the extrusion process also offers the possibility to increase thickness at critical locations, thus reducing stresses and improving fatigue performance.

4.3. Cost and Environmental Impact

Initial construction cost and life-cycle cost comparisons of aluminum structures, including bridges and bridge components, have been conducted by a number of researchers. The material cost of aluminum alloys fluctuate in comparison with structural steel. However, a cost per unit mass for aluminum that is greater by a factor of four (4) is typical. If a 50% weight reduction is achieved through the use of aluminum, then this translates to a two (2) times greater in material initial cost in comparison with a similar steel structure. Although this sounds like a high premium, it should be noted that these are material costs, which make up only part of the total cost of constructing a new bridge. It should be noted that fabrication hours may also be reduced due to the higher welding speed (GMAW process) as well as easy of cutting and machining aluminum. In [A5], costs are compared for 40 alternative aluminum vehicular bridge designs, with spans ranging from 15-35 m. The best result from aluminum from the point of view of initial cost was a 70% premium, with respect to a comparable concrete slab on steel girder bridge. In this study, however, a number of important construction costs were not considered on the basis that they would be the same, regardless of the structure type. These included the costs of constructing the piers, abutments, foundations, rebar, supports, and secondary structural elements (e.g. cross bracing). Clearly, if these costs are considered, it can be expected that the premium (as a percentage) for constructing a bridge out of aluminum will decrease. In general, however, it is expected that a primary reason for choosing aluminum in bridge applications will be the reduction in long term or life-cycle costs. When compared on this basis, aluminum structures can be competitive, as demonstrated in a number of studies on aluminum bridge replacement decks [A4] and pedestrian bridges [A9,C6].

It is generally acknowledged that there is a high energy cost required to produce new aluminum from bauxite (ore). Thus, in order for aluminum use in vehicular bridges to make sense from the point of view of minimizing environmental impact, efforts must be taken to offset this cost through the use of recycled aluminum in these structures, and through targeting applications where light weight and durability can lead to significant environmental benefits, such as those achieved by:

- extending the service lives of structures,
- reducing user delays during retrofitting interventions,
- avoiding environmentally sensitive maintenance actions (e.g. the removal of paint).

Recycling is already a well established practice; with about 95% of the aluminum currently used in the construction industry being recycled. This has significant implications, since the recycling process consumes only about 5% of the energy required to make new aluminum [A18].

According to [A12], aluminum use in structures can be competitive in comparison with conventional construction materials, when evaluated from a sustainability perspective, if at least 80% recycling and a 50% reduction in the weight of the structure are achieved. This means that aluminum structures must be designed with a goal of minimizing weight and they must be “designed for disassembly” at the end of their service lives. Although the applications investigated in this reference were building structures, it can be concluded from studies such as this that aluminum can be the best option in certain cases, where the light weight, durability, and recyclable nature of this material make its use preferable from a sustainability perspective.

In general, however, it is expected that a primary reason for choosing aluminum in bridge applications will be the reduction in long term or life-cycle costs.

5. Use of Aluminum for Retrofitting of Existing Bridges

In order for aluminum structures to be competitive with structures built from conventional construction materials, applications must be targeted that exploit the positive attributes of aluminum, including [A8,A18]:

- light weight (i.e. low density, high strength-to-weight ratio),
- the high durability (i.e. corrosion resistance), and
- the high degree of formability (i.e. the possibility to extrude complex, customized shapes).

In the current section, several opportunities are highlighted and discussed, where these attributes could be advantageous for applications involving the retrofitting of existing bridges. In Section 6, a similar discussion is provided, with a focus on the use of aluminum in the construction of new vehicular bridges.

5.1. Extruded Aluminum Bridge Deck

The use of aluminum for bridge deck replacement has been investigated in a number of studies [A4,A13,A16, A17,A19] and several proprietary products are currently on the market (e.g. [C7]). A Canadian study on the feasibility of aluminum replacement decks is described in [A4]. Several existing deck products are identified, including: the ALCOA and Alumadeck (Reynolds) systems from the US and the Svensson deck from Sweden (see Figure 3). A significant advantage of the latter system is that it contains no welding, implying a reduced likelihood of fatigue problems. The Svensson deck has as little as 1/10th the weight of a comparable concrete slab [A4]. An asphalt surface can be applied over top of it, or a light weight resin/aggregate coating can be applied to provide skid resistance and deck protection. Other benefits of aluminum deck include the possibility for rapid deck replacement (24h installations are possible) and increased durability (up to an 80 year service life is promised by one manufacturer). In [A4], it was found that the best applications were steel bridges where the existing concrete slab did not act compositely with the supporting girders or trusses. When applied to composite bridges, the increase in bridge capacity is limited, since the weight reduction is offset by the loss of composite behaviour. In [A4], a life-cycle cost analysis of aluminum and wood deck replacement alternatives is performed, and the aluminum deck results in a lower life-cycle cost, even though the initial cost is higher.

Further discussion of the Swedish deck products can be found in [A13]. According to this reference, about 70 bridges in Sweden have now been retrofitted with aluminum decks. The described SAPA product comes in two sizes, which can span between support lines (i.e. girders) up to 1.2 or 3 m apart, and is competitive with a concrete replacement deck, even on the basis of an initial cost comparison, according to [A13].

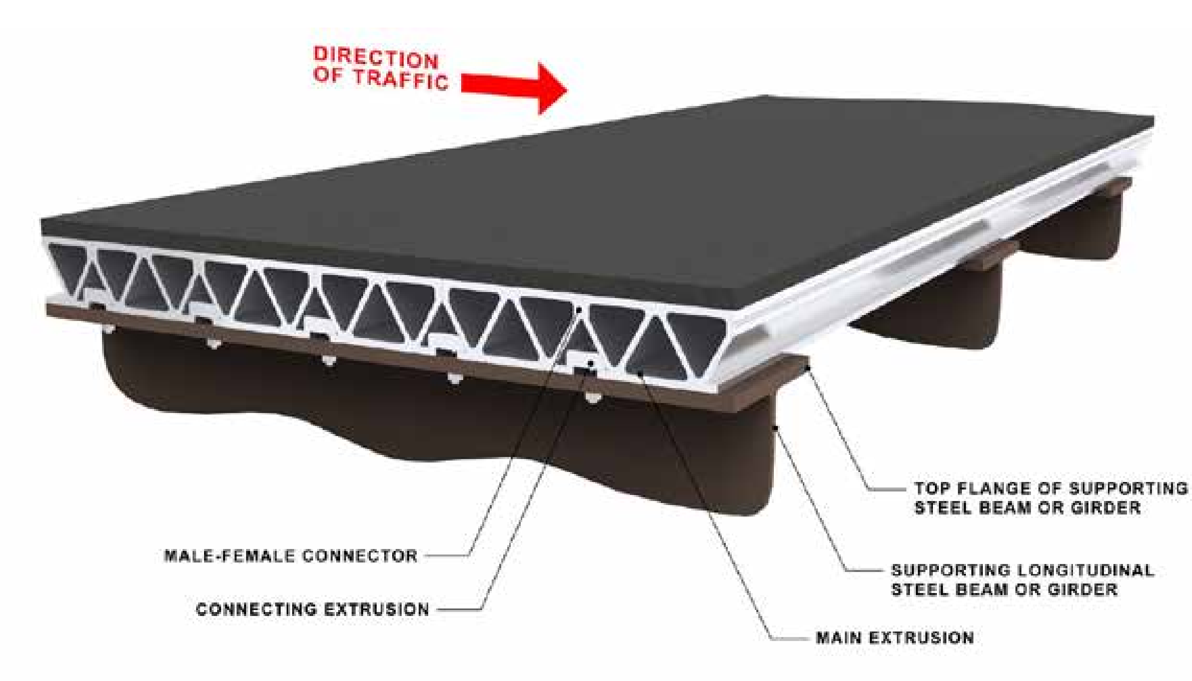


Figure 3. Extruded aluminum bridge deck system.

Extruded aluminum replacement decks have been used successfully on numberous projects and shown to be competive from the point of view of both initial and life-cycle cost. In general, the challenges associated with these decks include the fatigue verification of the developed deck system and the integration of a durable and skid resistant deck surface. The cross sectional dimensions of the extruded deck panels will be limited by the diameter of the extruder. In North America, 20" (508 mm) is a typical limit.

Aluminum seems particularly well suited for replacement decks, since this application exploits all three of the positive attributes of the material (light weight, corrosion resistance, and extrudability). Thus, it is not surprising that this is one of the first bridge applications where aluminum use has become prevalent.

5.2. Deck Widening or Sidewalk / Bike Path Addition

A second vehicular bridge retrofitting application where the light weight and durability of aluminum make it an obvious choice is for increasing deck widths (e.g. to add lanes or widen existing lanes) and providing structural support for new sidewalks or bike paths. This kind of retrofit is becoming increasingly commonplace, as the functional requirements of bridges change over time, due to traffic volume increases and the need to integrate healthier and more environmentally friendly travel modes, such as walking or biking.

In considering alternative structural systems for this kind of retrofit, minimizing self-weight is critical, since the existing bridge will normally not have been designed to carry the additional load. Thus, the initial cost premium due to the selection of aluminum can be more than offset by the high cost associated with structural strengthening, if a heavier system is chosen, or the high cost of replacing of the entire structure.

Figure 4 (left) shows an example of a recent bike path addition on an existing bridge. The light-weight all- aluminum solution includes a cantilevered structure, along with aluminum deck and railings.

5.3. Rapid Bridge Replacement

Rapid bridge replacement projects are becoming increasingly popular in densely populated areas, where the societal costs associated with the user delays that would result from normal construction practices justify the cost associated with the required additional equipment and expertise. Several high profile projects in Ontario have involved the replacement of short span overpass structures in 24 hours or less [C9]. According to the engineers working on these projects, the additional owner costs associated with the required heavy-lift technology (see Figure 4 (right)) and the associated logistics can be recuperated through the savings that result from reducing the duration of the traffic control from over a year to less than one day.

To date, these projects have primarily focused on shorter spans (on the order of 25 m) and employed steel- concrete composite construction. Given the significant weight savings offered by aluminum structures, it stands to reason that they would be particularly well suited for rapid bridge replacement projects. These structures would enable the replacement of shorter spans with more conventional and readily available cranes, or they would enable the replacement of larger spans using existing heavy lift technologies.

Again, this application is one where aluminum makes sense, due to the immediate economic benefits that can be derived from reducing the self weight of the structure. The high corrosion resistance of the resulting structure would be an additional benefit that would result in additional savings over the life of the structure.

Figure 4. Cantilevered aluminum bike path (left) [C8], rapid bridge replacement in Ontario (right).

6. Opportunities for Aluminum use in New Bridge Construction

In new bridge construction there are also opportunities where aluminum may offer advantages over conventional construction materials. In this section, the various elements of a vehicular bridge that might be constructed out of aluminum are discussed, including primary structural members and secondary bridge components.

6.1. Primary Structural Members

The primary structural members of a vehicular bridge that one might consider fabricating out of aluminum include the bridge deck, and the bridge superstructure, including the longitudinal girders, diaphragms, and cross bracing. Aluminum can be used for each of these member types exclusively or in combination with conventional construction materials, such as steel and concrete. Figure 5 illustrates several material combinations that can be envisioned for the primary structural members of a typical multi-girder vehicular bridge.

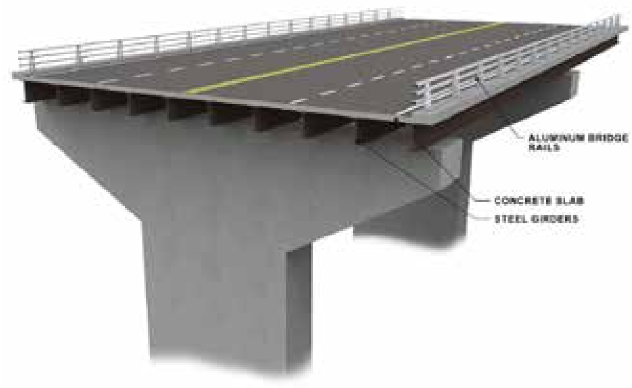
A study comparing the initial construction costs of aluminum vehicular bridges with concrete slab on steel girder bridges is described in [A5]. Girder and truss bridges with spans ranging from 15 to 35 m were investigated. The study concluded that based on initial construction cost, bridges with aluminum primary structural members were not competitive under the current economic conditions (a 70% initial cost premium is predicted). Life-cycle owner and user delay costs due to maintenance interventions were not considered in this comparison.

In a recent master's thesis project [B3], simply-supported multi-girder vehicular bridges were designed using the CAN/CSA-S6 bridge code [D5], along with a draft of the new Chapter 17 for this code. Spans ranging from 25 to 40 m were investigated. Several bridge variants were designed for each span (see Figure 5):

- Variant 1 consisted of a concrete slab on steel I-girders,
- Variant 2 was an all-aluminum design with an extruded aluminum deck system on aluminum I-girders,
- Variant 3 consisted of an aluminum deck system on steel I-girders.

Strength, serviceability, and fatigue limit states were verified. Figure 6 shows the resulting weight versus span curves for each variant. In the case of Variants 1 and 3, two sub-variants were designed – one(a) with hot-rolled girders having cross-section properties that don't vary along the span and another (b) with welded plate girders having web and flange thicknesses that do vary along the span.

Variant 1: Steel girders, concrete deck



Variant 2: All-aluminum superstructure

Variant 3: Steel girders, aluminum deck

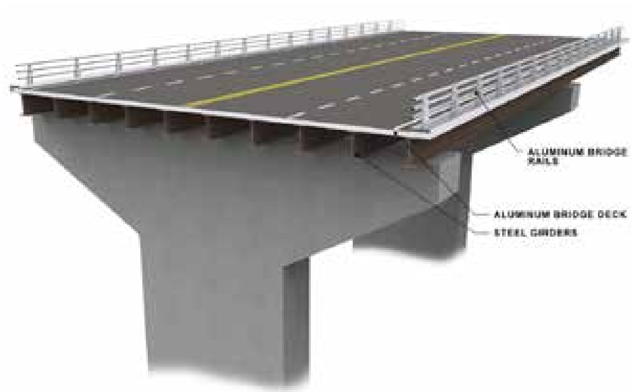


Figure 5. Alternative bridge configurations employing aluminum (adapted from [B3]).

Looking at Figure 6, a number of important trends can be observed. Firstly, a significant reduction in the weight of the bridge is achieved by replacing the concrete deck with an aluminum one. Comparing the weights of the Variant 1 and 3 structures, the Variant 3 structure weighs 1/4 to 1/3 as much, depending on the span. Secondly, although further weight savings are achieved with the use of aluminum girders, the incremental weight savings are less than what is achieved by building the deck out of aluminum (rather than concrete).

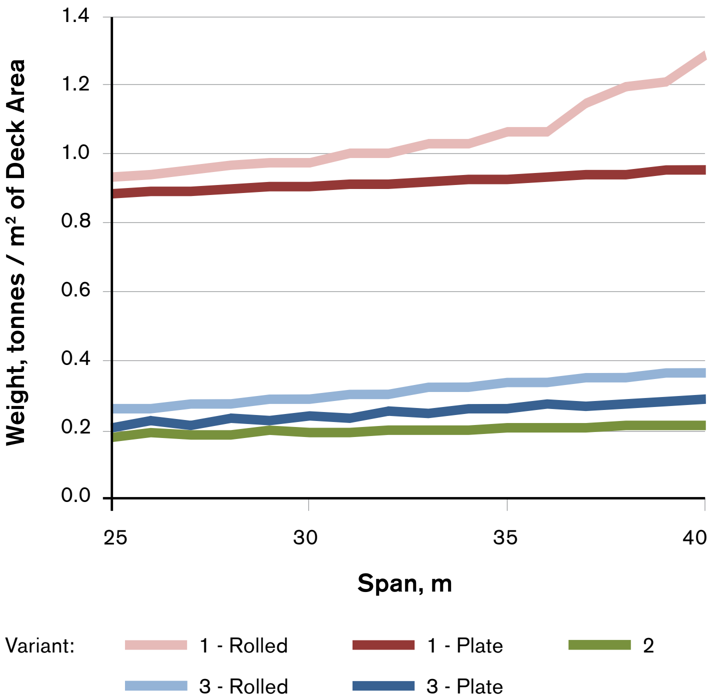


Figure 6. Weight versus span for alternative bridge configurations (adapted from [B3]).

In [B3], an 80% initial construction cost premium is estimated, on average, for choosing Variant 2 over Variant 1(b). In this study, it is reported that the lower maintenance associated with the aluminum variant is not sufficient to offset the initial cost premium over a 75 year analysis period, assuming an average painting cost of 117 $/m2 (CAD) of steel surface area and that repainting will be required every 15 years for the steel variant. If the painting cost is increased, however, then the aluminum variant would become competitive. Based on subsequent consultations with industry experts, the assumed average painting cost in [B3] is arguably a best case scenario and more typical of the cost of factory painting or painting on site, minus the cost of providing access to the structure and environmental protection (i.e. to capture materials during the surface preparation). These additional owner costs can be several times greater than the basic cost of painting, depending on the accessibility and environmental sensitivity of the bridge site. This suggests that an unpainted aluminum bridge would result in lower life-cycle owner costs for cases where these costs are expected to be high.

Also not considered in [B3] are the significant life-cycle costs to stakeholders other than the owner, which may be incurred with frequent bridge closures for maintenance interventions. In a recent study [A22], a “total cost analysis” was performed to evaluate alternative corrosion management strategies for a steel vehicular bridge in Switzerland. Based on this analysis, it was concluded that the critical cost ratios for choosing more corrosion-resistant steel grades (e.g. weathering steel) or using more durable protective coatings (e.g. zinc metallizing) increase dramatically with detour length and traffic volume, when the costs to all of the bridge stakeholders (e.g. the owner, users, and general public) are considered, instead of just owner costs.

Although aluminum was not one of the alternatives investigated in this study, the maintenance costs for the steel girders from this study can be used to quantify the cost of corrosion, and thus the potential savings that can be achieved by using more durable materials for the primary structural members of a vehicular bridge. This idea is presented graphically in Figure 7. The bridge investigated in [A22] carried two lanes of traffic over a river and had two simply-supported spans, each approximately 25 m in length. A range of detour lengths and traffic volumes were analyzed. In Figure 7, two cases are illustrated, including a typical case (2.4 km detour, 650 ADT) and a second case with both the detour length and traffic volume significantly (but realistically) increased (10 km detour, 8000 ADT). In Figure 7, the effect of varying the owner cost of painting is also investigated. It was assumed in [A22] that the life of the paint coating was 20 years, on average.

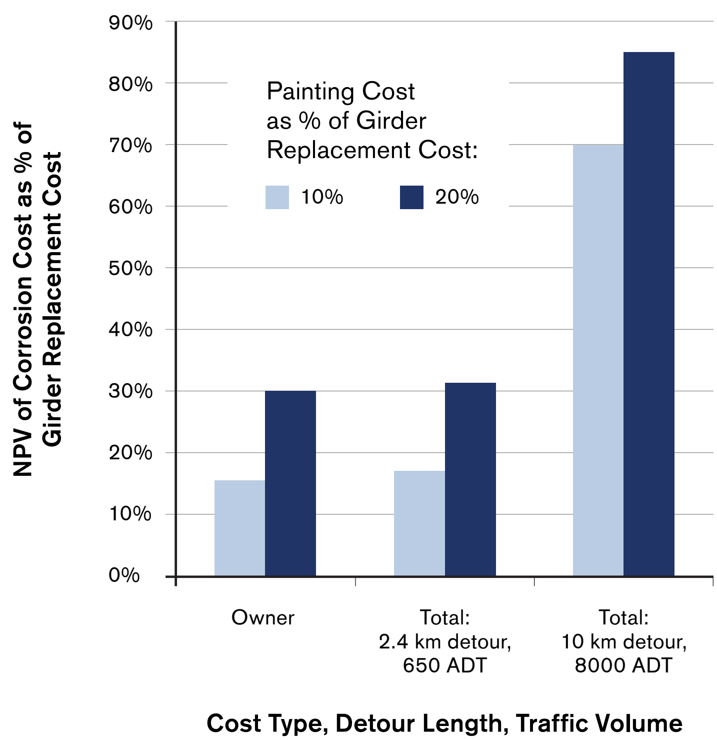


Figure 7. Corrosion cost for a painted steel girder bridge in a severe environment (adapted from [A22]).

The results in Figure 7 were calculated assuming a discount rate of 2% and a 100 year service life. A severe corrosion environment is assumed (i.e. high exposure to chlorides). The results show that the net present value (NPV) of the corrosion cost is less than the typically assumed premium for fabricating girders out of aluminum (70-80%) if only owner costs are considered or if the detour length and traffic volume are small. However, the total corrosion cost can exceed the cost of aluminum if the detour length, the traffic volume, or the painting cost are increased. On this basis, it can be concluded that due to its high corrosion resistance, unpainted aluminum is a material of interest for superstructure components in bridges, in situations where one or several of the following conditions are present: 1) a severe corrosion environment, 2) a high expected painting cost (e.g. due to site access or environmental constraints), or 3) a high expected user cost associated with maintenance interventions (e.g. due to a high detour length or average daily traffic volume).

This result only considers one of the positive attributes of aluminum – the strong corrosion resistance. Additional economic benefits due to the light weight that might be derived in the case of rapid bridge replacement projects or movable bridges (for example) are not considered. Further study of these aspects would be beneficial, as well as extension of the work in [A22] to consider other bridge types and geometries (e.g. overpasses, concrete girder bridges, box girders, longer spans), and expected costs applicable to North America.

6.2. Secondary Bridge Components

In addition to the primary structural members, there are a number of secondary bridge components that can and are frequently fabricated out of aluminum. These are illustrated in Figure 8.

Aluminum sidwalk and bike path support structures can be incorporated in new bridges for the same reasons that they are advantageous in the retrofitting of existing bridges, i.e. due to their light weight, durability, and the asthetic qualities of the unpainted metal. Although many bridges are only ever viewed from afar or while passing over them in fast moving vehicles, sidewalks and bike path structures often receive closer scrutiny, as the users of these components have more time to look at them, while they are passing over the bridge. Aluminum is a commonly used material for luminaires (i.e. light poles) and sign support structures. Established standards are available for the design of these components [D5,D6], and companies exist who specialize in their fabrication (e.g. [C10]). Again, this is an application where light weight, corrosion resitance, and extrudability make aluminum an obvious contender. Cast aluminum elements are also used in this application. In general, aluminum luminaires and sign structures have performed very well, historically. Corrosion problems have been noted when proper detailing has not been provided in locations where aluminum and concrete come in contact. A number of fatigue failures have been observed. These have often been the result of extreme loading events, such as hurricanes. Research on this potential problem has resulted in improved understanding of the loading and fatigue behaviour of these components as well as recommendations for improved detailing [A15,B1].

Aluminum bridge rail products are recognized in a number of guidelines and standards [D5,C11] and a number of fabricators of these products also exist (e.g. [C12]). In general, the guidelines and standards for these components pre-approve designs for different vehicle impact loads, which are specified by the bridge designer. In general, the highest capacity bridge rail products tend to be steel. However, where a lower impact load is permitted, the aluminum products are of interest, due to their high corrosion resistance. In addition, they may be selected for architectural reasons on landmark structures, due to their asthetic qualities.

Figure 8. Use of aluminum in secondary bridge components.

7. Summary and Conclusions

In this report, a brief history of aluminum use in vehicular bridges is provided, the positive attributes of aluminum are then discussed, and opportunities for most effectively exploiting these attributes in vehicular bridges are identified. Based on the presented material, the following conclusions are drawn:

1. Aluminum has a track record of good performance in vehicular bridge applications dating back almost 80 years. The feasibility of constructing vehicular bridges entirely out of aluminum has been demonstrated in a number of projects. The most frequent and successful applications have included: replace deck retrofits and pedestrian, lift (or bascule), floating, and temporary bridges.

2. A number of modern codes and standards exist to facilitate the design of aluminum vehicular bridge structures. Where possible, they have been written to resemble the more familiar steel standards, in order to minimize the difficulties associated with their comprehension and use.

3. From a materials perspective, the positive attributes of aluminum alloys include: light weight, high corrosion resistance, and extrudability. The best opportunities for aluminum use in vehicular bridges tend to be ones that exploit one or several of these positive attributes.

4. The properties of aluminum that present the greatest challenges for structural applications include: its lower elastic stiffness and fatigue strength than steel, and the reduction in the local yield strength that accompanies welding for many aluminum alloys, and the higher initial material cost. These isssues can be mitigated through smart detailing, the use of modern friction stir welding (FSW) techniques where possible, and material selection on the basis of life-cycle cost.

5. The opportunities for aluminum use in the retrofitting of existing bridges include: deck replacement, deck widening, sidewalk / bike path addition, and rapid bridge replacement projects.

6. The primary structural members in new vehicular bridges that can be constructed out of aluminum include: bridge decks, longitudinal girders, diaphragms, and cross bracing. The benefits of aluminum use in these applications are most apparent in severe corrosion environments, when comparisons are made based on life-cycle costs incurred by all of the bridge stakeholders. Aluminum performs best when the painting cost is high, due to site access or environmental constraints, and the user cost associated with maintenance interventions is high (e.g. due to a high detour length or traffic volume).

7. Aluminum is currently being used for secondary bridge components, including: sidewalk and bike path support structures, luminaires, sign support structures, and bridge rails. In these applications, the primary benefits of aluminum are its light weight, durability, and aesthetic qualities.

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