The Brown & Root Aluminium Gantry

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Abstract

A new aluminium gantry has been designed by Brown & Root and a prototype commissioned and built by Advanced Aluminium Solutions Ltd. The gantry exploits the structural design advantages offered by extrusions. A system of components connected using alloy pin and collar fasteners is suitable for manual handling, and facilitates rapid assembly. The gantry is light enough to allow the pre-installation of signal equipment on the superstructure prior to lifting the entire span to its permanent location.

1 Introduction

The problems of an overloaded highways network in the UK are well known. More and more traffic is competing for the same road space. When the roads network is substantially complete, and there is little scope for easing traffic congestion by building new roads, it is important to address the issue of managing the traffic on the system better. The essential requirements of a traffic management system are: a means of detecting the traffic flow; a means of informing traffic users; and a means of regulating the speed of traffic (variable mandatory signals). Multi-lane highways such as motorways require detection, information, and control equipment over individual lanes. Controlled motorways (such as the Heathrow section of the M25) use a greater number of signal gantries per kilometre than other motorways.

Many existing sign and signal gantries present too much information together, often confusing road users. A recent standard published by the HA requires designers to provide gantries for signs, and additional gantries for the signals where possible [1].

With an anticipated increase in demand for gantries, the Highways Agency invited teams of engineers and architects to develop new gantry designs. Brown & Root teamed up with Yee Associates, and one of the ideas proposed
was for an aluminium gantry. The idea has been followed through by Brown & Root, and a commercial company (Advanced Aluminium Solutions Ltd) has been established to market and manufacture this new product.

2 Aluminium Alloy in Construction

The lightness, durability, and availability of new cross sections make alloy extrusions ideal for mobile and rapidly erected structures, including roofing systems and demountable long span structures. The featherweight infantry bridge [2], weighs 340 kg (550kg when loaded on the transport frame), spans 30m, can be assembled within 6 mins, and carry 135kg loads at 10m centres.

Civil engineering commonly involves the construction of temporary structures (falsework) to facilitate the placement of in-situ concrete. The construction industry is required to comply with European directives [3] on the amount a man is permitted to carry. In locations where access for mechanical handling plant is limited, lightweight aluminium falsework systems are now a practical necessity, rather than a more expensive alternative.

Other applications of aluminium in construction, including a hoistable deck for a car ferry, are identified in TALAT (Training in Aluminium Technologies) [4].

Gantries are characterised by relatively long spans (typically up to 55m for motorway intersections), with low live loads for maintenance access only. Therefore the design is very sensitive to self-weight of the structure. Construction work on or near motorways is dangerous and requires costly traffic management schemes. The aluminium gantry requires no additional protective coating (or future re-coating), and the superstructure complete with signs, signals, and cables can be lifted onto the aluminium support legs, thus reducing cost to the contractor, and reducing delay to road users.

3 Aluminium Alloy - Basic Properties

A working knowledge of aluminium alloys is a fundamental prerequisite to engineering a structure with it. As aluminium has different properties to steel, the design concept must be appropriate to the properties of aluminium alloy, not steel.

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Youngs Modulus (kN/mm²)</th>
<th>Coefficient of expansion (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium Alloy</td>
<td>2700</td>
<td>70</td>
</tr>
<tr>
<td>Steel</td>
<td>7600</td>
<td>205</td>
</tr>
</tbody>
</table>

Aluminium alloys have only a third of the weight, and a third of the Youngs modulus of steel. Long span lightweight trusses are a particularly suitable structural form for these material properties. Motorway signal gantries are
generally not subject to limitations in structural depth, therefore the structural depth of the truss can be chosen which is suitable to satisfy the prescribed deflection limits for UK gantries.

Aluminium alloy has a coefficient of expansion, which is twice that for steel. However, restraint to expansion of the gantry is not an issue with this design.

Aluminium with a purity of above 99% is very durable, but not very strong. The introduction of alloying elements alters and controls a number of other properties of the metal, including strength, durability and extrudability.

### 4 Extrusions for Structural Members

There are eight basic families of alloys available. The 1000 and 3000 series alloys are non-heat treatable, and fairly low strength (ultimate tensile strength ($f_u$) of 150N/mm$^2$ and 200N/mm$^2$ respectively). The 4000 series is good for non structural castings. The 5000 series is ideal for sheet and plate products, but extrusions are only available in non-heat-treatable form, with low $f_u$.

Three heat-treatable high strength alloys are available for extrusions. The 2000 and 7000 series both offer a higher $f_u$ than the 6000 series alloys, but they have inferior corrosion resistance and extrudability.

6000 series alloys are therefore very suitable for extrusions and are the most widely used by extruders. The combination of high strength, good corrosion resistance, and good availability made the 6000 series alloy (aluminium-silicon-magnesium) the optimum choice for the gantry structural members.

#### 4.1 Heat treatment of aluminium alloy

Heat treatment involves the two-stage process of solution treatment, and ageing. The solution treatment requires the metal to be heated to 510°C, to allow the alloying agents go into solution. The metal is then tempered (for most 6000 series extruded sections, this means spraying the metal with fine jets of water, as soon as the extrusion emerges from the die (press quenching), such that the temperature is reduced to about 25°C within 150cm of the die face). The rapid cooling of the alloy traps the alloying elements in solution. The alloying elements (forming the intergranular compound $\text{Mg}_2\text{Si}$) remain dissolved, but in time precipitate out as small hard clusters at the grain boundaries, which provide resistance to the movement of dislocations in the metal, when a stress is applied. This process of age hardening occurs naturally over a few days, but can be accelerated by holding the metal at a temperature of 100°C to 200°C for 7 - 12 hours. The alloy is made stronger (higher $f_u$, with corresponding increase in 0.2% proof stress, $f_{0.2}$) but less ductile by this process.

The skill of the extrusion manufacturer is to minimise the energy required to extrude, whilst maintaining the highest possible extrusion rate, without 'tearing' the section. Some extruders can achieve 70 - 80m per minute with the 6082 alloy. Care is required with very asymmetric sections, as cooling rates across the section will vary, resulting in lengths of extrusion which are curved.
out of straight. This effect can be partially controlled by cold working the extrusion as it is formed. As the extrusion is pushed through the die, it is also stretched (typically by 1%) [5].

5 Mechanical properties of 6000 Series Alloys

The properties of an aluminium alloy are derived from the alloying elements used.

Table 2. Chemical composition % of the 6000 series alloys used in the gantry[6]

<table>
<thead>
<tr>
<th>Grade</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Ni</th>
<th>Zn</th>
<th>Ti</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-T6</td>
<td>0.40-0.80</td>
<td>0.7</td>
<td>0.15-0.4</td>
<td>0.15</td>
<td>0.8-1.2</td>
<td>0.04-0.35</td>
<td>-</td>
<td>0.25</td>
<td>0.15</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>6082-T6</td>
<td>0.7-1.3</td>
<td>0.5</td>
<td>0.1</td>
<td>0.4-1.0</td>
<td>0.6-1.2</td>
<td>0.25</td>
<td>-</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
<td>0.15</td>
</tr>
</tbody>
</table>

The iron, copper chromium and zinc are impurities in 6082 alloy. The iron is an impurity with double disbenefit: Firstly it can reduce ductility of the alloy by the formation of the brittle iron magnesium silicon complex at the grain boundary; and secondly it can reduce the ultimate strength of the alloy, by a corresponding reduction in the amount of Mg2Si that can be formed for precipitation hardening in the body of the material. Stricter control of the iron content improves $f_u$ and $f_{0.2}$, as well as the elongation at failure[5].

Table 3. Compare BS 8118 design properties [7], with SECO 6086-T6 test results [5]

<table>
<thead>
<tr>
<th></th>
<th>0.2% proof stress N/mm²</th>
<th>Ultimate stress N/mm²</th>
<th>Minimum Elongation %</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS 8118</td>
<td>255</td>
<td>295</td>
<td>7</td>
<td>Table 2.1</td>
</tr>
<tr>
<td>SECO</td>
<td>280</td>
<td>310</td>
<td>15</td>
<td>SECO test results, guaranteed min values.</td>
</tr>
</tbody>
</table>

The stress / strain relationship is commonly obtained using the empirical Ramberg-Osgood (RO) formula [8]. Mazzolani presents the more precise mathematical expressions [8], but the R-O relationship, as modified by Faella is sufficient for design.
The above properties of the alloy are reliable (virtually no variation) between -50°C to +80°C, which is beyond the normal civil engineering temperature range. Strength increases with lower temperatures (+40% at -200°C), and decreases with higher temperatures (-70% at +200°C) [9]. None of the aluminium alloys suffer from brittleness at low temperatures, and there is no transition point below which brittle fracture occurs [6].

6 Corrosion Resistance of 6000 Series Alloys

The surface of 6082-T6 alloy oxidises naturally to form a stable corrosion inhibiting film of aluminium oxide to an initial depth of approximately 50 angstroms (0.005 microns). This natural layer is adequate protection against further serious corrosion in all but the most severe environments (such as marine and industrial) [10], and therefore satisfactory for most gantry locations. However, the appearance and durability of the aluminium alloy, can be further improved by artificially increasing the thickness of the oxide layer electrolytically to more than 20 microns (anodising), at very little cost.

The fasteners are made from similar alloy to the structural sections (6061-T6). The alternative, stronger (forged) 2024 rivets are commonly available, but were not adopted. The 2024 alloy contains copper (providing the increased strength), which reduces the corrosion resistance of the alloy considerably.
Aluminium lends itself to innovation in design. Ingenious interconnecting sections abound in the glazing, display and motor industries particularly [11]. A designer of civil engineering applications can find a great deal to inspire new applications by talking to experienced extrusion manufacturers. The aluminium extrusion industry has a wealth of experience, which is indicated by the fact that it is impossible to put a number to the dies in existence. With aluminium alloy extrusions, engineers have freedom to design the most suitable structural system from scratch [12]. Individual extrusions are linear prismatic members, but designers commonly produce large asymmetric members from a series of smaller extrusions. With rare exceptions, the only limitation is in the skill and imagination of the designer.

Steel truss structures are commonly fabricated by cutting, welding together standard shape steel hollow sections. After fabrication, and testing of welds, the protective coating must be applied. The approach for the aluminium gantry was different. Design effort was employed to create a series of extrusions, which could be used together, and connected with mechanical fasteners. The new gantry design comprises a schedule of components (cut, drilled and anodised), which are connected on assembly jigs to ensure that the geometry of the final structure is maintained.

The cost of aluminium extrusions is approximately £2 per kg. The cost of cutting and drilling the aluminium components is modest, and the assembly of a full 15m prototype superstructure was achieved in less than a day, by 4 men. Fabricated steel trusses in hollow section costs typically £2.0 to £2.5 per kg. The aluminium gantry weighs approximately half its steel equivalent, and the fabrication process is quicker and cheaper than that required for a welded steel structure. Aluminium structures also have the added bonus of a residual material value beyond the design life of the structure. Aluminium is a valuable material, which can be re-cycled. The current scrap value of aluminium is approximately £1 per kg.

8 Structural Connections

The main design limitation for the gantry is the deflection of the superstructure. The main members are compact, with high buckling strength. This Vierendeel truss structure used is arranged to be limited by the capacity of the joints. Welded joints offer significant advantages in steel fabrication, as connections can be fitted and welded neatly, and with the full strength of the parent material. With aluminium, however, a different approach to connections is required. Welding techniques (MIG, TIG etc) can be used, but the heat affected zones around welds mean a reduction of aluminium strength of up to 50% [7]. Although it is possible to correct this by heat treatment, the process of welding, testing, and heat treating would add cost to the gantry.

There are alternatives to conventional welding, for example friction stir welding (where the heat input to the weld, and hence strength reduction for the alloy is very much less. The aerospace industry has used riveted
connections for aluminium in aircraft for many years. Bolted connections, both ordinary and high strength friction grip are available.

The main connection method adopted was to combine a simple and efficient set of interconnecting extrusions, fixed with heavy duty alloy pin and collar fasteners. This fastener system was chosen because it cannot be loosened by vibration (there are no threads, only parallel grooves for the collar to be swaged into), and the installation is fast and reliable. With bolts, visual inspection alone will not reveal if the correct torque has been applied. This system comprises a pin, collar fastener and installation tool, which is designed such that correct installation is only possible when the collar has been swaged, and the stress at the notch reaches $f_u$, causing the pintail to break away from the shank.

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1. Insert pin into joint. Place collar over pin.

2. Apply installation tool over pintail.

3. Fully swage collar and break pintail.

4. Tool pushes off installed fastener and pintail is ejected.

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Fig 2. Installation of the pin and collar fastening
9 Superstructure

A structural system based on a Vierendeel girder [13] was adopted for two main reasons. Firstly, the simple arrangement of vertical members (rather than diagonals) presents an uncluttered appearance to road users. Information on gantries needs to be presented clearly without the distraction of a preponderance of structural members. Secondly, the arrangement of members in the truss should not impede the installation of signals. The vertical members over the carriageway are spaced at 1.83m intervals, to accommodate standard matrix signals over the centre of each lane.

When compared to more common diagonally braced trusses, the Vierendeel girder deflects more under the same applied loads. However, as long as the minimum headroom is provided, the depth of the truss is not generally critical for gantries, and deeper structural depths can be used to keep the deflections within acceptable limits.

10 Prototype Gantry

Brown & Root designed, and Advanced Aluminium Solutions Ltd have built a 15m span prototype gantry, to demonstrate that the structural system was practical to build, and that the performance (in terms of deflections) was consistent with the model. The analytical model for the gantry focussed primarily on the forces in the pin connectors.

Fig 3. Prototype gantry frame
The production of the components proved to be straightforward, and the assembly of the superstructure was achieved in less than a day. Some aspects of the design have been improved, by modifying the extrusions.

The gantry was manufactured by assembling subframes, to which were attached the longitudinal chord members to form part gantry sections of up to 5500mm long. The next stage was to connect the sections together with chord splices, and then add the support legs.

Wind bracing in the form of flat bar section between node points in the roof of the gantry, and floor panels attached to the deck beams, provided the necessary lateral stiffness.

10.1 Interim conclusions from manufacturing and testing the prototype.

At the time of writing, the prototype had been built, but not fully tested. However, the work done to date has enabled the designer and manufacturer to draw some interim conclusions.

An important finding from the prototype work, was the importance of providing the right tolerance in the bolt holes (both for the strength of the joint, and to ensure assembly of the joints is practical). The holes drilled for the 12mm diameter pin and collar bolts were 13mm diameter, and the fit between some extrusions needed adjustment by increasing the depth of some of the new 'filler' sections slightly.

The self-weight deflection can be compensated by a designed precamber for the superstructure, produced by slightly bending the longitudinal chord members. The length of the top chord members needs to be longer than the bottom chords to achieve this.

The main joint connections were tested independently to verify the ultimate strength of the alloy pin connectors. The pins appeared to shear in a predictable manner.

11 Future Work

During the course of meetings between the manufacturer, designer, and Highways Agency, additional equipment and facilities were accommodated into the design. The structural system has proved to be very tolerant of changes in the design, and very easy to manufacture and assemble.

At the time of writing the 15m prototype is being rebuilt with modified filler sections in the chord members (to improve the connection), and a designed precamber to counteract selfweight deflection.

A 22m span signal gantry is being built for the Surface Transport 2000 Exhibition at the Transport Research Laboratory, UK.
References