Aluminum Alloys for Transportation, Packaging, Aeropsace, and Other Applications
Edited by Subodh K. Das, Weimin Yin
TMS (The Minerals, Metals & Materials Society), 2007

ALUMINUM ALLOYS FOR BRIDGES AND BRIDGE DECKS

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Keywords: Aluminum Alloys, Bridges, Design, Construction

Abstract

Aluminum alloys have been used in bridge structures since 1933, when the first aluminum bridge deck was used to replace an earlier steel and wood deck on Pittsburgh's Smithfield Street Bridge in order to increase its live-load carrying capacity. While still not considered a standard for bridge structures, aluminum alloys have much to offer for such applications, and continue to be used where their light weight, high strength-to-weight ratio, and excellent corrosion resistance satisfy service requirements.

This paper will provide in detail the advantages and limitations of aluminum alloys for bridge structures, including the key factor that they never require painting or any other type of coating for corrosion protection. A brief overview of the history of the use of aluminum in bridges in the United States and other locations throughout the world will also be presented.

Introduction

Aluminum alloys have been used in bridge structures for more than 70 years. In 1933, the first aluminum bridge deck was used to replace an earlier steel and wood deck on Pittsburgh's Smithfield Street Bridge in order to increase its live-load carrying capacity. Since that time aluminum has been used in various ways in hundreds of bridge structures around the world, and most remain in service today, including some for more that 50 years.

While still not considered a standard for bridge structures, aluminum alloys have much to offer for such applications, and continue to be used where their light weight, high strength-to-weight ratio, and excellent corrosion resistance satisfy service requirements and justify the additional initial cost. When considered on a life-cycle cost basis, aluminum bridges components have clear superiority.

The advantages of aluminum for bridges

Aluminum alloys have several important performance characteristics that make them very attractive for bridge structures, namely:

- Light unit weight, only one third that of steel;
- Strengths comparable to typical bridge steels;
- Excellent corrosion resistance, with negligible corrosion even in the presence of rain and road salts;
- High toughness and resistance to low-ductility fracture, even at very low temperatures, and free of any ductile-to-brittle transition that has sometimes been fatal to older steel bridges; and
- Excellent fabricability, including ease of production of extrusions to complex hollow shapes optimized for structural design and assembly

These performance characteristics provide significant advantages over conventional steel and concrete in the design, fabrication and erection of aluminum bridges and bridge components:

- Lighter weight and comparable strength enables the use of a higher ratio of live load to dead load, making the aluminum bridge girders and decks more efficient than steel or concrete components;
- Superior corrosion resistance eliminates the need to paint the aluminum components, except perhaps for aesthetic purposes, resulting in lower maintenance costs;
- Superior low-temperature toughness eliminates concerns about brittle fracture, even in the most severe Arctic weather;
- Ease of extrusion enables the design of more weight-efficient beam and component cross-sections, placing the metal where it is most needed within a structural shape or assembly, including providing for interior stiffeners and for joints; and
- The combination of light weight and ease of fabrication enables the entire aluminum structure or major portions of it to be pre-fabricated, carried to the site, and erected quickly with minimum interruption in the flow of traffic and thus less inconvenience to drivers.

It is appropriate to note, however, that there are some offsets to the advantages for aluminum that have deterred its broader usage in bridges, especially within the USA.

The most important of these is the higher initial cost (first cost) of aluminum bridge components over comparable steel and/or concrete components, which may depending upon design range from 25-75%. While the lower maintenance costs of aluminum bridge components over the life of the structure (principally, the lack of need for periodic painting) result in a lower total cost over the entire life of a bridge (life-cycle cost), the usual reliance upon separate new construction and maintenance budgets in most federal, state, and local highway districts has precluded the acceptance of the higher initial fabrication and erection costs in the USA. Greater use of aluminum for bridge structures has been made overseas (1-3) as will be described later, where such decisions are typically handled in a more centralized fashion.

Another factor limiting the use of aluminum for bridges has been the lack of general knowledge of the properties and design rules for aluminum in structural applications by many engineers and, as a result, their unwillingness to break away from the familiar patterns of use of steel and/or concrete structures. This is despite the availability for many years of the Aluminum Design Manual (1) produced by the aluminum Association, and aluminum's inclusion in most building codes.

In addition, colleges and universities focus primarily on steel and concrete when teaching structural engineering, with the result that few engineers come into the field with any knowledge of the use of aluminum in structural applications.

The net results is that despite the fact that aluminum makes up around 90% of the structural metal in aircraft and spacecraft, subject to very severe static and dynamic loadings, few civil and structural engineers in other industries know about the advantages of aluminum alloys.

There are some other factors that make designing aluminum bridge structures a bit different from designing steel structures, for example:

- Aluminum's lower modulus of elasticity (10 million psi [70 GPa] vs. 30 million psi [210 GPa] for steel).
- The fatigue strength of aluminum is about one-third that of steel.
- Aluminum's coefficient of expansion is about twice that of steel or concrete, so thermal stresses must be considered when aluminum components are fastened to these materials.

However such factors are readily handled by efficient design practices, for example, by using slightly deeper spans and thicker sections for aluminum than for steel. Even with such accommodations, aluminum structures, on average, weigh about one-half comparable steel structures.

Considerably more background and detail on aluminum structural design is included in References 2 through 9. The design specifications for aluminum structures (4) are included in the Aluminum Design Manual (1). Additional information of the design and application of aluminum for a variety of structural applications including bridges is given in Reference 10.

The early applications of aluminum bridges in the USA

The practical use of aluminum in bridge applications can be traced to 1933 when the timber and steel floor system in the Smithfield Street Bridge in Pittsburgh, PA, was replaced by an aluminum deck (2). The change was made to significantly lighten the structure's deadload and, thereby, significantly increase its live-load-carrying capacity. The new deck was a riveted orthotropic deck, about 300 ft. (100 m) in length. The components were rolled 2014-T6 plate, the most widely used high-strength structural aluminum alloy at the time (though by today's standards it was not the best choice from the corrosion resistance standpoint).

This new aluminum deck structure enabled the bridge to carry the new electrified trolley cars being introduced at the time in the City of Pittsburgh. It carried two lanes of motor traffic and two tracks for trolleys moving both directions. The Smithfield Street Bridge became the major artery of the time carrying such traffic across the Monongehela River from the "Golden Triangle" to the South Side. The 1933 structure remained in service without problems for 34 years, until in 1967 the deck was upgraded with a new welded aluminum orthotropic deck, further increasing its ability to handle more and bigger trolleys and trucks. The new deck was of the orthotropic design, and the deck plate alloy was 5456-H321, a more corrosion-resistant alloy than the 2014-T6 used in the earlier deck. This plate was welded to 6062-T6 extrusions with 5556 filler wire; the extrusions were bolted to the bridge superstructure. This aluminum deck stayed in service without problems until1993 when it was replaced by a steel deck (the decision being based upon short-term economics, not life-cycle cost).

The first all-aluminum bridge in the USA was constructed in 1946 for railroad traffic. One 100-ft (30.5 m) single-track span of a plate girder railroad bridge was constructed by Alcoa on a line serving their Massena smelter, probably as an illustration of the capability of aluminum in such applications. In this case, the girders were made of Alclad 2014-T6 plate, riveted with 2117-T4 rivets; the use of 2014 clad with relatively pure aluminum (1100) cladding was recognition of the lesser corrosion resistance of bare 2014 plate, as noted earlier.

The first all-aluminum highway bridge in the North America was erected in Arvida, Canada, over the Saguenay River in 1950 (Fig. 1). It was (and is today) a 290-ft (88 m) long, arch span bridge with multiple 20-ft (6 m) approach spans. It was erected by the Aluminum Company of Canada (Alcan), probably also as a working demonstration of aluminum's capability, and carried trucks with aluminum ores and products to and from various parts of the aluminum refining and smelting plants. It was then and remains today a very handsome bridge.

The 1950s and 1960s: Broader use of aluminum girder systems

In the period from about 1958 to about 1965, there was a national effort underway to upgrade the highway bridges across the USA and to find the most economical means of improving the safety of superhighways by incorporating cloverleaf intersections in them rather than dangerous crossroads. Aluminum alloys were among the materials of construction widely considered for these new or replacement bridges. In addition to its natural advantages, aluminum was seriously considered for bridges in the 1950s and 1960s in part because of the long lead times to obtain steel during that period. The interest was sufficient that, as we shall see, five significant new aluminum bridges were built in the USA over that seven-year period (1958-1967).

The first two of these were of relatively conventional built-up I-beam designs. A two-lane, four-span welded plate girder bridge was erected near Des Moines, IA, and a pair of two-lane, riveted plate girder bridges in Jericho, NY.

The Iowa bridge was a two-lane four-span bridge carrying 86th St. over I-80, and erected in 1958. The girders were of 5083-H113 aluminum plate welded with 5183 filler wire, with a concrete deck. These spans remained in service until about 1993, when they were removed because of an entirely new design of intersection being introduced at that location for which that bridge would no longer be needed. A thorough field and laboratory research program was conducted on the aluminum girder components as they were removed (3,11), and both tensile and fatigue tests of representative components of the girders were carried out. In every case, the test results showed that after about 40 years in service, the aluminum alloy members had tensile and fatigue properties comparable to those when the bridge was first erected and consistent with what would be expected in new structures today.

The twin Jericho, NY structures were two-lanes each, carrying I-495 traffic on the Jericho Turnpike, and were erected in 1960. The dual 77-ft (23.5-m) single span girders were fabricated of 6061-T6 plate with 2117-T4 riveted connections, and also had concrete decks. These spans were replaced in 1992 when the intersection was re-designed.

The last four aluminum bridge applications erected during that period were of the unique riveted, stiffened, triangular box beam girder concept referred to as the "Fairchild design" (12). This designation resulted from the fact that the design was conceived and put forth in the late 1950s by the Fairchild Kinetics Division of what was then called the Fairchild Engine and Airplane Company of Hagerstown, MD. Almost all commercial and military aircraft of the day were fabricated of high-strength aluminum alloys, and Fairchild engineers applied the current aircraft design concept of riveted, internally-stiffened sheet structures to bridge girder design. The design was also sometimes referred to as the "Unistress" design (13), because of the use of that term in a Kaiser Aluminum & Chemical Co. patent taken out about that time on one variation of it.

The cross-section of one of these bridges is illustrated in Fig. 2. It is a series of triangular box beams with common upper and lower flanges, plus end-frames. The result is a very stiff semi-monocoque design (2,12). In a monocoque structure, the skin absorbs all or most of the stresses to which the spans are subjected.

As part of the investigation of this innovative design, a full-scale 50-foot long bridge with a composite concrete deck was designed, fabricated, and tested by the Fritz Engineering Laboratory at Lehigh University (14). The advantages of the aluminum semi-monocoque design in providing lower dead load stresses (higher ratios of live load to dead load), lighter substructures, and reduced costs for transportation and erection were confirmed.

The first of the four bridges of the Fairchild or Unistress design was erected in 1961 in Petersburg, VA, carrying Route 36 over the Appomattox River. It was a single-span, two-lane bridge, with a concrete deck. The girder system was fabricated of 0.090-in (2.5 mm) 6061-T6 sheet. Like all three of the Fairchild designs it has remained in service for over 40 years.

As word of the opportunity to utilize a unique aluminum girder system to maximize the live loads of bridges became more widely known, construction of such bridges was also begun in Sykesville, MD and Amityville, NY.

The Sykesville Bypass Bridge, which carried MD Route 32 over the Patapsco River as well as the paralleling River Road and CSX Railroad (then the B&O), was the longest of this design ever built. The three nearly equal length spans total about 293 ft (almost 100 m). The MD State Highways Administration (SHA) engineers undertook the design of such a bridge for the planned new bypass of Route 32 around Sykesville, MD (15). Primarily because of (a) galvanic corrosion resulting from failure to maintain the isolation of the aluminum components and the steel bearings plus (b) an inadequate internal drainage system permitting water to lay inside the hollow sections, the Sykesville spans experienced galvanic and pitting corrosion; because of the high expense to repair it, the bridge was taken out of service in 2004 and replaced by an adjacent steel bridge.

In view of the unique nature of the bridge design and its use of aluminum components, the MD SHA, under the leadership of Rita Suffness, Architectural Historian and Cultural Resources Manager, recognized its historical significance and in coordination with the Maryland State Preservation Officer (MD SHPO), confirmed its place on the National Register of Historical Places in 1999. It has also been included in the MD SHA Historic Bridge Inventory, and in the Historic Bridges of Maryland (16).

The last two installations of the Fairchild design were in Amityville, NY, where a pair of three-lane, four-span bridges carry Route 110 over the Sunrise Highway. The Amityville spans, like the Sykesville spans, have deteriorated over the years; a renovation of the bridge, primarily to reduce the bearing stresses and assure isolation of bearing surfaces, has been proposed (17) and is being engineered by the New York State Department of Transportation.

Another innovative design of aluminum girder bridge seriously considered during this same period was conceived by Georgio Baroni for the Reynolds Metals Co. around 1958 (18). It employed a series of roll-formed inverted U-shaped cells placed longitudinally across the span, linked transversely, and integrated with the concrete deck to operate in semi-monocoque fashion. While believed to hold some promise at the time, and scheduled for erection in Alabama in 1960, the project was never completed.

A summary of the early aluminum usage in bridges in the USA is given in Table 1.

Table 1 – Early Use of Aluminum in Bridge Structures in North America

Location	**Bridge Type**	**Use**	**Number Of Lanes**	**Span(s) m (ft)**	**Year Erected**	**Deck**	**Alloys Used**
Pittsburgh, PA – Smithfield St.	Riveted Orthotropic Deck	Highway, Trolley	2 + 2 Tracks	Approx 100 (300)	1933	Aluminum Plate	2014-T6
Massena, NY – Grasse River	Riveted Plate Girder	Railroad	1 Track	30.5 (100)	1946	- - -	Alc 2014-T6 2117-T4 Rivets
Arvida, Canada – Saguenay River	Riveted Arch	Highway	2	5@6, 88, 5@6 (20,290,20)	1950	Concrete	2014-T6 Alc Plate, Extrusions 2117 rivets
Des Moines, IA – 86th St. over I-80	Welded Plate Girder	Highway	2	12,21,21,12 (41,69,69,41)	1958	Concrete	5083-H113
Jericho, NY I495 over Jericho Tpk	Riveted Plate Girder	Highway	4 (2 Bridges)	23.5 (77)	1960	Concrete	6061-T6
Petersburg, VA, Rte 36, Appomattox River	Bolted, Stiffened Triangular box Beam	Highway	2	29.5 (97)	1961	Concrete	6061-T6
Amityville, NY, Rte110 Sunrise Highway	Riveted Stiffened Triangular Box Beam	Highway	6 (2 Bridges)	18 (60)	1963	Concrete	6061-T6
Sykesville, MD, Rte 32 Patapsco River	Riveted Stiffened Triangular Box Beam	Highway	2	28,29,32 (93,94.106)	1963	Concrete	6061-T6
Pittsburgh, PA – Smithfield St.	New Welded Orthotropic Deck	Highway, Trolley	2 + 2 Tracks	Approx. 100 (300)	1967	Aluminum Plate	5456-H321

The use of aluminum bridge structures overseas

A summary of some of the earlier applications overseas is given in Table 2. There was considerable interest in what was going on in the USA, as illustrated by the attention to the USA applications described in the European press (examples: Ref. 12 and 13, articles from the French metallurgical publication, Revue De L'Aluminium).

As illustrated in Table 2, the three earliest European applications, from 1948-1950, were all in Great Britain, two of which were movable bascule bridges taking advantage of the lighter weight of aluminum spans (22,23), and the other a pedestrian bridge (24). Over the next ten years, six other aluminum structures were erected in Germany, Switzerland and England; four of the six were pedestrian bridges. Additional information on some of these applications is included in References 2 and 4.

While there was no widely publicized use of aluminum bridges in France until around 1968-1970, several applications during and after that period were reported in the principal French journal on aluminum, Revue De L'Aluminium (25-31). For example, it was reported that "the world's longest pedestrian bridge" at the time was erected in 1968/9 at Dunkerque (25) and, beginning in 1973, several bridge deck replacements of aluminum for steel/concrete decks were made to increase live load capacity of relatively old bridges (e.g., Montmerle, 1973; Groslee, 1976/7; and Chamalières, about 1978). The bridge at Chamalières (30) is of special interest as it also employed an aluminum girder system in its upgrade to permit widening the bridge from two to four lanes.

Table 2 – Early Use of Aluminum in Bridges Overseas

Location	**Bridge Type Connection**	**Use**	**Number Of Lanes**	**Span(s) m (ft)**	**Year Erected**	**Deck**	**Alloys Used**
Hendon Dock, England	Riveted Double Leaf Bascule	Highway, Rail	1 + 1 Track	37 (121)	1948	Aluminum Plate	2014-T6 6151-T6
Tummel River Scotland	Riveted Truss	Pedestrian	- - -	21,52,21 (69,172,69)	1950	Aluminum Sheet	6151-T6
Aberdeen, Scotland	Riveted Double Leaf Bascule	Highway, Rail	1 + 1 Track	30.5 (100)	1953	Aluminum Sheet & wood	2014-T6 6151-T6
Dusseldorf, Germany	Twin Web Plate, Arched Ribs	Pedestrian	- - -	55 (180)	1953	- - -	- - -
Lunen, Germany	Riveted Warren Truss	Highway	1	44 (145)	1956	Aluminum Shapes	6351-T6
Lucerne, Switzerland (two bridges)	Suspension Stiffened Girder	Pedestrian & Cattle	- - -	20 (65) 34 (112)	1956	Timber	5052
Rogerstone South Wales	Welded W Truss, Thru Girder	Pedestrian	- - -	18 (60)	1957	Corrugated Aluminum Sheet	6351-T6
Monmouth-Shire, England	Welded	Pedestrian	- - -	18 (60)	1957	Corrugated Aluminum Sheet	6351-T6
Banbury, England	Riveted Bascule	Highway	1	3 (9.5)	1959	Corrugated Al Sheet	6351-T6
Gloucester, England	Riveted Bascule	Highway	1	12 (40.5)	1962	Extruded Al Shapes	6351-T6

Aluminum bridge applications today

In the mid-1990's Reynolds Metals (now a part of Alcoa, Inc.) developed several aluminum bridge deck designs. The first was developed specifically for the 320 ft long, 12'-6" wide historic Corbin suspension bridge over the Juniata River near Huntingdon, PA (Fig. 3). The steel bridge deck had deteriorated, limiting the live load to 7 tons. The aluminum replacement deck was an approximately 5 in. (130 mm) deep 6063-T6 multiple hollow extrusion that was welded on its top flange only. The deck extrusion was oriented transversely to traffic and supported by 10 in. (250 mm) deep 6061-T6 aluminum extruded I beams oriented parallel to traffic. By reducing the dead load, the new deck permitted the live load rating of the bridge to be increased to 22 tons.

The second Reynolds bridge deck was used on a US Route 58 bridge over the Little Buffalo Creek near Clarksville, VA. The bridge was 54'-9 ¾" long and 32'-0 wide. This deck was made of 12" deep 6063-T6 extrusions welded on both the top flange and the bottom flange from one side with a removable backing. The extrusions were oriented parallel to traffic and attached to the four longitudinal steel bridge beams.

An issue with aluminum bridge decks encountered by Reynolds and others is the need to provide a surface on the aluminum that affords slip resistance to traffic. The Reynolds decks used a 3/8" thick epoxy with embedded aggregate, similar to that used occasionally on concrete decks.

There has been in recent years relatively greater use of aluminum bridge decks overseas, primarily to replace or update decks in older bridges where capability to carry greater live load is an objective. In Sweden, for example, the Svensson/Petersen design (1,3,32) using hollow stiffened 6063-T5 or T6 extrusions (Fig. 4) has been in use for about 20 years in more than 30 replacement decks around Stockholm alone; an example is illustrated in Figs. 5. In this case of a bridge providing access to a major throughway near Stockholm in which, in order to minimize traffic interruption in a major artery, the deck was replaced overnight.

In 1995, an all-aluminum installation in Norway at Forsmo (3) used an aluminum deck combined with aluminum girders. This provided a quickly assembled portable structure that could be carried on a truck to the site (Fig. 6) and dropped into place in a single crane operation (Fig. 7). The cross-section of the Foresmo bridge is shown in Figure 8, and the completed bridge is shown in Fig. 9.

The most recent bridge deck installation in the U.S. was that in Clark County, KY (33), where a fast replacement was needed for a rural road carrying school and hospital traffic. The deck was made with hollow, integrally stiffened 6063-T6 shapes pre-fabricated off-site and placed in position in just a few hours, minimizing the disruption in traffic.

Life-Cycle Cost Analysis is Key

For today's application of aluminum alloys to bridges and bridge decks, internally stiffened hollow extruded panels, similar to the U.S. or Swedish designs, are of most interest, and assessment of their economic value must be based upon total life cycle cost, not initial erection cost alone.

As an example, using hypothetical figures to avoid variations resulting from site-related variables, let us assume that a steel bridge deck can be built for $75/sqft, and a 300-ft long, two lane (20 ft) wide bridge is to be built: the nominal cost of the deck in steel would be $450K. The cost of an aluminum deck would be $125/sqft; that cost would be $750K. However the steel deck will have to be painted every ten years of a 50-year assumed life, and the cost of each re-painting is estimated to be about 1/3 the cost of original construction because of the considerable environmental requirements. Therefore the cost of the steel deck over its 50-year life would be $450K + 4x$150K or $1,050K. The aluminum deck never has to be repainted, so the life-cycle cost remains $750K.

There are the following specific added benefits provided by the fact that the aluminum bridge deck may be pre-fabricated off-site, in whole or two or three sections, and transported to the site for erection. Therefore the bridge does not have to be closed until it is time to erect the new span, greatly minimizing the closure time for the bridge and the disruption of traffic for drivers. It is difficult to place a monetary value of such savings, but they are considerable in the public mind.

Aluminum alloys recommended for bridge decks

A great number of aluminum alloys might be chosen for bridge and bridge deck construction (5), but those most highly recommended and used currently because of their superior combination of strength, corrosion resistant, and overall ease of fabrication are illustrated in Table 3. In general, alloys of the 5xxx series are used for the plate components, and the 6xxx alloys are used for the extruded shapes. Alloy 6063 is a particular favorite for the latter if complex and/or hollow sections are required.

It is also appropriate to note at this stage that the Fairchild design of aluminum bridge discussed earlier (Sections 3.0 and 4.0) would not be considered practical and cost effective today. The complex buildup of sheet and extrusion components and its riveted construction is very labor intensive and, hence, very expensive compared to other designs of aluminum structures. Current design practice is for the use of structural aluminum decks in combination with steel or reinforced concrete girders, where the aluminum decks are made up of long lengths of aluminum plates and/or extrusions requiring only minimal assembly.

Conclusions

Aluminum alloys have much to offer for bridge and bridge deck applications, and continue to be used, primarily overseas, where their light weight, high strength-to-weight ratio, and excellent corrosion resistance satisfy service requirements.

Aluminum alloys have been used in U.S. bridge structures since 1933, when the first aluminum bridge deck was used to replace an earlier steel and wood deck on Pittsburgh's Smithfield Street Bridge in order to increase its live-load carrying capacity. Aluminum girders and bridge decks have been used in about 10 other bridges in the USA, the most recent recognized here in 1997. While still not considered a standard for bridge structures in the USA, they are more widely used overseas, as for example around Stockholm, where more that thirty bridges have been rehabilitated with aluminum decks.

With proper design and maintenance, aluminum girders and decks may provide lower life cycle costs and as long or longer lives than steel and/or concrete alternatives.

Acknowledgements

The authors wish to acknowledge the Aluminum Association, Inc., notably the Engineering & Design Task Force, J. Randolph Kissell, Task Force Administrator, as the basis of much of the information contained herein.

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33. Press Release "Aluminum Deck on a Kentucky Bridge," Issam Harik, University of Kentucky, July 18, 2006

Listing of Figure Captions

Figure 1 - All-aluminum arch span over Saguenay River in Arvida, Canada, erected 1950, still in service today

Figure 2 - Drawing of cross-section of girder system of Route 32 Sykesville Bypass Bridge, As-built drawing, MD SHA Archives

Figure 3 - Aluminum hollow extruded 6063-T6 shape used in Reynolds design of bridge deck

Figure 4 - The historic Corbin Bridge near Huntington, PA, where an innovative aluminum replacement deck was used to increase live-load capability by 300% in 1996

Figure 5 - Representative cross-sections of 6063-T6 extruded shapes making up Swedish bridge deck system

Figure 6 - Stockholm highway bridge for which an aluminum deck was installed overnight to minimize traffic interruption on a major artery

Figure 7 - View of the Forsmo, Norway all-aluminum bridge during transportation to the site, illustrating one important advantages of lightweight aluminum, bridge construction

Figure 8 - View of the Forsmo, Norway all-aluminum bridge during erection, illustrating another important advantages of lightweight aluminum, bridge construction

Figure 9 - Cross-section illustrating design of all aluminum girder system of Forsmo Bridge

Figure 10 - View of Forsmo Bridge completed for service

Table 3 – Minimum (design) properties of some aluminum alloys for bridge components (Ref: The Aluminum Design Manual[1,2]									
				Temsion		Compression	Shear		Compressive
			Thickness	Ultimate	Yield	Yield	Ultimate	Yield	Modulus of
Alloy	Temper	Product	Range	Strength	Strength	Strength	Strength	Strength	ElasticityY(3)
Metric/SI units			mm	MPa	MPa	MPa	MPa	MPa	GPa
5083	O	Sheet & Plate	1.20-6.30	275	125	125	170	70	71.7
5083	H116	Sheet & Plate	4.00-40.00	305	215	180	180	125	71.7
5083	H321	Sheet & Plate	4.00-40.00	305	215	180	180	125	71.7
5086	O	Sheet & Plate	0.50-50.00	240	95	95	145	55	71.7
5086	H32	Sheet & Plate	All	275	195	180	165	110	71.7
5086	H34	Sheet & Plate	All	300	235	220	180	140	71.7
5086	H116	Sheet & Plate	All	275	195	180	165	110	71.7
5454	O	Sheet & Plate	0.50-80.00	215	85	85	130	48	71.7
5454	H32	Sheet & Plate	0.50-50.00	250	180	165	145	105	71.7
5454	H34	Sheet & Plate	0.50-25.00	270	200	185	160	115	71.7
6061	T6, T651X	Extruded Shapes	All	260	240	240	165	140	69.6
6063	T5	Extruded Shapes	Up thru 12.50	150	110	110	90	62	69.6
6063	T5	Extruded Shapes	12.50-25.00	145	105	105	85	59.0	69.6
6063	T6	Extruded Shapes	All	205	170	170	130	95	69.6
Engineering units			in.	ksi	ksi	ksi	ksi	ksi	103 ksi
5083	O	Sheet & Plate	0.051-1.500	40	18	18	25	10	10.4
5083	H116	Sheet & Plate	0.188-1.500	44	31	26	26	18	10.4
5083	H321	Sheet & Plate	0.188-1.500	44	31	26	26	18	10.4
5086	O	Sheet & Plate	0.020-2.000	35	14	14	21	8	10.4
5086	H32	Sheet & Plate	All	40	28	26	24	16	10.4
5086	H34	Sheet & Plate	All	44	34	32	26	20	10.4
5086	H116	Sheet & Plate	All	40	28	26	24	16	10.4
5454	O	Sheet & Plate	0.020-3.000	31	12	12	19	7	10.4
5454	H32	Sheet & Plate	0.020-2.000	36	26	24	21	15	10.4
5454	H34	Sheet & Plate	0.020-1.000	39	29	27	23	17	10.4
6061	T6, T651X	Extruded Shapes	All	38	35	35	24	20	10.1
6063	T5	Extruded Shapes	Up thru0.500	22	16	16	13	9	10.1
6063	T5	Extruded Shapes	0.501-1.000	21	15	15	12	8.5	10.1
6063	T6	Extruded Shapes	All	30	25	25	19	14	10.1
Footnotes		1 - Reference: Aluminum Design Manual 2000, The Aluminum Association							
		2 - For tensile yield strengths, offset = 0.2%							
		3 - Typical values; for deflection calculations, average modulus of elasticity is used,							
		which is 0.1 ksi or 0.7 Gpa lower than values in this column							


Fig 1


Fig 2


Fig 3

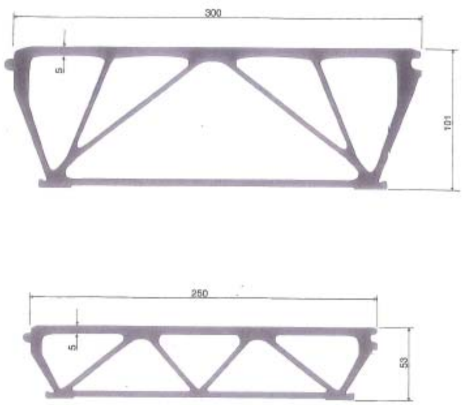

Fig 4


Fig 5


Fig 6