On the use of aluminium alloys in sustainable design, construction, and rehabilitation of bridges: emerging applications and future opportunities

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Abstract

Over the last few decades, aluminium alloys have been widely used as primary structural material in building construction. This is due to their advantageous properties such as low density, high strength-to-weight ratio, durability and excellent corrosion resistance, and high recyclability. The scope of this review paper is to explore the potential use of aluminium alloys in bridge design and construction. To this end, a thorough discussion of the material properties is presented to identify if the aluminium alloys can meet the bridge design and construction requirements. Particular emphasis is also given on total life-cycle cost of aluminum alloys and their potential role towards sustainability and decarbonisation of bridge structures. Moreover, the possibility of using aluminium alloys as an alternative for bridge rehabilitation and strengthening is investigated herein. A review of the existing research on the static, dynamic and fatigue structural response of aluminium bridge decks is also conducted. The main findings are highlighted, and research gaps are identified. Finally, corresponding future research to fill these gaps is recommended.

Keywords: aluminium alloys/bridges/sustainability/decarbonisation/review

1. Introduction

Aluminium alloys have been used in bridge structures for more than 70 years. The first aluminum bridge deck is dated back in 1933 and was used to replace a composite steel-wood deck on Pittsburgh's Smithfield Street Bridge (Figure 1). The substantial reduction in self-weight was deemed beneficial increasing the bridge's live-load carrying capacity. Since that time aluminium alloys have been used in different ways in hundreds of bridge structures around the world, and most remain in service today, including some for more than 50 years. Aluminum alloys have several performance characteristics that make them very attractive for bridge structures, namely low density, high strength-to-weight ratio, great durability, excellent corrosion resistance, high recyclability and favourable life-cycle cost. However, partial ignorance combined with design misconceptions have deterred their broader usage in bridge design and construction.

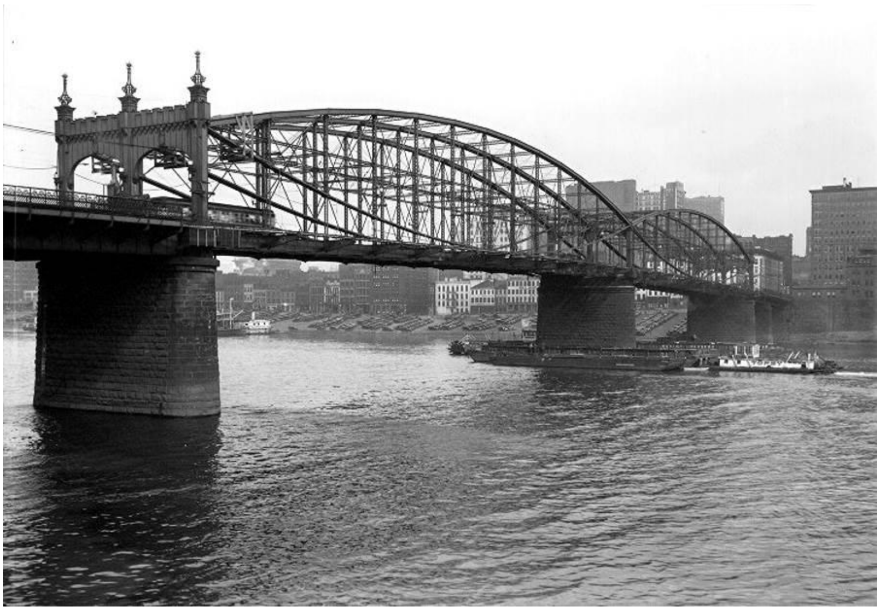

Figure 1: Pittsburgh's Smithfield Street Bridge in 1933 (Brookline Connection, 2023a).

The objective of this paper is to explore the potential use of aluminium alloys in bridge design and construction, and encourage researchers, bridge engineers, consultants and contractors towards a more frequent deployment of this material in future applications. Upon a brief introduction in Section 1, the advantageous features of aluminium alloys are thoroughly discussed in Section 2. Section 3 presents the aluminium alloys and forms suitable for bridge structures. Section 4 focuses on the design considerations that need to be factored in, whilst Section 5 investigates the possibility of using aluminium alloys for bridge rehabilitation and strengthening. A comprehensive review of the experimental and numerical research work to date on static, dynamic and fatigues performance of aluminium bridge decks is provided in Section 6. Finally, concluding remarks accompanied by suggestions for future work are presented in Section 7.

2. Why aluminium alloys?

Aluminum alloys have several important performance characteristics that make them very attractive for design, fabrication and erection of aluminum bridge structures.

2.1. Ease of extrusion

The versatility of aluminium alloys as a metal is complemented by the ease of the extrusion process. Aluminium alloys' ability to be extruded into any bespoke shape offers design flexibility allowing to place the material where it is most needed and thus reducing material waste. Therefore, the power of the "put-the-metal-where-you-need-it" flexibility can yield significant benefits in manufacturing cost and energy consumption reflecting sustainable practices. Most bridge applications involve tonnages of material which allows to create optimised component cross-sections, and thus the designer is free to create innovative and structurally efficient solutions (Tindall, 2008).

2.2. Lightness and high strength-to-weight ratio

Aluminium alloys are characterised by low density and high strength-to-weight ratio. Particularly, aluminium alloys' density is of 2.7 g/cm^3 which is about a third of that of steel. In spanning structures such as bridges, where the mass is a huge concern, aluminium alloys unlike steel can satisfy the minimum strength requirements without a weight penalty. The high strength-to-weight ratio minimises the total weight of the superstructure and thus minimises the substructure costs, which is particularly beneficial in poor ground conditions or where existing substructures are to be reused. The inherent light weight of aluminium alloys could also be a great advantage for structural applications located in seismic prone regions. Since seismic forces are inertia forces due to accelerating mass; the lower the mass, the lower the seismic design forces. Moreover, minimising self-weight is an important factor in the cost of transporting and handling components. Particularly, it helps vehicles to reduce fuel consumption or allows to increase the number of components that they can carry.

2.3. Accelerated bridge construction

Aluminium alloys' lightweight nature in combination with ease of fabrication makes them suitable for accelerated bridge construction which is a process that involves constructing large portions of bridges off-site, then installing them quickly on-site. Accelerated bridge construction provides several advantages such as (a) reduces construction time, and therefore, reduces traffic delays during construction, (b) improves work zone safety for the travelling public and highway workers, (c) results in significantly more durable bridges owing to aluminium alloys' corrosion resistance (d) reduces the environmental impact owing to shorter construction time on-site, and (e) results in significant whole-life cycle cost savings as it reduces the project delivery time (cost- and time-effective technique). It is noteworthy that at present, it is possible to build a 40 m bridge span using prefabricated aluminium alloy elements (Mazzolani, 2006). Figure 2 shows a German military bridge composed of prefabricated units, easy to transport and erect. The Sandisfield bridge (Figure 3) is a great example of aluminium alloys' recent deployment in accelerated bridge construction (AlumaBridge, 2022). An aluminium bridge deck installed in 30 minutes in Sandisfield in Massachusetts replacing a 1950 bridge with a lighter and quicker-to-install substitute. For this project, a lightweight aluminium deck was pre-attached to the steel superstructure and lifted into place by crane in one piece. The use of prefabricated panels, which are one-fifth the weight of concrete, dramatically reduced the overall weight of the structure, enabling the installation to be completed in a short time.

Figure 2: A German prefabricated aluminium military bridge during erection phase (Mazzolani, 2006).

Figure 3: Sandisfield bridge (AlumaBridge, 2022).

2.4. Durability and corrosion resistance

Aluminium alloys are characterised by great durability, as they quickly form a thin invisible protective oxide layer on their surface that gives them outstanding corrosion resistance in mild environments. However, in coastal and marine environments or in the presence of de-icing salt on the roads where the atmosphere becomes more aggressive, protection of some alloys is necessary (British Standards Institution, 2007a). The oxide layer is self-healing and when damaged, it immediately reforms, provided there is oxygen present. If oxygen is no present, the oxidation should be removed and corrosion protection should be established in conjunction with the engineer, manufacturer and if necessary a corrosion specialist. Aluminium alloy structures can be designed with minimum service life of 80 years with no maintenance and within this timespan the dominant material can maintain its inert properties in large temperature variations (All about aluminium, 2023). It is noteworthy that aluminium alloys offer superior low-temperature toughness and thus eliminate concerns about brittle fracture, even in the most severe Arctic weather (Das and Kauffman, 2007). Considering that the design service life of bridges in United Kingdom (UK) is 120 years, aluminium alloys provide a durable solution which minimises the long-term maintenance cost.

Bimetallic (galvanic) corrosion risks should be considered when aluminium alloys are coupled with other metals depending on the circumstances. Acidic or alkaline moisture, or abrasion breaks down the oxide layer, which acts as a natural barrier, exposing bare metal and thus activating bimetallic corrosion. Stainless steel fasteners in aluminium alloy plates or sheets are normally considered safe, as the contact is between the two oxide layers and there is no practical risk of bimetallic corrosion. In contrast, in a marine environment, severe localised pitting corrosion to the aluminium alloy treads of a ladder structure has been observed where un-insulated stainless-steel bolts were used to secure the treads in place. On the same ladder however, bolts with sound insulating washers did not show any pitting on the surrounding aluminium. This illustrates the beneficial effect of breaking the corrosion cell by isolating the two 'dissimilar' metals in marginal cases. Moreover, aluminium alloys in contact with dense compact concrete, masonry or plaster in a dry or marine environment should be coated in the contacting surface with a coat of bituminous paint. Details of the corrosion protection procedure required in these cases are given in (British Standards Institution, 2007a).

2.5. Sustainability

Recent technological advances across the entire production chain (i.e., mining, refining, transportation, power and anode production, smelting and casting) and the use of renewable energy from hydro, wind and solar power accelerate industry's move to a decarbonised future. In the aftermath, the required energy within the aluminium production process reduced more than 75% since 1995, lowering the industry's carbon footprint by almost 40% (The Aluminum Association, 2023). It has also been stated that "aluminum made in North America is more sustainable today than ever before" (The Aluminum Association, 2023). However, as the aluminium industry seeks to decarbonise, carbon dioxide (CO_2) emissions resulting from production are only the one part of the equation. Aluminium alloys are also a key material for circular economy as they are infinitely recyclable and retain their properties indefinitely. To put this into perspective, recycling aluminium alloys saves around 95% of the energy consumed in the 'primary' production process adding tangible value to the economics of production (Aluminium for future generations, 2023). In particular, Table 1 summarises data on energy requirements and carbon footprint for primary and secondary (recycling) production processes for steel and aluminium alloys (Grimes *et al*. 2008; Bureau of International Recycling, 2016). It can be seen that production of primary aluminium alloys through the Hall-Hèroult electrolysis process is more energy intensive than that of primary steel resulting in approximately 7 times larger carbon footprint. The recycling process of aluminium alloys, however, requires a lot less energy than their primary production, and thus emits approximately 0.6 tons CO_2-equivalents (CO_2e) per ton aluminium alloys which is marginally less compared to secondary steel production. Thus, secondary aluminium makes feasible to build a bridge with the same carbon footprint at production stage with an equivalent steel one. Considering the economic revenues resulting from the recycling process, these are one order of magnitude higher for aluminium scrap than for steel. Particularly, the potential gains may be calculated considering an average of 3760/t for aluminium alloys and an average of 376/t for steel (Choi *et al.* 2016). Therefore, the inherent recyclability of aluminium alloys can be exploited to a greater extent as the industry pursues its sustainability goals. Further to industry's climate-change mitigation commitments, aluminium alloys' lightness is desirable not only for cost reasons, but also for limiting the CO_2 emissions related to energy required for handling, transporting and erecting components. Moreover, minimum maintenance requirements as stated in Section 2.4 result in significantly reduced carbon footprint at the use stage of the life cycle of the bridge. From the above, it has become clear that aluminium alloys offer a less impactful option for bridge structures compared to steel, in large part due to the credits delivered by aluminium alloys' durability which requires less maintenance. However, a future comparative cradle-to-grave environmental life-cycle assessment (LCA) of an aluminium bridge with an equivalent structural steel alternative will allow to quantify and better assess the environmental impact of both bridge systems.

Table 1: Energy requirements and carbon footprint for primary and secondary (recycling) production processes for steel and aluminium alloys.

	Primary production			Secondary production		
Material	Manufacturing process	Energy consumption (MJ/kg)	Carbon footprint (tCO_2e/t)	Manufacturing process	Energy consumption (MJ/kg)	Carbon footprint (tCO_2e/t)
Aluminium alloys	Bayer-Hall Hèroult	184.4	13.3	Remelting and casting	5	0.6
Steel	BF-BOF* DRI + EAF**	21.9 26.7	1.97 1.76	EAF	11.7	0.7

BF-BOF*: Blast Furnace-Basic Oxygen Furnace process

DRI + EAF**: Electric Arc Furnace and Direct Reduction Iron process

2.6. Life-cycle cost

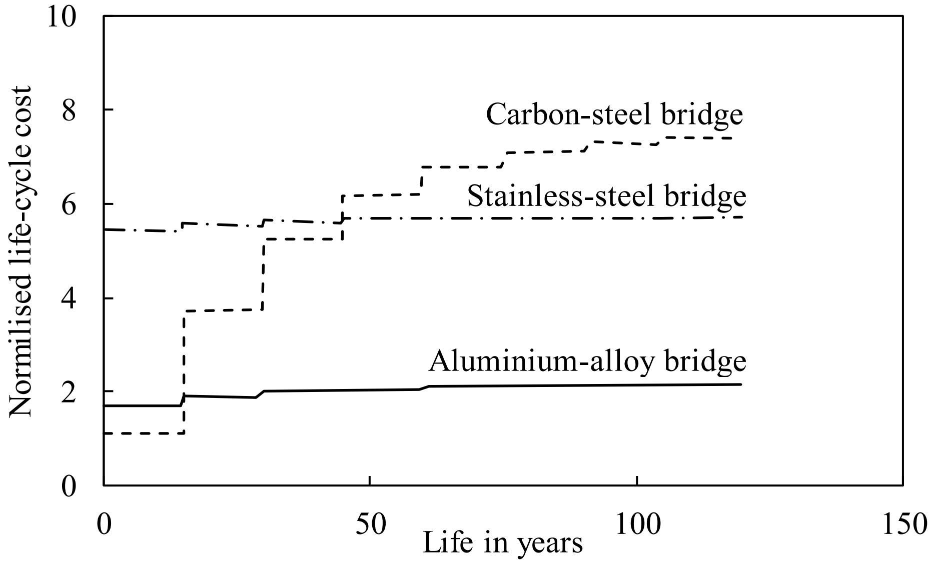

Figure 4: Accumulation of costs over the life cycle of the bridge structures (adopted from (Gardner *et al.*, 2007))

Aluminium alloys are not used in a widespread manner mainly due to high initial cost. Highway agencies do not favour high initial costs, particularly when the life cycle cost of relatively new structural materials is not known. To overcome this difference of the initial cost between the new materials and the conventional ones, a practical method such as life-cycle costing analysis could be performed. Life-cycle costing (LCC) analysis evaluates alternative materials in a comprehensive and consistent manner translating all expenses associated with a structure over its total life cycle into current funds.

A LCC study has been previously conducted on aluminium alloy, carbon-steel and stainless-steel bridges and a comparison has been made between the three materials (Gardner *et al.*, 2007). The LCC calculations accounted for the initial material costs and the costs associated with initial corrosion and fire protection. Maintenance costs, end-of-life costs and the residual value of the bridge were also considered within the study. However, indirect costs associated with economic and social impact caused by traffic diversion as well as environmental impact due to increased emissions resulting from maintenance activities were not included. As shown in Figure 4, aluminium alloys deliver the most competitive life-cycle solution for bridge structures. The same was also concluded by Das and Kauffman (2007) considering that the steel deck has to be painted every ten years of a 50-year assumed life, and the cost of each repainting is roughly 1/3 the cost of original construction. Of course, the cost savings increase more in case of implementing accelerated bridge construction technique. However, it is difficult to place a monetary value of such savings, but they are considerable in the public mind. Siwowski (2012) performed a comparative LCC analysis for deck replacement of a five span continuous Warren type steel truss bridge in Poland considering two conventional solutions; reinforced-concrete deck and steel orthotropic deck, and a new advance aluminium deck solution (Siwowski, 2009a). Assuming a 60-year bridge life and regular maintenance at different intervals for the three alternatives, aluminium deck outperforms clearly the other two conventional solutions. Recently, Pedneault *et al.* (2021) compared for first time a composite aluminium-steel deck with a conventional composite concrete-steel one in terms of life cycle cost and environmental impact. The results show that the initial cost of the aluminum-steel deck is double that of concrete-steel deck, but the overall cost is actually four times lower over the entire life cycle. From environmental perspective, the researchers found that the benefits of aluminium alloys are more pronounced than the concrete option.

3. Aluminium alloys and forms for bridge structures

Aluminium alloys are divided into two basic categories: wrought and cast alloys. The former comprises alloys which are melted in a furnace and then poured into moulds, whereas the latter includes alloys treated in a solid form. The Aluminum Association Inc. (The Aluminum Association, 2023) classifies the wrought alloys into 9 series using a four-digit system and each series comprises different combinations of alloying additions. The first digit (Xxxx) indicates the principal constituent alloy, whereas the second digit (xXxx) indicates the modifications made in the original alloy. The last two digits (xxXX) are arbitrary numbers so that the specific alloy can be identified in the series. Thus, the material properties can vary offering several options for applications. Wrought alloys and particularly 5xxx, 6xxx and 7xxx series are the most attractive for bridge engineering applications due to their mechanical properties as described below (Das and Kauffman, 2007; Tindall, 2008).

5xxx series−Aluminium-Magnesium alloys. These alloys are strain hardenable and have moderately high strength, excellent corrosion resistance even in salt water, and very high toughness even at cryogenic temperatures to near absolute zero. They are available in several different degrees of hardness (O denotes the base condition; the letter H followed by two numbers denotes work-hardened material). A common alloy is 5083-H12. They are easily welded by a variety of techniques, even at thicknesses up to 20 cm. They are readily available in the market but only in sheet or plate form and thus are a good choice if forming a bridge structure from plate materials. Typical ultimate tensile strength range (British Standards Institution, 2007a): 100 to 340 MPa.

6xxx series–Aluminium-Magnesium-Silicon alloys. These alloys are heat treatable and have moderately high strength coupled with excellent corrosion resistance. A unique feature is their great extrudability, making it possible to produce in single shapes relatively complex architectural forms, as well as to design shapes that put the majority of the metal where it will most efficiently carry the highest tensile and compressive stresses. They are available in a range of tempers indicated by the letter T followed by a number. A common alloy is 6063-T5. They are also readily available in sheet and plate form, and they can be easily welded by a variety of techniques. Typical ultimate tensile strength range (British Standards Institution, 2007a): 140 to 310 MPa.

7xxx series–Aluminium-Zinc alloys. These alloys are heat treatable and stronger than the 5xxx and 6xxx alloys. These alloys are not considered weldable by commercial processes and are regularly used with riveted construction. They are harder to form and are more expensive than other common alloys. Typical ultimate tensile strength (British Standards Institution, 2007a): 350 MPa.

4. Design considerations

Despite the fact that aluminium alloys offer unique properties, there are some disadvantages that have deterred their broader usage in bridge design and construction.

3.1. Initial cost

The high initial cost of aluminium alloys is mainly associated with the high energy consumption during primary production. This has often been regarded as a liability towards a more frequent employment of this material in bridge design and construction. Particularly, the higher initial cost of the aluminium bridge components over their steel and/or concrete counterparts ranges between 25–75% (Das and Kauffman, 2007). However, the “secondary” aluminium which is produced from recycled aluminium scrap significantly reduces the energy required during production and thus delivering a competitive position at acquisition. Nonetheless, to examine and compare the performance of different materials, a holistic consideration, e.g., through LCC analysis, of all phases in production, design, manufacturing, installation, service, and disposal or recycling processes is the only method to support well-informed decisions for a more sustainable future.

3.2. Lack of general knowledge

Another factor limiting the use of aluminium alloys in bridge design and construction is the lack of general knowledge of their structural behaviour and the design rules for aluminium structural applications by many engineers. This makes them favour other conventional materials such as steel or concrete that they are more familiar with. Moreover, the structural engineering curriculum in colleges and universities focuses mainly on steel and concrete and, as a result, only few engineers know how to employ aluminium in structural applications.

The current design guidelines for aluminium building structures are based on limited amount of structural data as aluminium alloys is a relatively new structural material with a limited research capacity. Moreover, sometimes designers adopt similar principles to their steel structure counterparts, without sufficient consideration of the differences between the two materials. However, over the last years, extensive research work on aluminium alloys structural behaviour has been published by the Author (Georgantzia *et al.,* 2021). This can lead to future modifications of the existing design codes and potentially increase structural engineers' confidence towards a more frequent employment of this material in building applications.

Contrary to other Eurocodes, Eurocode 9 does not provide separate document for aluminium bridge structures and is limited to some rules given in Annexes to EN1999-1-1 (British Standards Institution, 2007a). The Aluminum Design Manual (American Association, 2020) drops references to bridges, thus limiting its scope to building structures, defined in the Manual as a structure of the type addressed by a building code. Concluding, although aluminium alloys have been gaining great interest as bridge material, a complete standard for aluminium bridge structures has not yet been developed. Nevertheless, several aluminium manufacturers worldwide in collaboration with academic researchers have undertaken comprehensive research programs in order to develop new constructional solutions to expand the use of aluminium alloys (Siwowski, 2006).

3.3. Fatigue

Aluminium alloy structures that are subjected to fluctuating service loads in sufficient numbers are liable to fail by fatigue. Fatigue failure usually initiates at a point of high stress concentration such as toes and roots of fusion welds, machined corners and drilled holes, surfaces under high contact pressure and roots of fastener threads. For structures subjected to fatigue loading, the static limit state criteria cannot be relied on to give a reliable guidance for treatment of fatigue failure. Therefore, it is necessary to determine the extent to which the fatigue is likely to control the design. Detailed design, manufacturing method and degree of quality control may significantly influence the fatigue strength, and should be defined more accurately than for statically controlled members. This can have a major influence on design and construction cost. Djedid *et al.* (2020) proposed a manufacturing and assembly strategy for a highway bridge deck made up from aluminium panels which achieves high quality product at minimum cost.

To date, several small- and full-scale fatigue tests have been conducted and the obtained results were utilised to develop fatigue design procedures (Jaccard *et al.*, 1995; Kosteas, 2008). According to EN1999-1-3 (British Standards Institution, 2007c), designing a structure against the limit state of fatigue may be based on "safe life" design or "damage tolerant" method. Either of these methods may be supplemented or replaced by design assisted by testing. Particularly, "safe life" design approach suggests that the members are designed such that the predicted cyclic stress levels do not result in any fatigue cracks. This approach provides a conservative estimate of the fatigue strength and does not depend on in-service inspection for fatigue damage. The "damage tolerant" method allows for some fatigue cracking provided that the crack growth is monitored and kept under control by means of a fatigue inspection and maintenance programme. Therefore, it is of great significance for the owner(s) to ensure that the regular inspection programme is followed during the lifetime of the structure.

In general, aluminium alloys are more sensitive to fatigue than steel. This combined with the high ratio between the live load and the dead weight of an aluminium bridge, makes fatigue to be the governing design criterion. Particularly, the crack propagation life of aluminium alloy components is lower due to the (a) higher crack growth rate (approximately a factor 3 according to BS7910 (British Standards Institution, 2005) and Maddox (2003)) and (b) lower fracture toughness at room temperature which results in a smaller fatigue crack at the moment of fracture. Hence, the crack initiation period is relatively more important for aluminium alloy than for steel components. It is noteworthy that the same physical principles apply to the fatigue behavior of steel and aluminium alloy components, but the EN1993-1-9 (British Standards Institution, 2006a) and EN1999-1-3 (British Standards Institution, 2007c) standards contain a number of significant differences owing to different physical behaviour or different structural applications (Maljaars *et al.*, 2013). The most important issue to which this applies is the difference in fracture toughness. The fracture toughness of steel decreases with decreasing temperature, and the rules in EN1993-1-10 (British Standards Institution, 2006b) prevent applications with brittle material. Instead, the fracture toughness of aluminium alloys is relatively low at room temperature, and requirements on minimum toughness values are currently missing. This strongly influences the fatigue life and the possibility of assessments using inspection results.

3.4. Fire Safety

Aluminium alloys start to lose some of their strength when held at temperatures above 100 °C, and have lost a significant proportion by 350 °C (Maljaars *et al.*, 2010). However, their high heat transfer and reflectivity contribute towards reducing the impact of the heat on the structure. Less heat is absorbed, and, when absorbed, the heat is transferred away from the heat source much quicker. In addition, the emissivity of aluminium is 7–9 times lower compared to steel resulting in less heating-up of the direct surroundings (The Aluminium knowledge hub, 2023).

In case of bridge structures, fire incidents are commonly caused by crashing of vehicles and burning of gasoline in the vicinity of the bridge. In these accidents, very high temperatures will be attained within the first few minutes posing a severe threat to structural members. This could lead to permanent damage or even collapse of the bridge. EN1999-1-2 (British Standards Institution, 2007b) provides a comprehensive guidance for structural fire design considering the behaviour of the structural system at elevated temperatures, the potential heat exposure and the beneficial effects of active and passive fire protection systems, together with the uncertainties associated with these three features and the importance of the structure. However, it should be noted that the additional costs of insulation materials are far less than the monetary savings gained using a lighter structure that requires minimal maintenance (The Aluminium knowledge hub, 2023).

3.5. Low stiffness

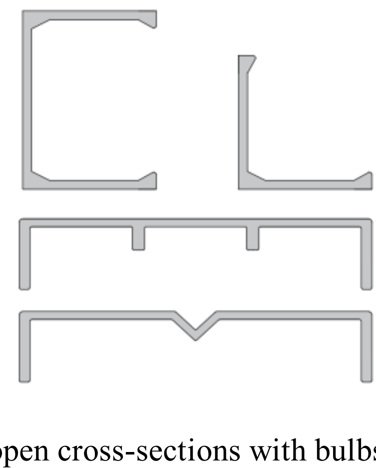

Figure 5: Typical extruded open cross-sections with bulbs and stiffeners (adopted from (Tindall, 2008)).

Aluminium alloys' Young's modulus E is approximately 70 GPa which is the one-third of that of steel. For bridge design this implies that the deformation, vibration, and buckling, govern the structural design – or at least are more decisive than for steel. Therefore, the design practice for aluminum bridges slightly differs from that for steel bridges. Particularly, in many cases, it involves increasing the second moment of area I by altering the geometry of the structure (e.g., deeper spans and/or thicker sections), so that the stiffness EI is sufficiently large. However, even with such arrangements, aluminum alloy structures, on average, weigh about one-half compared to steel structures (Das and Kauffman, 2007). Moreover, taking advantage of appropriate design techniques such as topology optimisation, along with the versatility of the extrusion process, cross-sections which are more structurally efficient could be produced resulting in more options for tailored solutions to structural problems (Tsavdaridis *et al.*, 2019). These sections are often asymmetric, more complex, contain thin walls and are reinforced with ribs, bulbs, and lips (Figure 5). Therefore, the designers should get familiar with the concept of placing material where it is efficient and thus optimising their design solution. Höglund (1994), Matteo (1997), Soetens and Van Straalen (2003), and Okura *et al*. (2004), proposed bridge deck panels made up from extrusions whose geometry was developed and optimised in line with domestic requirements and production possibilities.

An efficient way to control the vibration of the bridge caused by dynamic loading such as wind turbulence, earthquake and pedestrian excitation -particularly for footbridges-, and prolong its service life, is to increase its overall damping. To this end, He *et al.* (2022) tested single-span simply-supported 6016 aluminium alloy bridges considering three different damping mechanisms; (i) rubber sheet pavements, (ii) rubber bearings, and (iii) external passive damper. According to the findings, the external passive damper is the most efficient mechanism as it can increase the system damping one order greater than the rubber sheet pavements and rubber bearings. It is noteworthy that the rubber sheet pavement is inefficient in damping increase owing to the huge difference in elastic modulus between aluminium and rubber. Therefore, more research is suggested to explore additional materials that could be employed in damping mechanisms. Moreover, development of mathematical damping models capable of predicting the nonlinear behaviour of bridges are also necessary for each damping mechanism. These studies will give impetus towards understanding damping mechanisms in aluminium bridge systems.

3.6. Welding

Welding of the common structural alloys is readily conducted using the gas-shielded Metal Inert Gas (MIG) or Tungsten Inert Gas (TIG) fusion welding processes. Both techniques are similar to welding steel, although care needs to be taken to remove the oxide film and any contaminants from the fusion faces before welding. Moreover, in 1991, a friction-type method named Friction Stir Welding (FSW) was conceived by The Welding Institute, which allows a wide range of materials and geometries to be joined (Okura 1992; Dawes and Thomas, 1995; Nicholas, 1998). This welding process takes place at a temperature below aluminium alloys' melting point resulting in minimal heat distortion and low residual stress levels and thus making it easier to control deformation.

However, when strain hardened or artificially aged precipitation hardening alloys are welded, the welding process results in reduction in strength properties in the vicinity of welds. The reduction affects the yield strength of the material more severely than the ultimate tensile strength. The affected region, known as Heat-Affected Zone (HAZ), extends immediately around the weld, beyond which the strength properties rapidly recover to their full unwelded values. HAZ should be considered as a possible start point of fatigue crack because of the lower strength, possible geometrical and material discontinuity, thermal strains and residual stresses caused by welding. This is an important demerit of the welded aluminium structures which requires careful thought and detailed design (e.g., employing extruded cross-sections with local thickening ribs, building welded connections at points of contraflexure instead of points of high bending moment, etc.) to provide an efficient structure.

Current design codes give comprehensive rules for the extent of the HAZ, and how to account for the loss of strength on member capacity. EN 1999-1-1 (British Standards Institution, 2007a) considers the severity of softening through inferior material properties of the HAZ or by reducing the affected cross-sectional area. The fatigue strength curves provided by (British Standards Institution, 2007a) cover components and structures welded by MIG or TIG processes. However, over the last years, FSW has been increasingly employed in heavily loaded aluminium structures. Since it is a solid-state joining process, as mentioned above, is expected to result in welds with superior fatigue strength, adopting the existing design fusion weld curves for welds fabricated by FSW may be a conservative practice (Svensson *et al.*, 2000; Dickerson and Przydatek, 2003; de O Miranda *et al.*, 2015). To date, the available data on the fatigue strength behaviour of welds fabricated by FSW are scarce (Dickerson and

Przydatek, 2003; Guo, 2018; Guo *et al.*, 2019). In order to develop fatigue design provisions for FSW joints, more fatigue tests on fabricated FSW joint specimens are needed, under a range of loading conditions, including constant and variable amplitude simulating service conditions typical for vehicular bridge decks.

5. Bridge rehabilitation and strengthening

Ageing infrastructure, combined with increasing traffic growth, put into question the long-term viability of many rail and road reinforced concrete and steel bridges. According to RAC Foundation (2023), more than 3,000 council-maintained road bridges of the total 72,000 (about 1 in 23) in Great Britain are substandard due to deterioration and particularly corrosion damage. The UK rail network alone includes more than 35,000 bridges (Le and Andrews, 2013), and approximately 45% of these bridges are made of metal (cast iron, wrought iron, and steel) (Royal Institution of Chartered Surveyors, 2014), with 50% over 100 years old. Network Rail bridges' annual maintenance cost is estimated to be around £120m, which is approximately a third of their annual maintenance expenditure for civil structures (Royal Institution of Chartered Surveyors, 2014). In addition, the Department of Transport of UK estimates a total repair cost of £616.5m due to corrosion damage to road bridges (Broomfield, 2023). The bridges corresponding to this cost estimate represent about 10% of the total bridge inventory in the UK and therefore the total problem may be ten times the above estimate (Broomfield, 2023). Moreover, Balogun *et al.* (2019) performed a comparative study on environmental impacts as a result of ongoing maintenance for concrete, steel and masonry bridges. Using LCA they evaluated the environmental impacts of selected maintenance strategies, which accounts for the associated materials, energy and transport. Eight impact categories are used to evaluate the selected maintenance actions. The significance of their impact was defined based on human health, ecosystems and resources, using the European scale. They reported that the maintenance of steel and concrete bridges has approximately four time more environmental impact across all the selected indicators in comparison to masonry bridges. It also concludes that the structural engineers should consider revising the component parts of reinforced concrete and steel bridges as they play a critical role in the selection of maintenance options, which in turn influence the degree of the environmental impact.

To address these challenges and considering the longer term financial and environmental implications of projects, innovative bridge rehabilitation and strengthening techniques could be employed using aluminum alloys. Particularly, replacing an existing deteriorated bridge deck by another one made from aluminum alloys could significantly reduce the self-weight of the bridge. The reduction of the self-weight which acts as permanent load, enables for increase of the load-carrying capacity while preserving the other components of the superstructure and the substructure. The increased capacity, in turn, can allow for an increase in the allowable freight transport loads or the traffic flow through the use of a wider deck. The lighter aluminium alloy deck could also be suitable for bridges with structurally deficient substructure as it enables sustaining the current loads without strengthening the substructure. This rehabilitation technique was applied successfully at Pittsburgh's Smithfield Street Bridge. A new floor, including beams, stringers and deck, built entirely from high-strength aluminium alloy was placed within 24 days on the 51-year-old bridge extending its service life about 25 years (Historic Bridges, 2023). This was achieved because the new floor's weight was almost half than that of the original wrought iron and steel floor allowing for 1.5 times higher permissible load on the bridge. Figure 6 shows the original wrought iron and steel roadbed and the new lightweight aluminum decking. However, this technique applies mainly to bridges in which the deck does not act compositely with the supporting members in resisting the gravity loads. This type of deck, commonly made up of either a concrete slab, a steel grid, or timber, is generally supported by steel beams or girders. In this case the aluminium alloy deck can also efficiently cover the supporting elements and prevent them from being deteriorated due to rusting.

(a)

(b)

Figure 6: (a) The wrought iron and steel roadbed was replaced with (b) lightweight aluminum decking (Brookline Connection, 2023b,c).

6. Experimental work on aluminium bridge deck systems

Table 2: Summary of experiments on aluminium alloy decks (*in chronological order from most recent research*).

Reference	Number of tests	Type of test	Type of deck	Aluminium alloy	Failure mode
Vigh and Okura (2013)	5	Fatigue	Orthotropic	6005C-T5	cracking in the FSW region at the bottom flange
Vigh and Okura (2013)	1	Static	Orthotropic	6005C-T5	web crippling
Siwowski (2009a)	7	Static	Orthotropic	6005A-T6	local yielding and fracture under the load patch, fracture of HAZ
Lakota and Siwowski (2005)	N/A*	Dynamic	Orthotropic	N/A*	N/A*
Dobmeier *et al.* (2001)	2	Static	Orthotropic	6063-T6	local yielding and punching at load patch, failure of welds

N/A*: Not Available to the author at time of publication

In the early 1980s, Svensson and Peterson (1990) suggested a Swedish orthotropic deck system for bridge rehabilitation. The Svensson deck is composed entirely of multi-cellular 6063-T6 extrusions of trapezoidal form. In a following study, Arrien *et al.* (2001) investigated numerically the performance of Svensson deck under the loads according to the Canadian bridge code (Canadian Standards Association, 1988). The results showed that the Svensson deck yields reduced deflections and it allows a slightly superior load distribution across the main girders, when compared to a timber deck. Over the last 20 years, the reported experimental studies on aluminium alloy bridge decks are quite limited as summarised in Table 2. Dobmeier *et al.* (2001) examined the response of two 2.74 × 3.66 × 0.20 m simply-supported orthotropic deck panels under static loading. The panels comprised two-voided triangular 6063-T6 extrusions welded together at top and bottom flanges to form full-scale deck panel (Figure 7). Two loading configurations were considered, i.e., single and double loading points, and various loading rates from 222.41–1100 N/s. In one-point load test, local yielding and punching under the load patch was observed, while in two-point load test, the failure mode changed to weld failure on the tension face of the deck panel. In addition, the ultimate load of two-point load test was higher than that of the one-point load test.

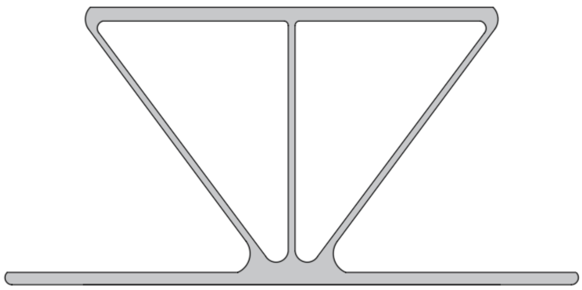

Figure 7: Cross-section of a typical orthotropic deck panel (adopted from Dobmeier *et al.* (2001).

Lakota and Siwowski (2005) studied both experimentally and numerically the dynamic behaviour of a multi-voided orthotropic deck panel. Later, Siwowski (2009a) tested 2.10 × 3.20 × 0.17 m prefabricated orthotropic deck panels in service and ultimate states according to Polish bridge code (Polish Standard Institution, 1992). A one-voided triangular 6005A-T6 extrusion was used to form the deck panel. As a side note, the tested panels exhibited failure at a load 3–4 times of the service load. The experimental results reported in (Lakota and Siwowski, 2005; Siwowski, 2009a) were utilised in a following study Siwowski (2009b) to develop an advance numerical modelling technique capable of efficiently predicting the static and dynamic behaviour of aluminium deck systems. Moreover, Saleem *et al*. (2010) tested simple (1.22 m) and two-span (1.22 m each) 110 mm deep orthotropic deck panels under static and fatigue loading. The test results showed that the deck panels have capacity/demand ratio of 2.0–3.0 and high fatigue resistance, showing no signs of distress after subjecting to 2 million cycles of fatigue loading. Recently, Vigh and Okura (2013) studied experimentally the static behaviour of an orthotropic deck panel made from 6005C-T5 extrusions welded using FSW method. The specimen failed due to web crippling denoting negligible influence of FSW in static performance. The same deck was, also, tested under fatigue loading and failed due to cracking arisen in the FSW region. The results showed that although the fatigue strength of the given butt weld is lower than at parent material, it is much higher than the one specified in (British Standards Institution, 2007a) for MIG butt welds.

The scarcity of the reported data reveals the need of additional small- and large-scale static and fatigue tests on aluminium alloy bridge systems with different types of decks. This will allow to adequately determine their structural behaviour and develop accurate design criteria for safe and economically efficient design solutions. Moreover, additional research work is needed considering different types of dynamic loading, e.g., a group of vehicles moving at constant and variable speed, a rocket motor that gives a controlled impulse or a standard track irregularity. Most highway bridges are subjected to irregular traffic loads that are of random character and may be idealized by a stochastic process randomly variable in space and time (Frýba, 1976). As the life of bridges is long namely 120 years, knowledge of the recent, current and expected strengths of bridges is very important for the estimation of their fatigue life. This problem is quite important, particularly for steel bridges where it was found that the stress ranges significantly influence the extent of their fatigue life (Fisher, 1984). In light of aluminium bridges being more sensitive to fatigue loading, they exhibit strong dependence of their fatigue life applied on the stress ranges during their lifespan. Therefore, structural health monitoring is suggested to be instrumented onto new aluminium alloy decks to confirm actual stress ranges at key details. The obtained data could be then utilised to inform future revisions to the design codes, both on the load side and on the fatigue stress/detail classification side. Moreover, quasi-static and dynamic tests with variable vehicle speeds on rehabilitated bridge systems are also recommended to better evaluate their structural performance. Finally, it is noteworthy that most research studies investigating the use of aluminium alloys for new deck construction and rehabilitation or strengthening of existing deteriorated decks are limited to highway bridges. Hence, future research studies should focus on exploring aluminium alloys' suitability for railway bridges where the vertical deflection limits, and fatigue and dynamic performance requirements are quite stringent.

7. Conclusions and future research work

The present paper explored the potential use of aluminium alloys in bridge design and construction. A thorough discussion concluded that aluminium alloys have much to offer in bridge design and construction, and particularly where the low self-weight, high strength-to-weight ratio and excellent corrosion resistance are primary design concerns. Further to this, considering that the environmental concerns are high on the agenda in most developed countries, aluminium alloys are strongly welcome as the solution to the two-fold problem of ageing infrastructure and high environmental impact of maintenance practices. Particularly, the use of aluminium alloy decking offers great potential for rapid construction of modern highway bridges and for re-decking of aging concrete or timber deck-on-girder bridges for an increased traffic load capacity and a prolonged service life with reduced maintenance. Since aluminium industry is currently investing in the journey towards net-zero carbon by shifting the aluminium alloy production process to produce low-carbon aluminium alloys, aluminium alloys could play significant role towards bridge decarbonisation. However, the history of structural aluminium alloys' application and testing in this field is relatively short and thus more research is needed to achieve deeper comprehension of their behaviour. Table 3 summarises the recommended future work on topics that were identified throughout this study and need further investigation. It is noteworthy that additional research work can lead to establishment of design standards for aluminium bridge structures and potentially increase structural engineers' confidence towards a more frequent employment of aluminium alloys in bridge design and construction.

Table 3: Summary of recommended future work.

Investigation topic	Methods of investigation (experimental & numerical)
Environmental impact assessment of aluminium bridge systems	Comparative cradle-to-grave environmental life cycle assessment of an aluminium bridge with an equivalent structural steel alternative
Static behaviour of aluminium highway and railway bridge systems	Small- and large-scale static tests considering different types of decks.
Fatigue behaviour of aluminium highway and railway bridge systems	Small- and large-scale fatigue tests considering different types of decks and loading amplitudes.
Damping performance of aluminium highway and railway bridge systems	Small- and large-scale tests considering different damping mechanisms and development of corresponding mathematical damping models.
Fatigue behaviour of FSW joints	Fatigue tests on FSW joints under a range of constant and variable amplitudes.
Dynamic response of aluminium highway and railway bridge systems	Small- and large-scale tests considering different types of dynamic loading.
Estimation of fatigue life of aluminium highway and railway bridge systems	Structural health monitoring to evaluate stress ranges and develop fatigue life prediction models.
Structural performance of rehabilitated bridge deck systems	Quasi-static and dynamic tests on rehabilitated bridge systems including variable vehicle speeds.

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