Highway Gantry using Aluminium Extrusions

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SYNOPSIS

A new modular lightweight highway gantry was conceived to meet the growing need for structures to support driver information messages on the UK highway network. David Morris (then with KBR) led a team, which included a UK specialist aluminium alloy extruder to design, fabricate, and test a prototype highway gantry, which comprised new aluminium alloy extrusions. The system of components, which was connected using the alloy pin and collar fasteners (Huck bolts), was found to be suitable for manual handling of elements (light weight), as well as facilitating rapid assembly. Uniquely, the prototype gantry proved to be light enough to allow the pre-installation of signal equipment on the superstructure prior to lifting the entire span to a permanent location. Aluminium extrusions were developed by the designer to provide a convenient and robust method of connecting the main sections. Huck bolts were used to avoid the strength reduction and fatigue issues associated with welded connections. The reduction in strength around welded joints is normally rectified in small components by the use of artificial ageing, but this is clearly not a practical proposition for a large structure such as a highway gantry. By using a modern equivalent of the rivet in conjunction with new structural sections, an efficient light, and economic structural system was produced. A 15m span prototype gantry was designed and load tested. The speed and ease of manufacture for the gantry, and the predictable performance of the gantry under load were confirmed during the prototype development and load testing.

1 INTRODUCTION

It is well known that problems associated with the overloading of a highways network (such as in the UK) have significance for the economy as well as the safety of road users. Traffic congestion and increased journey times are inevitable as more and more traffic uses 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 becomes important to address the issue of better managing the traffic on the system. 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.

1.1 Need for more highway gantries

Many existing sign and signal gantries present too much information together, often confusing road users. A design standard published by the Highways Agency, UK (HA) requires designers to keep the functions of fixed signs separate from signals on gantry structures (i.e. gantries for signs, and additional gantries for the signals) where possible [1]. This means that on new schemes many more gantries are likely to be required to provide gantries for fixed signs only, and signals only. In addition, controlled motorways (such as the

Heathrow section of the M25) use a greater number of signal gantries per kilometre than other motorways.

1.2 New ideas for highway gantries

With an anticipated increase in demand for gantries, the HA invited teams of engineers and architects to develop new gantry designs. The KBR / Yee Associates team conceived the aluminium gantry concept. The idea was followed through by KBR to support the production and testing of a full scale 15m span prototype. The span of the prototype was chosen to work within the limits of the testing floor and loading available.

1.3 Justification for using aluminium

UK highway gantries are characterised by relatively long spans (up to 55m for some motorway intersections), with low imposed loads (for access of maintenance crews). Clearly the design is very sensitive to self-weight of the structure. Construction work on or near motorways is inherently dangerous and requires costly traffic management schemes to mitigate the hazard from high speed road traffic adjacent to construction work. As the new 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, the time required for traffic management is reduced along with delay to road users, and cost to the contractor.

Fig 1: Artists impression of a new aluminium highway gantry

2 ALUMINIUM ALLOY IN CONSTRUCTION

Aluminium alloy has a good record as a light and durable structural material, however the greater scope for the exploitation of the virtually limitless range of extruded section shapes has received relatively little attention from designers in the construction sector. Aluminium extrusions have been utilised in some structural applications. Demountable roof frame designs have successfully employed aluminium extrusions. The armed forces have commissioned a lightweight infantry bridge made up of aluminium extrusions. 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. Other applications of aluminium in construction, including a hoistable deck for a car ferry, are identified in TALAT (Training in Aluminium Technologies) [4].

3 ALUMINIUM ALLOY - BASIC PROPERTIES

Engineering structures with aluminium alloys requires a working knowledge of the material. As aluminium has different properties to steel, the design concept must be appropriate to the properties of aluminium alloy, not steel.

	Density kg/m^3	Youngs Modulus kN/mm^2	Coefficient of expansion /^{o}C
Aluminium Alloy	2700	70	24x10^{-6}
Steel	7600	205	12 x10^{-6}

Table 1. The basic properties of aluminium alloy compared to mild steel

Aluminium alloys have (approximately) only a third of the weight, and a third of the Young's 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 (as set out in reference [1]).

Aluminium alloy has a coefficient of expansion, which is twice that for steel. However, the net effect on section stresses is minimal, due to the Young's modulus being only a third of the steel value.

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, and the 6000 series (aluminium-silicon-magnesium) is the best alloy for the high strength extrusions required for the gantry. The 1000 and 3000 series alloys are non-heat treatable, and fairly low strength (ultimate tensile strength (f_u) of 150MPa and 200MPa 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 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^{o}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^{o}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 Mg_2Si) 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^{o}C to 200^{o}C for 7 - 12 hours. The alloy is made stronger (higher f_u) 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.

Grade	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Other	Total
6061-T6	0.40-0.80	0.7	0.15-0.4	0.15	0.8-1.2	0.04-0.35	-	0.25	0.15	0.05	0.15
6082-T6	0.7-1.3	0.5	0.1	0.4-1.0	0.6-1.2	0.25	-	0.2	0.1	0.05	0.15

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

The iron, copper chromium and zinc are impurities in 6082 alloys. 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 Mg_2Si that can be formed for precipitation hardening in the body of the material. Stricter control of the iron content improves f_u and 0.2% proof stress ($f_{0.2}$), as well as the elongation at failure [5].

	0.2% proof stress N/mm^2	Ultimate stress N/mm^2	Minimum Elongation %	Ref
BS 8118	255	295	7	Table 2.1
SECO - ref [5]	280	310	15	SECO test results, guaranteed min values.

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

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.

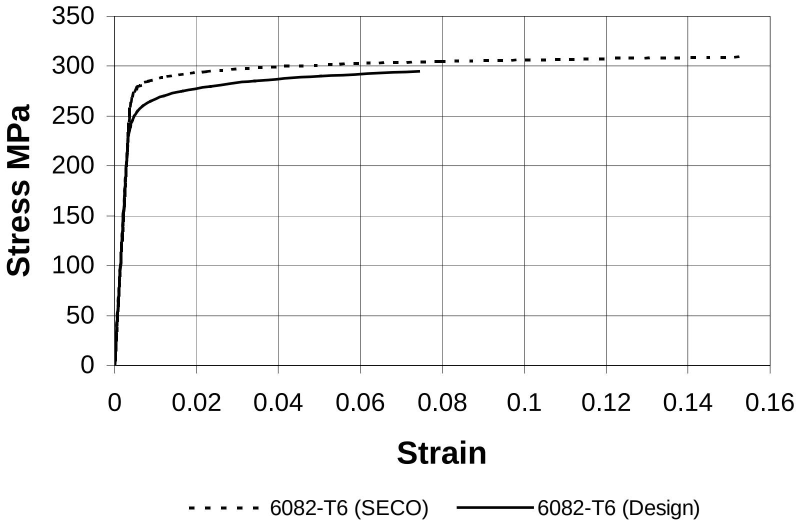

Fig 2: Stress strain curves for the design, compared with the SECO supplied material for the gantry (based on Ramberg-Osgood equation)

The above properties of the alloy are reliable (virtually no variation) between -50^{o}C to +80^{o}C, which is beyond the normal civil engineering temperature range. Strength increases with lower temperatures (+40% at -200^{o}C), and decreases with higher temperatures (-70% at +200^{o}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 alloys oxidises naturally to form a stable corrosion inhibiting film of aluminium oxide to a 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.

7 BENEFITS AND COSTS OF EXTRUSIONS

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]. Although there is a tendency for individual extrusions to be linear prismatic members, 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 design process was characterised by an exchange of sketches and ideas between designer and extruder over a period of roughly 3 months. The section shapes evolved to meet the key criteria of extrudability of the sections and buildability of the gantry. The new gantry design comprised a schedule of components (cut, drilled and anodised), which were connected on assembly jigs to ensure that the geometry of the final structure was maintained.

The cost of aluminium extrusions is approximately AU$4.90 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 AU$4.80 to $6.00 per kg. 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 AU$2.40 per kg

8 STRUCTURAL CONNECTIONS – A DIFFERENT APPROACH NEEDED

The key to many modular structural systems is the means of connecting the components, and this was particularly so for the gantry. The extrusions were developed with this in mind. The truss member sections were compact with high buckling resistance, which ensured that the governing strength aspect of the design was 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 utilised. 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. In addition, heat treatment of large fabrications is not practical.

There are alternatives to 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 for the project 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. The pin and collar fastener is correctly installed, only when the collar has been swaged, and the stress at the notch reaches f_u, causing the pintail to break away from the shank.

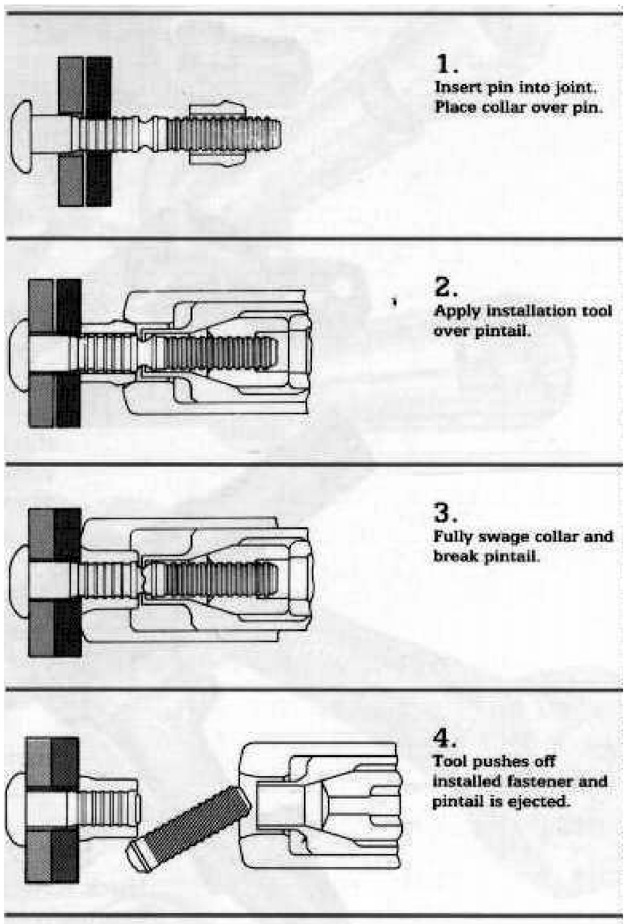

Fig 3: Installation of the pin and collar fastening

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. The cross section of a gantry for long spans is shown in fig 4.

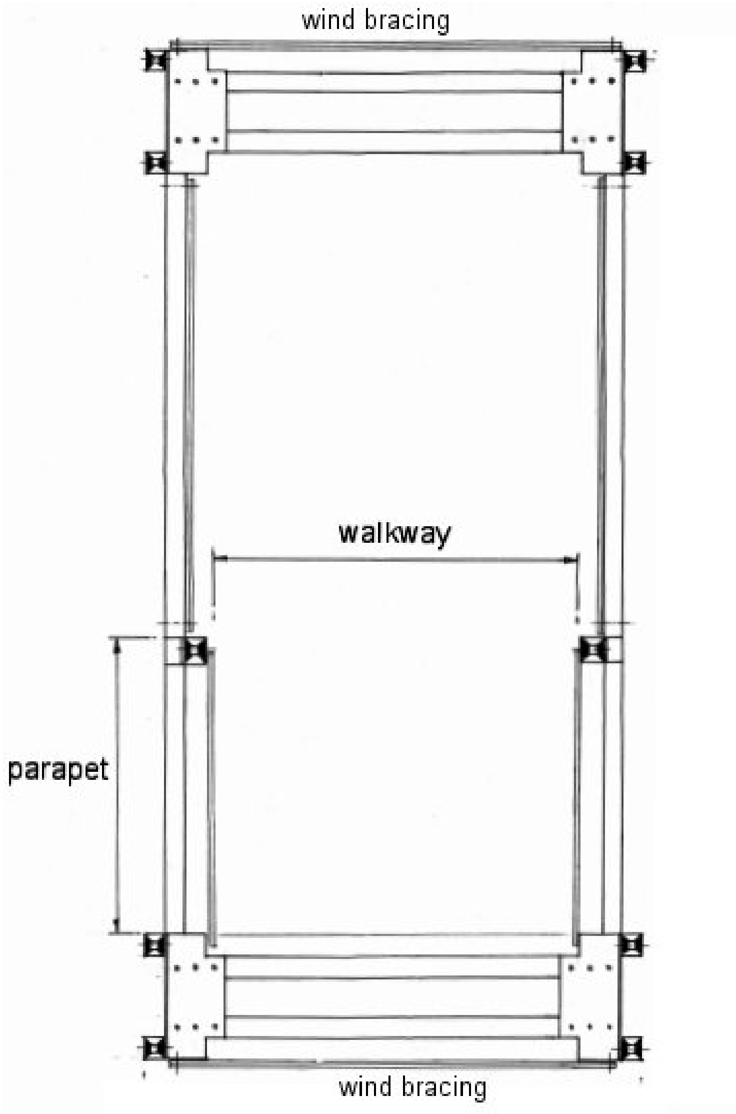

Fig 4: Cross section of a long span aluminium highway gantry

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 the onerous limits prescribed in reference [1]. If the depth of the gantry is an issue, the alternative solution is to introduce partial bracing to reduce live load deflections.

During development, the sections and conncections were proven to be robust for the cross section required and practical limits of the design. The strength of the main elements was not the limiting factor, as the deflection limits governed the design. Even though the limiting factor in the design was deflection, it was important to confirm that the failure of the gantry under ultimate load was predictable.

10 PROTOTYPE GANTRY

A 15m span prototype gantry was built to demonstrate that:

- the structural system was practical to build.
- the serviceability performance (in terms of deflections) was consistent with the model.
- the failure mode and load were as predicted in the analytical model

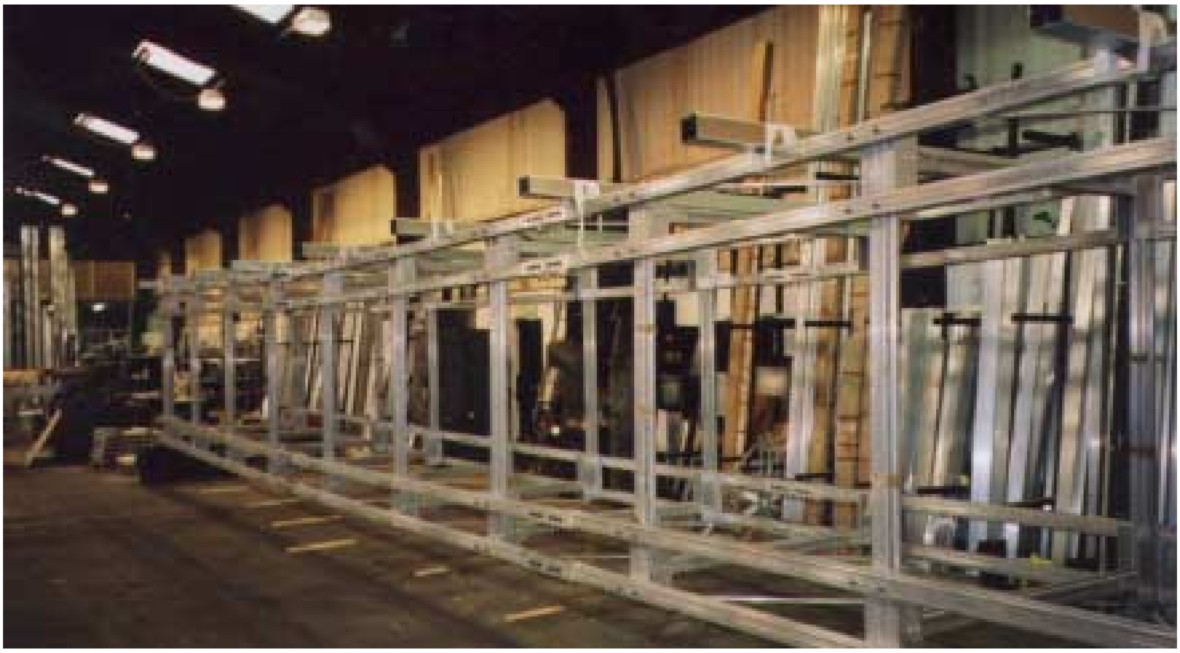

Fig 5: Prototype 15m span gantry prepared for load testing.

10.1 Fabrication of the gantry

The production of the components proved to be straightforward, and the assembly of the completed superstructure was achieved in less than a day. Some aspects of the design were improved, by modifying the extrusions. The shape of the sections which slid together to form the joints was altered to give a better fit. This sort of interaction between the extruder and designer ensures that manufacturing of the components meets the designer's intent in the most effective way.

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.

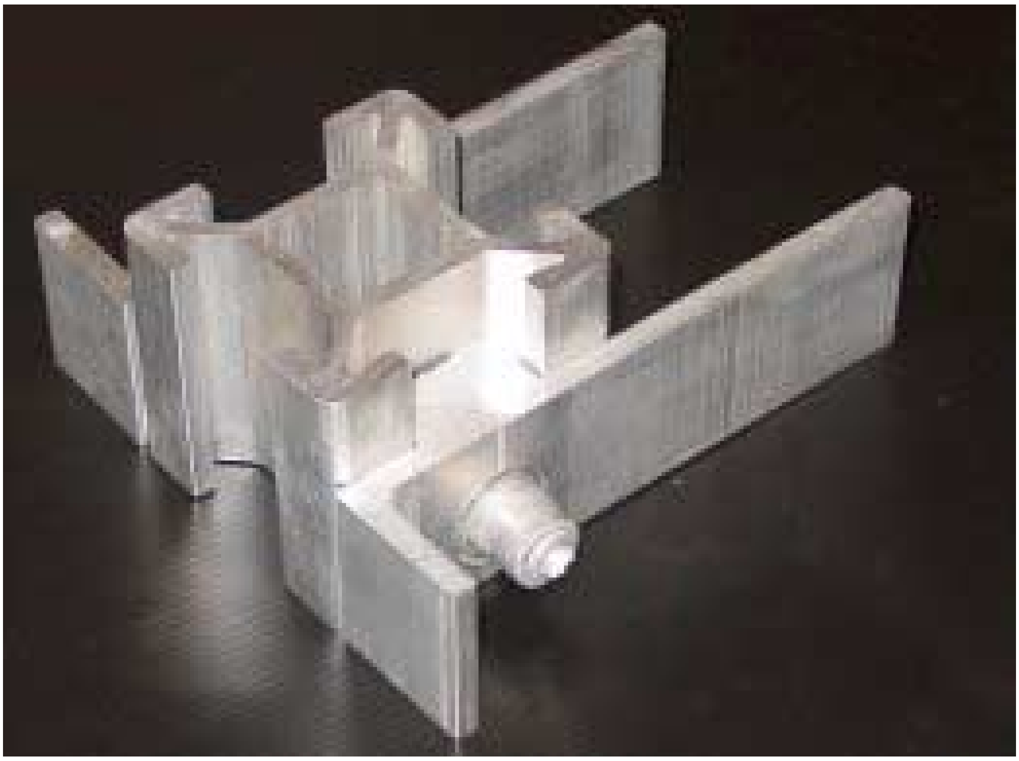

Fig 6: Joint assembly using the new extrusions and huck bolt.

10.2 Load testing the prototype.

The analytical model for the gantry focussed primarily on the forces developed in the pin connectors. The analysis predicted failure of a huck bolt (by shearing) in a connection adjacent to the support.

The prototype was assembled (without precamber to counteract dead load deflections) and loaded evenly along the span. Deflections were recorded and the failure mode carefully observed. Failure by shearing of a huck bolt in the joint adjacent to the support was observed at the given loading. The gantry continued to carry the load safely.

10.3 Conclusions from manufacturing and testing the prototype.

The experience of designing and manufacturing the prototype aluminium gantry yielded the following conclusions:

Conclusion 1) the importance of providing the right tolerance in the bolt holes. 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 loose fit of the pins and some extrusions meant that the midspan self-weight deflections were 80mm, rather than the 13mm predicted by the analysis (where perfect fit is assumed).

Conclusion 2) midspan deflections cannot be eliminated, and therefore midspan deflections, including that due to self-weight should 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.

Conclusion 3) the alloy pins in the connections sheared in a predictable manner. The main joint connections were tested independently to verify the ultimate strength of the alloy pin connectors, and the failure of the joint.

Conclusion 4) the deflection on the vierendeel girder under design imposed load exceeded HA BD 51/98 permissible values, therefore the addition of limited panel bracing was required to control this serviceability state.

Conclusion 5) the structural system proved to be very tolerant of modifications in the design, and was straightforward to manufacture and assemble.

11 FUTURE DIRECTION FOR ALUMINIUM GANTRY STRUCTURES

The HA's anticipated incorporation of this gantry (with other new designs) into a motorway contract did not materialise. The reason for this was primarily the additional design and certifying costs for a new standard design to be borne by a single motorway contract.

A lightweight modular aluminium highway gantry structure offers significant benefits for the Australian highway network.

12 ACKNOWLEDGMENTS

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