Aluminium

J B Dwight MA, MSc, CEng, FIStructE, MIMechE
Fellow of Magdalene College and Emeritus Reader in Structural Engineering, University of Cambridge

Contents

14.1 Introduction 14/3
14.1.1 History 14/3
14.1.2 Comparison with steel 14/4

14.2 Production of structural material 14/4
14.2.1 Primary production 14/4
14.2.2 Wrought products 14/4
14.2.3 Castings and forgings 14/5

14.3 Control of strength 14/5
14.3.1 Heat-treatable and nonheat-treatable material 14/5
14.3.2 Heat treatment 14/5
14.3.3 Cold-working 14/5

14.4 Alloys 14/5
14.4.1 Alloy numbering system 14/5
14.4.2 Selected alloys – properties 14/6
14.4.3 Heat-treatable alloys 14/6
14.4.4 Nonheat-treatable alloys 14/7
14.4.5 Alloy selection – summary 14/7

14.5 Fabrication 14/8
14.5.1 Cutting and forming 14/8
14.5.2 Mechanical joints 14/8
14.5.3 Welding 14/8
14.5.4 Adhesive bonding 14/9
14.5.5 Use of extruded sections 14/9

14.6 Durability and protection 14/10
14.6.1 Unpainted use of aluminium 14/10
14.6.2 Protective systems 14/10
14.6.3 Contact with other materials 14/10

14.7 Structural calculations 14/10
14.7.1 Principles of design 14/10
14.7.2 Section classification 14/11
14.7.3 Resistance of cross-section 14/11
14.7.4 Softening at welds 14/12
14.7.5 Buckling 14/13
14.7.6 Connections 14/14
14.7.7 Fatigue 14/14

References 14/14

Bibliography 14/14
14.1 Introduction

14.1.1 History

Although the most abundant metal in the Earth's crust, aluminium was ranked as a precious metal until 1890. In that year the modern electrolytic method of smelting was invented, which transformed the status of aluminium as an industrial metal. Today, it is second-cheapest, after steel, among the metals suitable for structural use. Its volume usage roughly equals that of all the other nonferrous metals put together.

The first strong alloy ("Duralumin") was developed in 1905, which made possible the structural use of aluminium in the German Zeppelins of the First World War. Between the wars its use was developed in aircraft, leading to a vast increase in aluminium production during the Second World War. This was accompanied by a dramatic decrease in cost relative to other metals. After 1945 there was great pressure to develop fresh outlets for aluminium and many new markets were found. By now it is well established in a wide range of industries. Aerospace accounts for a fairly small, but important, part of the total tonnage.

The use of aluminium for civil engineering structures was pioneered in the US during the early 1930s, the first epic example being several 45 m dragline jibs used on the Mississippi's levees. This was followed by the replacement of the steel deck of the Smith Street Bridge in Pittsburgh by an aluminium one in 1933, thus uprating its load capacity. This deck lasted for over 40 yr until replaced by a second aluminium one. Today, aluminium is acknowledged as a general structural material. It is chosen for main structures in situations where its special properties - low density and nonrustability - justify the extra metal cost compared with steel. Figure 14.1 shows a large aluminium roof structure built in Malaysia. This structure is mechanically jointed. Welding is also now widely used as, for example, in the aluminium military bridge shown in Figure 14.2.

A much greater tonnage of aluminium is consumed in secondary structural applications, such as maintenance gantries, glazing bars, window frames, curtain walling, shopfitting, prefabricated buildings, greenhouses, balustrades, crash-barriers, road signs and lamp posts. It is also used widely in the form of profiled sheeting for the cladding of buildings.

Figure 14.1 Aluminium roof of 50 m diameter structure for the Selangore State Mosque, Malaysia. Tubular construction, employing special extruded node units for the joints. Tubes in 6061-T6 alloy, and all other extrusions in 6082-T6. (Triodetic system. Courtesy: British Alcan Aluminium plc)
14.1.2 Comparison with steel

The following is a crude statement of how aluminium differs from steel as a structural material (G = good, B = bad):

<table>
<thead>
<tr>
<th>Property</th>
<th>Aluminium</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>one-third the density</td>
<td>G</td>
</tr>
<tr>
<td>Nonrusting</td>
<td>seldom needs painting</td>
<td>G</td>
</tr>
<tr>
<td>Extrusion process</td>
<td>design your own sections</td>
<td>G</td>
</tr>
<tr>
<td>Fabrication</td>
<td>generally easier</td>
<td>G</td>
</tr>
<tr>
<td>Brittle-fracture</td>
<td>not susceptible</td>
<td>G</td>
</tr>
<tr>
<td>Expensive</td>
<td>about 3 times the cost by volume</td>
<td>B</td>
</tr>
<tr>
<td>Deflections</td>
<td>$E$ one-third that of steel</td>
<td>B</td>
</tr>
<tr>
<td>Fatigue</td>
<td>more susceptible</td>
<td>B</td>
</tr>
<tr>
<td>Buckling</td>
<td>more critical</td>
<td>B</td>
</tr>
<tr>
<td>Ductility</td>
<td>tends to be lower</td>
<td>B</td>
</tr>
<tr>
<td>Welded strength</td>
<td>suffers from heat-affected zone (HAZ) softening</td>
<td>B</td>
</tr>
</tbody>
</table>

Other differences from steel are:

- Thermal expansion: twice that of steel
- High conductivity (electrical and thermal)

All aluminium alloys have a rounded stress-strain curve (Figure 14.3), in which they resemble cold-rolled rather than hot-finished steel. Yield is defined in terms of the 0.2% proof stress.

14.2 Production of structural material

14.2.1 Primary production

Aluminium is obtained from the ore bauxite, the first stage being to extract pure alumina. The smelter comprises lines of relatively small furnaces ('pots'), in which the alumina powder is dissolved in liquid cryolite and smelted electrolytically using big carbon electrodes. The output of the smelter is pure aluminium ingot, a major item in the cost of which is the electricity. The ingot is shipped to secondary plants where it is remelted and alloyed to produce wrought ('semi-fabricated') products, in the form of plate, strip, sheet, sections and tube.

14.2.2 Wrought products

14.2.2.1 Flat material

Mill practice for this is much as for steel. Continuously cast slabs are hot-rolled to produce plate, which may then be cold-
gradually harden at room temperature, reaching its final
quench has little immediate effect, but with time the metal will
when better strength and ductility are needed.

Larger quantities). Aluminium forgings can fill a similar role
and attachments. They may be sand-cast, or else chill-cast (for
conjunction with wrought material, typically for small fittings
Aluminium castings (see section 14.4.4.5) may be employed in
and naturally aged'.

The strengthening process for heat-treatable alloys consists of
hot-finished sections. There are two main kinds of
heat-treatable; and (2) 'nonheat-treatable'. The pro-
derivatives, the former by heat treatment, and the latter
as cold-working. The heat-treatable alloys are generally the
stronger, but less tough, and are more often the choice for main
structural use. The nonheat-treatable alloys typically appear in
the form of sheet, for which the necessary cold-working is
provided during manufacture by the reduction in the rolling
operation. Either type can be softened again by annealing.

It is essential for extrusions to be in heat-treatable alloy, since
there is no way of cold-reducing them during manufacture.
Drawn tube can be of either type.

14.3 Control of strength

14.3.1 Heat-treatable and nonheat-treatable material

Nearly all the aluminium alloys, unlike steel, are unacceptably
weak in the hot-finished state. There are two main kinds of
alloy: (1) 'heat-treatable'; and (2) 'nonheat-treatable'. The pro-
derivatives, the former by heat treatment, and the latter
by cold-working. The heat-treatable alloys are generally the
stronger, but less tough, and are more often the choice for main
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operation. Either type can be softened again by annealing.

It is essential for extrusions to be in heat-treatable alloy, since
there is no way of cold-reducing them during manufacture.
Drawn tube can be of either type.

14.3.2 Heat treatment

The strengthening process for heat-treatable alloys consists of
quenching ('solution treatment') followed by ageing. The
quench has little immediate effect, but with time the metal will
gradually harden at room temperature, reaching its final
strength after several days. Such material is said to be 'quenched
and naturally aged'.

The ageing process is speeded up usually by heating the metal
in a furnace for some hours at about 150 to 200°C ('precipi-
tation treatment'). Such material is stronger than if naturally
aged. It can be described as 'quenched and artificially aged', or
more commonly as 'fully heat-treated'.

The quench ideally takes place from a carefully controlled
temperature in the region of 500°C. The resultant distortion has
to be corrected, usually by stretching (before artificial ageing).
With wide, thin, extrusions distortion is a major problem, and
may well dictate the thickness and, hence, economy of a design.
A common practice with the 6000-group alloys is to spray-
quench thin extrusions as they emerge from the die, which is
more economic and causes less distortion than if they were
heated and quenched in a tank as a subsequent operation. For
very slender profiles in the 6063 alloy it is even possible to turn
off the water entirely and rely on an air-quench at the die,
thereby reducing distortion even more. Ideal quenching is
obviously not achieved with air-quenching and the resulting
material has reduced properties.

14.3.3 Cold-working

Nonheat-treatable aluminium material is strengthened by
means of cold-working applied during manufacture. This is
possible for products that are cold-reduced in bringing them to
their final thickness, i.e. sheet and drawn tube. It is also possible,
to a lesser degree, for plate at the lower end of the thickness
range ('cold-rolled plate').

The required properties are achieved by careful control of the
reduction passes and of interpass annealing. It is common to
refer to cold-worked material as being one-quarter, one-half,
three-quarters or fully hard, as an indication of its 'temper', i.e.
of the extent to which it has been strengthened. The strongest
temper is fully hard, but a lower temper may be called for when
formability is a factor. For the stronger of the nonheat-treatable
alloys the fully-hard temper is not offered.

14.4 Alloys

14.4.1 Alloy numbering system

The specification of aluminium materials has been much simpli-
ified by the recent worldwide adoption of the US numbering
system. Engineers should abide by this and use no other.

A given alloy, i.e. composition, is referred to by a four-digit
number, the first digit of which indicates the alloy group to
which it belongs. The alloys are grouped according to main
alloying elements as follows, the groups of interest to civil
engineers being given asterisks:

Heat-treatable alloys:

- 2000 group Copper
- 6000 group Magnesium
- 7000 group Zinc

Nonheat-treatable alloys:

- 1000 group (Pure)
- 3000 group Manganese
- 4000 group Silicon
- 5000 group Magnesium

Apart from the alloy it is necessary to specify the condition (heat
treatment or temper). This is done by means of appropriate
symbols written after the alloy number. For heat-treatable
alloys:

<table>
<thead>
<tr>
<th>Temper</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T6</td>
<td>Fully heat-treated, i.e. quenched and artificially aged</td>
</tr>
<tr>
<td>T5</td>
<td>Air-quenched and artificially aged (extrusions)</td>
</tr>
<tr>
<td>T4</td>
<td>Quenched and naturally aged</td>
</tr>
</tbody>
</table>

For nonheat-treatable alloys:

<table>
<thead>
<tr>
<th>Temper</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H12 or H22</td>
<td>Quarter-hard temper</td>
</tr>
<tr>
<td>H14 or H24</td>
<td>Half-hard temper</td>
</tr>
<tr>
<td>H16 or H26</td>
<td>Three-quarter-hard temper</td>
</tr>
<tr>
<td>H18 or H28</td>
<td>Fully hard temper</td>
</tr>
</tbody>
</table>
14/6 Aluminium

For all alloys:

| O  | Annealed          |
| F  | As-extruded or as-rolled |

Thus, typical material specifications would read as follows:

6082-T6  An alloy with a particular aluminium–magnesium–silicon composition, in the fully heat-treated condition
3103-H14 An alloy with a particular aluminium–manganese composition, in the half-hard temper

In the temper designation for non-heat-treatable alloys the first digit after the H (1 or 2) is of academic interest to the average user; it merely shows whether the material has been cold-reduced to the final temper, or has been partly annealed after the last pass. What matters is the ensuing digit (2, 4, 6 or 8) which indicates the actual hardness.

The F-condition is ill-defined. It essentially refers to hot-finished material (extrusion, plate) that has received no further treatment, the properties of which cannot be specified closely.

14.4.2 Selected alloys – properties

14.4.2.1 Strength values

Table 14.1 gives a short list of structural aluminium materials that are of interest in civil engineering. The quoted mechanical properties are based on BS 1470 (flat products) and BS 1474 (extruded sections). The reader is urged to refer to these or other national standards for fuller information.

14.4.2.2 Physical properties

Approximate values roughly applicable to all aluminium alloys are as shown in Table 14.2. Weight of aluminium material may be estimated using the following formulae:

\[
\text{Weight of section (N/m)} = 0.027 \times \text{area in square millimetres}
\]

\[
\text{Weight of plate (N/m)} = 27 \times \text{thickness in millimetres}
\]

Table 14.2

<table>
<thead>
<tr>
<th>Density</th>
<th>2.7 g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity ( E )</td>
<td>70 kN/mm²</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>26 kN/mm²</td>
</tr>
<tr>
<td>Poisson’s ratio ( \mu )</td>
<td>0.33</td>
</tr>
<tr>
<td>Linear expansion coefficient</td>
<td>( 24 \times 10^{-6} ) per °C</td>
</tr>
<tr>
<td>Melting point</td>
<td>660°C</td>
</tr>
</tbody>
</table>

14.4.3 Heat-treatable alloys

14.4.3.1 2000-group

This group of alloys, sometimes referred to as ‘Duralumin’, is typified by a high copper content (around 4%). It includes most of the strong alloys used for aircraft, an example being 2014-T6 with a tensile strength approaching 450 N/mm². These alloys are seldom used outside the aerospace industry, because of their low ductility in the T6 condition, higher cost, inferior corrosion resistance and non-weldability. They have to be fabricated with great care. To reduce corrosion it is possible to use them in the form of ‘clad sheet’, a product with rolled-on pure aluminium facings.

14.4.3.2 6000-group

This very important group, covering aluminium alloyed with magnesium and silicon, essentially comprises two basic grades of alloy: (1) a stronger; and (2) a weaker grade. The stronger comes in slightly different versions in different parts of the world, the European version, 6082, being broadly similar to the 6061 more commonly used in North America. Material of this type in the T6 condition may be regarded as the ‘mild steel’ of aluminium, and is the commonest choice for general structural use. It has a 0.2% proof stress about equal to the yield of mild steel, although with a lower tensile strength and less ductility. It is readily welded, but with nearly 50% loss of strength in the heat-affected-zone (HAZ) (Figure 14.3). A particular feature is the ease with which these alloys can be extruded into thin intricate sections.

The second type of alloy in the group is 6063, which is considerably weaker. This is the extrusion alloy par excellence.
Figure 14.3 Typical stress–strain curves. \( f_0 = 0.2\% \) proof stress

(even better than 6082) and is the automatic choice for slender complex architectural shapes, such as window sections and curtain-wall mullions, where stiffness rather than strength is important. Another feature is its smooth surface finish (with a well-made die). Extrusions in 6063 can be produced in the normal T6 or else in the weaker T5 condition (air-quenched), the latter being suitable for very slender profiles that would not otherwise be feasible; 6063 is not supplied in the form of plate or sheet.

### 14.4.3 7000-group

This group, comprising aluminium alloyed with zinc and magnesium, was originally developed in the form of ultra-strong materials for use in military aircraft, having tensile strengths exceeding 500 N/mm². Of value to the civil engineer are the less-strong alloys 7020 and 7019, which are of special interest for welded construction. With these, the heat-affected material adjacent to a weld gradually regains strength over a period at room temperature, and after a month gets back to 75% or more of the full T6 properties. Both alloys extrude nearly as well as 6082. The weaker version 7020 has comparable strength to 6082 in the T6 condition, while 7019 is up to 30% stronger.

Material of 7000-type is susceptible to stress corrosion, when the amount of the alloying elements exceeds a critical level. The alloy 7020 was developed and standardized in Europe with this danger taken into account. As a result it is safe, but hardly any stronger than the cheaper and more readily available 6082. The stronger 7019 version would seem more attractive to a designer. However, 7019, being more highly alloyed, is closer to the critical level for stress corrosion. It was developed in the UK for military bridges, in which form some 15,000 tons have been used satisfactorily. But this success was only achieved by very careful control of fabrication procedures. It is essential for an intending user to realize that 7019 is not as simple to fabricate as 6082 or 6061, and to seek advice before doing so.

### 14.4.4 Nonheat-treatable alloys

#### 14.4.4.1 1000-group

This comprises nominally pure aluminium with different levels of guaranteed purity, material too weak for serious structural use. The cheapest version is 1200 with a minimum aluminium content of 99.0%. Higher purities are available, and in the annealed condition these can provide a valid alternative to lead as a soft flashing material.

### 14.4.4.2 3000-group

This covers material with manganese as the main alloying element. The two common versions are 3103 and 3105, of which 3105 is slightly the stronger. Used in the fully hard H18 temper, they represent the standard type of material used for profiled aluminium sheeting as employed for cladding of buildings.

### 14.4.4.3 4000-group

The only interest here in this minor group (aluminium plus silicon) is that it includes one type of weld filler wire.

### 14.4.4.4 5000-group

This comprises a range of alloys having varying amounts of magnesium as the main alloying element. They are characterized by their ductility and toughness. They are generally unsuitable for use as extruded sections.

The most important in structural terms is the strongest (5083), a plate material. Until recently this was supplied either in the annealed O condition, or else in the indeterminate F condition (as-hot-rolled). Its use was confined to low-stress applications, where toughness rather than high yield was needed as, for example, for the entire superstructure of the liner Queen Elizabeth II. Material 5083-O has too low a proof stress (only 125 N/mm²) for use in highly stressed structures; 5083-F will often have a proof stress 40% higher, but this cannot be guaranteed and the designer must still work to the low O-condition properties. Recently, 5083 plate in thicknesses up to 6 mm has become available in the H22 temper; in this condition it becomes much more attractive, its properties matching those of 6082-T6 for which it is a valid replacement.

Other 5000-group alloys in decreasing order of strength are 5154A, 5454 and 5251. They are typically used in the medium tempers, where their combination of formability and toughness makes them suitable for boatbuilding and sheet metal fabrication generally.

### 14.4.4.5 Casting alloys

A useful casting alloy contains aluminium with a nominal 12% Si (known as LM6 in the UK). This has a tensile strength roughly comparable to that of 6063-T6, but with a proof stress 50% lower. It has excellent foundry characteristics and good ductility. An alternative is the Al–5% Mg alloy (known as LM5) which is better in terms of surface finish, but which can only be cast into simple shapes; it is less ductile and slightly weaker than LM6.

### 14.4.5 Alloy selection – summary

For highly stressed welded construction the ideal choice is 7019-T6, because of its good strength and less severe degree of HAZ softening. But it is vital to realize that this is not a material for amateurs in anything but the simplest fabrications because of the latent risk of stress corrosion if correct procedures are not followed.

A more common choice is 6082-T6 or 6061-T6, which is somewhat weaker but more straightforward to fabricate. HAZ softening at welds is more severe than with 7019, and this calls for ingenuity in the location and design of joints.
For welded stiffened plating where toughness is needed, the normal choice would be 5083-F plate welded to 6082 (or 6061)-T6 extruded stiffeners. At thicknesses up to 6 mm the plate is available as 5083-H22 with higher and more precise properties.

For triangulated structures (trusses, space frames) the normal choice is 6082 (or 6061)-T6. Mechanical joints are often used, instead of welding, to avoid the problem of HAZ softening. For extruded members whose design is governed by stiffness rather than strength, as for intricate architectural profiles, the natural choice is 6063-T6. If the section is on the limit of feasibility due to its slenderness, the weaker condition 6063-T5 has to be used instead.

Profiled sheet used for the cladding of buildings is normally supplied in 3105-H18 or the slightly weaker 3103-H18. Sheet metal fabrications of secondary importance can be readily made in 5251-H14 which is ductile and formable. Pure aluminium in the form of 1200-H14 can be useful for unstressed sheet-metal work. Pure aluminium is also employed, in higher purities, for chemical plant (as an alternative to stainless steel) readily made in 5251-H14 which is ductile and formable. Pure aluminium is also employed, in higher purities, for chemical plant (as an alternative to stainless steel) and for electrical conductors (busbars and transmission lines).

A good general-purpose casting alloy is the Al-12% Si (known as LM6).

### 14.5 Fabrication

#### 14.5.1 Cutting and forming

##### 14.5.1.1 Cutting and machining

Thin material can be sheared like steel, but more readily. For thicker material cold-sawing is used, with either a circular or band saw. Aluminium (except in the softest tempers) can be sawn faster than steel, especially if suitable coarse-toothed saws are used.

Aluminium is also more readily machined than steel, and it is not unusual in design to employ extrusions incorporating attachment flanges which are machined away over the greater length of the member. (Stiffened panels in aircraft are often machined out of the solid.)

Ordinary flame-cutting is unsuitable for aluminium, because of the ragged edge produced. Instead, one can employ plasma-arc cutting, an adaptation of the tungsten inert gas (TIG) welding process.

##### 14.5.1.2 Bending

The heat-treatable alloys in the full strength T6 condition are less easily manipulated than steel. They will only accept a small deformation when bent cold, due to their lower ductility. Heating, on the other hand, distorts the heat treatment and causes severe softening. One solution is to form the material in the more ductile T4 condition and then bring it up to the full T6 strength by subsequent artificial ageing in a low-temperature furnace.

With the nonheat-treatable alloys the practice for forming is more as for steel. Cold-bending is employed when possible, the temper of the material being selected to suit the severity of the bend. Springback is more than for steel. For severe manipulations it is possible to apply local heating with a gas flame, the necessary temperature being 450 to 500°C. Great care is necessary to avoid overheating the aluminium, since there is no colour change at this temperature. Temperature-sensitive crayons may be used; alternatively one can rub a pine stick on the heated area and see if it leaves a mark.

#### 14.5.2 Mechanical joints

##### 14.5.2.1 Riveting

For many years, riveting was the normal means of making shop joints in aluminium. More recently there has been a wholesale move to welding, even for structures in the 6000-group alloys which are severely affected by HAZ softening. Riveting is little used and rivets have become hard to get. One wonders if the swing to welding has not been overdone.

Small solid rivets would usually be in 5154A alloy with the small ‘pan’ head driven cold. Squeeze riveting is preferred to hammering. Larger rivets can be driven hot. Alternatively, one can use 6082-T4 rivets (or equivalent) which have been held in a refrigerator since quenching, to suppress natural ageing. These are readily driven cold, after which they age-harden in position to attain their proper T4 strength.

Proprietary fasteners such as ‘Pop’ and ‘Chobert’ rivets are available for joints in sheet-metal work. These are suitable for blind riveting, i.e. from one side, and are quick to use.

##### 14.5.2.2 Bolting

Aluminium structures can be assembled using either ordinary bolting (dowel action) or high-strength friction-grip (HSFG) bolting (friction action).

Ordinary bolting is used with clearance or close-fitting reamed holes as appropriate, possible bolt materials being: 6082-T6 aluminium (or equivalent), steel (suitably coated) or stainless steel (316S16 or 304S15). Aluminium bolts are none too good in tension, especially in fatigue. On the other hand it may be difficult to get steel bolts with a coating of sufficient durability to match that of the aluminium, unless they are painted. The ideal answer is stainless steel, which is usually worth paying for.

In recent years it has become acceptable to employ HSFG bolting for aluminium, taking care with the protection of the steel bolts. Bolt material (high yield steel) and torquing procedures follow HSFG practice in steel. Proper attention must, of course, be paid to the condition of the contact surfaces, which should be grit-blasted. The slip resistance can be improved by applying epoxy resin (HSFG bolting is not recommended for use on plates having a 0.2% proof stress under 230 N/mm²).

##### 14.5.2.3 Screwing

Tapped holes in aluminium tend to be unsatisfactory. Patent stainless-steel thread-inserts are available, which give good service on parts that have to be screwed and unscrewed repeatedly.

#### 14.5.3 Welding

##### 14.5.3.1 Welding processes

Alloys in all groups except 2000 are readily welded. Unfortunately, welding is accompanied by local HAZ softening. This occurs to a greater or lesser degree depending on the parent alloy (see section 14.7.4), except with annealed material.

The standard arc-welding process is manual inert gas (MIG), using d.c. current. This is similar to CO₂ welding of steel except that the shielding gas is argon (or helium in North America). It is easy to operate and ideal for positional welds. It can be used on thicknesses down to about 2 mm. With the MIG process, aluminium can be welded as easily as steel, after an initial training period. Current settings are higher and deposit areas tend to be greater.

For thin work the TIG process is used instead of MIG. In this mode the arc is struck from a nonexpendable tungsten electrode, the filler wire being held in the left hand. This is an a.c. process which needs more skill than MIG. It is slower and causes more distortion.

Aluminium can be spot-welded, but with higher energy inputs than for steel.
14.5.3 Filler wire

Simplified recommendations for selection of arc welding filler wire material are shown in Table 14.3. For further information refer to BS 3019 or 3571.

Table 14.3

<table>
<thead>
<tr>
<th>Parent alloy group</th>
<th>Filler composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000*</td>
<td>5% Si (4043A), or 5% Mg (5056A, 5356)</td>
</tr>
<tr>
<td>5000 or 7000</td>
<td>5% Mg (5056A or 5356)</td>
</tr>
<tr>
<td>3000 or 1000</td>
<td>Parent composition</td>
</tr>
</tbody>
</table>

Note: *When welding 5000 to 6000 use the 5% Mg wire.

14.5.4 Adhesive bonding

Aluminium is eminently suitable for glued joints using epoxy resin, a technique successfully used for lamp posts and other components. The epoxies are attractive because of their ability to tolerate poor fit-up. Shear strengths up to 15 N/mm² can be developed, but it is essential to guard against premature failure due to peeling from the end of a connection. An extruded tongue-and-groove feature is often a good way of preventing this.

The resin can be used cold or, alternatively, can be hot-cured to give improved strength. In the latter case the curing temperature is the same as that needed for artificial ageing. Thus, with heat-treatable alloys it is economic to order the material in the T4 condition, and rely on the hot-curing operation to harden the aluminium (up to T6).

14.5.5 Use of extruded sections

14.5.5.1 Availability

The relatively low cost of extrusion dies often makes it economic to design one’s own section or ‘suite’ of sections to suit the job in hand. The use of such sections can reduce fabrication costs and produce an improved final product provided, of course, the quantities are sufficient.

Extrusion is mainly confined to the 6000 and 7000 alloy groups, the order of merit for extrudability being: (1) 6063; (2) 6082 or 6061; and (3) 7019 or 7020. Complex sections, including hollows, are produced in all of these. Extrusions are also possible in 2014 (high-strength) and 5083 (high-ductility), but with severe limitations on profile and at much higher cost.

Hollow sections are normally produced using a ‘bridge die’ in which a mandrel, defining the internal shape, is supported on feet locating on the body of the die (which defines the outer shape). Since the hot plastic metal has to flow around these feet and reunite, the final section contains longitudinal welds. These cannot be seen and, in the vast majority of applications, are quite acceptable. But there are some situations where they would be regarded as a potential danger. Hollow sections extrude more slowly than nonhollows, and thus cost more per kilogram; the die charge is also higher.

Apart from custom-made profiles, the designer has a wide range of conventional sections from existing dies to choose from, such as channels, angles, T- and I-sections and boxes. Stockists hold these, usually in 6082-T6 or equivalent.

Sections are extruded in long lengths and can be supplied up to 20 m long to meet special needs. The normal limit on length is much less than this and is dictated by handling and transport.

14.5.5.2 Limiting dimensions

Sections generally are available up to about 300 mm wide from small and medium extrusion presses. With large presses, using special die assemblies, it is possible to extrude sections up to 600 mm wide, depending on the shape. But relatively few mills contain such equipment.

The designer often wants a section to be as thin as possible, for economy. In 6063 alloy the lower limit on thickness can very roughly be taken as the lesser of 1.0 mm and width/120. In 6082 (or equivalent) the corresponding values are 1.5 mm and width/80, while in 7019 they are somewhat more. Sections of 6063 at the limit of slenderness can be supplied in the T5 condition (air-quenched) to reduce the amount of post-extrusion straightening needed to correct distortion.

14.5.5.3 Section design

Figure 14.4 shows a few of the devices that can be incorporated in the design of extruded shapes. Figure 14.4(a) shows a lipped channel space-frame chord, which is a more efficient shape than a plain (unlipped) channel, having greatly increased local buckling resistance. The planking section (Figure 14.4(b)) incorporates various features, including integral stiffeners, interlock, and anti-slip surface. Planking sections, first developed as flooring for trucks, have also been employed in bridge decks and (after piercing) for open-work flooring. Figure 14.4(c) shows a double-sided planking section, again interlocking.

![Figure 14.4 Examples of extruded sections](image-url)
14.6 Durability and protection

14.6.1 Unpainted use of aluminium

14.6.1.1 The corrosion process

Atmospheric corrosion of unprotected aluminium proceeds by localized pitting, a radically different process from the rusting of steel. The oxide corrosion products formed at the pits are voluminous, giving an exaggerated impression of the actual damage. The rate of attack, defined by the depth of pitting, becomes stifled by the corrosion products and slows down after the first 2 or 3 yr. In outdoor sites the corrosion is less when the surface is regularly washed or rained on.

Corrosion failures, on the rare occasions that they happen with aluminium, usually stem from contact with other materials (see section 14.6.3).

14.6.1.2 Durability rating

Aluminium will usually last for ever unprotected, even out of doors. The decision whether or not to paint in an exposed environment depends on the durability rating of the alloy as shown in Table 14.4.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Alloy groups</th>
<th>Whether to paint</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000, 3000, 5000</td>
<td>Usually no need</td>
</tr>
<tr>
<td>B</td>
<td>6000</td>
<td>Only necessary when exposed to severe industrial or marine environment</td>
</tr>
<tr>
<td>C</td>
<td>2000, 7000</td>
<td>Generally necessary, except in dry unpolluted situation</td>
</tr>
</tbody>
</table>

14.6.2 Protective systems

14.6.2.1 Conventional painting

When an aluminium structure has to be painted, it is important that the priming and subsequent coats contain no copper, mercury or graphite, and preferably no lead. A zinc chromate priming coat is recommended.

14.6.2.2 Powder coating

In recent years, powder coating has become an economic process for the coating of aluminium components, on a mass-production basis, and has to some extent replaced anodizing. The powder is sprayed on and stoved, the resulting coat having a more even thickness than with solvent-based paint. Components are often powder coated for purely decorative purposes.

14.6.2.3 Anodizing

This is a process whereby the inherent oxide film is artificially increased electrolytically, the minimum oxide thickness for 'architectural anodizing' being 25 μm. This gives a pleasant satin appearance, which will last for years if regularly washed. Colour anodizing is also available, but only in a limited number of shades.

14.6.3 Contact with other materials

When aluminium is in direct contact with certain other metals under moist conditions, the adjacent aluminium gets eaten away. This is known as 'electrolytic' or 'galvanic' corrosion. Failure to take suitable precautions is likely to cause serious trouble.

Such corrosion occurs when aluminium is in contact with steel (other than stainless) or cast iron and, more severely, with copper, brass and bronze. The attack can be stopped by preventing direct contact, either by means of bituminous paint, or preferably with an interposed tape or gasket. Electrolytic corrosion need not be a problem if suitable precautions are taken.

With copper the electrolytic effect is so strong that water dripping off a copper roof on to aluminium sheeting will quickly perforate the aluminium, because of dissolved copper ions. The action between aluminium and lead is only slight. When aluminium and zinc are in contact it is the zinc that suffers. Galvanized bolts in an exposed aluminium structure tend to lose their protection more quickly. Aluminium that is to be embedded in concrete should be protected with bituminous paint; otherwise it will suffer attack while the concrete is 'green'.

14.7 Structural calculations

14.7.1 Principles of design

14.7.1.1 Codes of practice

At the time of writing (1987) existing codes for aluminium design are in the process of being redrafted into limit state format. In the UK, BS 8118 Structural use of aluminium which is near to publication and due to replace CP 118:1969, will be in two parts. Part 1: 'Code of practice for design' and Part 2: 'Specification for materials, fabrication and protection'. The simplified design rules given below have been broadly based on the draft to Part 1, which is still subject to possible alteration.

14.7.1.2 Basic requirements

All structures should satisfy: (1) the ultimate, and (2) the serviceability limit state. Fatigue may also be a factor (see Section 14.7.7).

14.7.1.3 Ultimate limit state

Every component, i.e. member, joint, must satisfy the following:

$$\text{Action under factored loading} \leq \text{factored resistance}$$

where action means moment or force, as appropriate, resistance means ability to withstand that action, factored loading is nominal loading × γ_m, and factored resistance is calculated resistance/γ_m.

The partial factor γ_m, applied to the nominal working loads, has basic values as follows:

<table>
<thead>
<tr>
<th>Members</th>
<th>Joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead loads 1.20 1.25</td>
<td></td>
</tr>
<tr>
<td>Imposed loads (except wind) 1.33 1.30</td>
<td></td>
</tr>
<tr>
<td>Wind loads 1.20 1.30</td>
<td></td>
</tr>
</tbody>
</table>

However, when more than one imposed or wind load acts simultaneously it is permissible, in the case of that which produces the second, third or fourth most severe action, to multiply the basic value by 0.8, 0.6 or 0.4 respectively.

The partial factor γ_m, applied to the ideal calculated resistance, is taken thus:

| Nonwelded construction Members 1.20 Joints 1.25 |
| Welded construction Members 1.25 Joints 1.30 |
14.7.1.4 Limiting design stresses

Resistance calculations (see sections 14.7.2 to 14.7.5) involve the use of limiting stresses \( p_0 \) and \( f_l \), listed in Table 14.1 for selected alloys. \( p_0 \) is usually taken to be equal to the guaranteed 0.2% proof stress. However, a reduced value is taken for materials having a high ratio of ultimate to proof stress, such as 5083-0, for which the stress–strain curve tends to be more rounded. This is to prevent plastic deformation at working load.

14.7.1.5 Combined actions

When a member carries simultaneous axial load and moment, the ultimate limit state is satisfied if:

\[
P/P_R + M/M_R \leq 1.0
\]

where \( P \) and \( M \) are actions arising under factored load and \( P_R \) and \( M_R \) are the separate factored resistances.

14.7.1.6 Serviceability limit state

The requirement is that recoverable elastic deflection under nominal (unfactored) loading should not exceed the specified limiting value. In view of the lower modulus it is common to accept larger deflections in aluminium than those normal with steel.

14.7.2 Section classification

14.7.2.1 Compact and slender sections

The first step in checking a member for the ultimate limit state, except in simple tension, is to establish whether it has a compact cross-section. If, instead, it is of slender section, the resistance will be reduced by premature failure due to local buckling.

14.7.2.2 Classification for axial load or moment

The plate elements comprising a section are of two basic sorts: outstand and internal (Figure 14.5). The procedure for classifying the section is as follows:

1. Determine the parameter \( \beta/e \) for each of the elements comprising the section (except the tension flange of a beam). \( \beta \) depends on the width:thickness ratio \( b:t \) as follows, with \( b \) measured to the toe of the root fillet (if any):

   - Plain outstand element, uniform compression \( \beta = b:t \)
   - Internal element, uniform compression \( \beta = b:t \)
   - Web of beam, neutral axis at centre \( \beta = 0.35b:t \)
   - \( \varepsilon = \sqrt{250/p_0} \) with \( p_0 \) in newtons per square millimetre (Table 14.1).

2. Classify the individual elements, according to the value of \( \beta/e \), in Table 14.5.

3. The classification of the section is then taken as that of the least favourable element.

14.7.2.3 Reinforced outstand elements

The ability of outstands to resist local buckling can be increased by stiffening the free edge with a lip or bulb (Figure 14.5). For such an element, if reinforced by a standard lip of thickness \( t \) equal to that of the plate, a more favourable value of \( \beta \) may be taken as follows:

\[
\beta = (b:t)(1 + 0.03(c:t)^{-1/3})
\]

(14.1)

where \( c \) is the internal lip height (Figure 14.5).

If \( c \) is large, there is the chance of the lip itself buckling prematurely as a plain outstand, and this should be checked. With any other shape of reinforcement, \( \beta \) should be found by replacing it with an equivalent standard lip (thickness \( t \)), the inertia of which about the mid-plane of the plate is the same as that for the actual reinforcement.

(Note: In channel-section struts it is immaterial if lips face in or out. But in a beam any lip on the compression flange must be inward facing to be effective.)

14.7.2.4 Classification for shear force

This depends on the depth:thickness ratio \( d:t \) of the web or webs and on \( \varepsilon \) (defined in section 14.7.2.2), as follows:

- Compact \( d:t \leq 49\varepsilon \)
- Slender \( d:t > 49\varepsilon \)

14.7.3 Resistance of the cross-section

14.7.3.1 Axial load resistance

The factored resistance \( P_R \) of an unwelded section is found as follows:
Tension: $P_R = \text{lessen of } p_a A / y_m$ and $p_0 A / y_m$  \hspace{1cm} (14.2)

Compression (with overall buckling prevented):

Compact, unwelded section $P_R = p A / y_m$  \hspace{1cm} (14.3a)

Other sections $P_R = p_0 A / y_m$  \hspace{1cm} (14.3b)

where $p_a$, $p_0$ = limiting design stresses (Table 14.1), $A$, $A_n$ = gross and net section areas, $A_e$ = area of effective section (see sections 14.7.3.3, 14.7.4.4) and $y_m$ = partial safety factor (see section 14.7.1.3).

14.7.3.2 Bending moment resistance

The moment resistance $M_R$ of an unwelded section in the absence of lateral-torsional buckling, is found thus:

Fully compact, unwelded section $M_R = p_0 S / y_m$  \hspace{1cm} (14.4a)

Fully compact, welded section $M_R = p_0 S / y_m$  \hspace{1cm} (14.4b)

Semi-compact, unwelded section $M_R = p_0 Z / y_m$  \hspace{1cm} (14.4c)

Other sections $M_R = p_0 Z / y_m$  \hspace{1cm} (14.4d)

where $S$ and $Z$ are plastic and elastic section moduli and $S_e$, $Z_e$ are the same for the effective section (see sections 14.7.3.3 and 14.7.4.4).

14.7.3.3 Effective section

For sections classified as slender (see section 14.7.2.2) the effect of local buckling is catered for by basing the section properties ($A_e$ and $Z_e$) on an effective section, instead of the true one. In unwelded construction the effective section is found by taking a thickness of $k_L$ times the true thickness for any slender element within the section. $k_L$ is read from Figure 14.6, the quantities $\beta$ and $\epsilon$ needed to enter which are as defined in sections 14.7.2.2 and 14.7.2.3.

The effective section to be used for welded members, to allow for HAZ softening at welds, is defined in section 14.7.4.4.

14.7.3.4 Shear force resistance

The factored shear resistance $V_R$ is found thus for sections having unwelded compact webs, normally orientated:

$V_R = 0.6 p a A / y_m$  \hspace{1cm} (14.5)

where $A_e$ is the web area.

For unwelded webs classified as slender (see section 14.7.2.4) the following formula may be used:

$V_R = \frac{600 \times 10^3 A}{(d/t)^\alpha} y_m$  \hspace{1cm} (14.6)

For welded webs, refer to section 14.7.4.4. Note that Equation (14.6) becomes oversafe if applied to very slender stiffened webs.

14.7.3.5 Moment and shear combined

The moment resistance is unaffected by the presence of a shear force $V$ not exceeding half the value of $V_R$. For higher values of $V$, $M_R$ becomes reduced as follows:

$M_R = M_{R_0} \left\{ 1 - 8(V/V_R - 0.5)^3 \right\}$  \hspace{1cm} (14.7)

where $M_{R_0}$ is the factored resistance in the absence of shear.

$\begin{array}{c}
\text{Figure 14.6} \text{ Local buckling factor } k_L \text{ for slender plate elements.} \\
(a) \text{ Outstand; (b) internal. N=unwelded, W=welded}
\end{array}$

14.7.4 Softening at welds

14.7.4.1 Severity of softening

In welded construction the designer must allow for the local softening that occurs in the HAZ adjacent to welds, except when the parent metal is in the annealed (O) condition. It is assumed that within a certain distance of each weld the material properties are reduced to the parent properties multiplied by a softening factor $k_i$, which depends on the alloy as follows:

7000-group, T6 condition $k_i = 0.75$
The shear resistance of a welded web of slender proportions may be (1) above; and (2) based on Equation (2) compact sections using (2). For any plate element that is both slender (14.5) with HAZ effects allowed for in the calculation of A.

There are two possible modes of overall buckling to be considered: (1) flexural; and (2) torsional. Torsional buckling tends to become critical for thin open sections such as angles and channels.

The factored resistance for either mode is taken as the basic resistance \( P_e \) of the section (Equation (14.3a) or (14.3b)) times the factor \( k_e \), which is read from Figure 14.7. In order to enter the figure the quantity \( \varepsilon \) is found as follows, with \( p_e \) in newtons per square millimetre:

The use of Figure 14.7 may tend slightly to overestimate buckling strength of struts that are: (1) welded; or (2) of very asymmetric section (buckling axis much nearer to one edge than the other).

### Table 14.6

<table>
<thead>
<tr>
<th>Butt</th>
<th>Fillet</th>
</tr>
</thead>
<tbody>
<tr>
<td>7000-group</td>
<td>4.5( t ), or 35 mm</td>
</tr>
<tr>
<td>5000-groups</td>
<td>3( t ), or 25 mm</td>
</tr>
<tr>
<td>6000-group</td>
<td></td>
</tr>
</tbody>
</table>

It is important to exercise rigorous thermal control during welding to limit the extent of the HAZ. The values of \( z \) given above are only valid if the metal temperature adjacent to a weld at the start of deposition, of any pass, does not exceed 40°C (for 7000- and 5000-group parent alloys) or 50°C (for 6000). If these temperatures are exceeded, the predictions in section 14.7.4.2 will underestimate the affected area. Also, with 7000-group material the softening factor \( k \), may drop below 0.75.

### 14.7.4.4 Effective section of welded members

To allow for the effects of HAZ softening, the true section is replaced by an effective one, which is assumed to have full parent properties throughout, but with reduced thickness in the HAZs. The resistance is then found generally as in section 14.7.3, using section properties based on the effective section:

1. **Compact sections.** The effective section is obtained by taking an assumed thickness in the HAZ equal to \( k_1 t \) instead of the true thickness \( t \).
2. **Slender sections.** For any plate element that is both slender and affected by welding, the assumed thickness is taken as the lesser of \( k_1 t \) and \( k_{1/2} t \) in the HAZ and as \( k_{1/2} t \) elsewhere in that element. The rest of the section is treated according to (1) above or section 14.7.3.3 as appropriate.

The shear resistance of a welded web of slender proportions may be taken as the lower of two values: (1) based on Equation (14.5) with HAZ effects allowed for in the calculation of \( A \), using compact sections in (1) above; and (2) based on Equation (14.6) with HAZ effects ignored.

### 14.7.5 Buckling

#### 14.7.5.1 Buckling of struts

There are two possible modes of overall buckling to be considered in axial compression: (1) flexural; and (2) torsional. Torsional buckling tends to become critical for thin open sections such as angles and channels.

The factored resistance for either mode is taken as the basic resistance \( P_e \) of the section (Equation (14.3a) or (14.3b)) times the factor \( k_e \), which is read from Figure 14.7. In order to enter the figure the quantity \( \varepsilon \) is found as follows, with \( p_e \) in newtons per square millimetre:

When considering ordinary flexural buckling, the slenderness parameter \( \lambda \) is simply the effective slenderness ratio \( k_e n \) as used in conventional steel design. For torsional buckling, \( \lambda \) may be obtained from the general expression:

\[
\lambda = \pi \sqrt{EA/P_e}
\]

where \( P_e \) is the elastic critical load for torsional buckling of a strut, as given in textbooks, allowing for interaction with flexure when necessary.

For struts of plain angle section (unreinforced) the torsional buckling check may be waived when the section is compact (section 14.7.2.2). If the angle section is slender, it can be assumed that torsion is adequately covered by simply taking \( P_e \) based on the effective section, with \( k_e = 1 \).

(Note: The use of Figure 14.7 may tend slightly to overestimate buckling strength of struts that are: (1) welded; or (2) of very asymmetric section (buckling axis much nearer to one edge than the other).)

#### 14.7.5.2 Lateral-torsional buckling of beams

The factored moment resistance for a member prone to lateral-torsional buckling is taken as the basic resistance \( M_e \) of the section (based on Equation (14.4a), (14.4b), (14.4c) or (14.4d)) times the factor \( k_e \), which is again read from Figure 14.7. In entering the figure \( \varepsilon \) is now found as follows, again with \( p_e \) in newtons per square millimetre:

$$
\varepsilon = \sqrt{(250/p_e)} \quad (14.8a)
$$

Other sections

$$
\varepsilon = \sqrt{(250A/P_e)} \quad (14.8b)
$$
14/14 Aluminium

Fully compact, unwelded section \( \varepsilon = \sqrt{(250/p_c)} \) (14.10a)

Other sections \( \varepsilon = \sqrt{(250S/M_c)} \) (14.10b)

The slenderness parameter \( \lambda \) may be obtained from the following general expression:

\[ \lambda = \pi \sqrt{(ES/M_c)} \]

where \( M_c \) is the elastic critical moment for lateral-torsional buckling, as given in textbooks. Alternatively, for beams of conventional I-, channel, T-shapes, \( \lambda \) may be found using the appropriate steel data.

14.7.6 Connections

14.7.6.1 Ordinary riveting and bolting

Limiting stresses for aluminium fasteners, to be used in conjunction with an appropriate value of \( \gamma_m \) (see section 14.7.1.3), are given in Table 14.7 in newtons per square millimetre. The corresponding bearing stress on the ply is taken as \( 2p_p \) (see Table 14.1). Limiting stresses for steel fasteners should normally be taken as \( 0.7p_p \), \( 2p_p \), and \( p_p \) respectively for shear, bearing and tension, where \( p_p \) is the yield stress.

<table>
<thead>
<tr>
<th>Fastener</th>
<th>Shear</th>
<th>Bearing</th>
<th>Tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>5154A rivet</td>
<td>125</td>
<td>400</td>
<td>—</td>
</tr>
<tr>
<td>6082-T4 rivet</td>
<td>95</td>
<td>310</td>
<td>—</td>
</tr>
<tr>
<td>6082-T6 bolt</td>
<td>170</td>
<td>550</td>
<td>220</td>
</tr>
</tbody>
</table>

14.7.6.2 Friction grip bolting

The factored resistance in shear (depending on friction capacity), again with an appropriate \( \gamma_m \), may be based on a slip factor of 0.3. This is valid provided: (1) the surfaces are grit-blasted; (2) the bolt diameter is not less than the combined ply thickness; and (3) the 0.2% proof stress of the ply material is not less than 230 N/mm².

14.7.6.3 Welded joints

Suitable limiting stresses for weld metal, used in conjunction with an appropriate \( \gamma_m \) (see section 14.7.1.3), are given in Table 14.8 in newtons per square millimetre. These assume that the weds are sound, and that the right filler wire is used (see section 14.5.3.2).

<table>
<thead>
<tr>
<th>Parent alloy</th>
<th>Tension</th>
<th>Shear</th>
</tr>
</thead>
<tbody>
<tr>
<td>7019, 7020, 5083</td>
<td>240</td>
<td>170</td>
</tr>
<tr>
<td>6082, 6061, 5251</td>
<td>150</td>
<td>100</td>
</tr>
</tbody>
</table>

14.7.7 Fatigue

Fatigue calculations are generally based on stress arising under nominal working loads (unfactored). In the new aluminium codes (e.g. BS 8118) fatigue data will be presented in terms of stress range, following steel practice. Details are classified broadly as in steel. For a given detail the stress range to be used in design, corresponding to a given number of cycles, is about one-third of the corresponding stress range for steel. It is largely independent of the alloy used.

References


Bibliography

Robertson, I. and Dwight, J. B. ‘HAZ softening in welded aluminium, 3rd international conference on aluminium weldments, Munich.'