

# Bolted Aluminium Tube Construction for Minimum Aeroplanes

Ben Syson  
Chief Technical Officer  
British Microlight Aircraft Association



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## ABSTRACT

Bolted aluminium tube construction was one of the factors that drove the microlight boom of the late 1970s and early 1980s – and has been used in this category of aeroplane ever since. The introduction of the deregulated ‘SSDR’, or ‘sub-115kg’, single seat category in the UK in 2007 effectively introduced an experimental category for minimum aeroplanes. For the amateur wishing to take advantage of this category, bolted aluminium tube construction remains an effective way to design and construct a simple yet lightweight airframe. This paper discusses the sizing of a minimum aeroplane before moving on to the detail design of a bolted aluminium tube airframe. Sections are included on suitable materials and structural analysis techniques. Wing structural design and the detail design of joints between tubes are also discussed.

## 1 INTRODUCTION

The microlight boom of the late 1970s and early 1980s was driven by a number of factors that permitted practical flying machines to be produced at lower cost than ever before. Emergent technologies included Dacron (polyester) sailcloth, aluminium tube and 2-stroke engines<sup>1</sup>. A general lack of regulation<sup>2</sup> of very light flying machines promoted experimentation and the development of these technologies into what we now recognise as microlight aeroplanes.



**Figure 1.1: Huntair Pathfinder. Early microlight aeroplane featuring wire braced bolted aluminium tube construction, Dacron sailcloth covering and 2-stroke engine (Pingstone, A).**

Today, microlight aeroplanes (and the regulatory environment!) have matured into proper little aircraft, which, at the heavy and sophisticated end, have left their

roots behind and merge seamlessly into heavier, more conventional (and more expensive) forms of aviation. However, in 2007 a new deregulated aeroplane category was introduced in the UK for lightweight single seat machines (see section 3). This ‘SSDR’ category has, at least in a limited way, returned us to the regulatory landscape of 30 years ago, again making it easier for amateurs to design, build and fly their own flying machines.



**Figure 1.2: Comco-Ikarus C42. Modern microlight aeroplane, which is not dissimilar to a conventional light aeroplane. However bolted aluminium tube construction, and sailcloth wing covering, are retained (Pingstone, A).**

The technologies that originally spawned the microlight boom – and particularly bolted aluminium tube construction – remain eminently appropriate for this class of flying machine, and provide the low financial and technical entry costs required by the amateur designer.

### 1.1 ‘Microlight’ versus ‘minimum aeroplane’

The term ‘microlight’ was coined in the early 1980s for the new breed of minimum aeroplanes. It is now a legal definition in the UK and has grown to encompass aeroplanes that are arguably no longer ‘minimum’.

<sup>1</sup> And the ubiquitous Rogallo hang-glider wing.

<sup>2</sup> In a surprisingly large number of countries around the world, including the UK [5].

'Microlight' is only used in this paper as a historical term to describe the minimum aeroplanes of the late 1970s and early 1980s, and subsequent aeroplanes that complied with the microlight definition then in force. 'Minimum aeroplane' is used to describe a truly minimum aeroplane.

## 2 HISTORICAL PERSPECTIVE

There are many striking similarities between the flying machines of the Edwardian era<sup>3</sup> and contemporary minimum aeroplanes.

The aim of the Edwardian designer was simply to achieve a practical, man-carrying flying machine. However he was restricted to using the low power, heavy powerplants of the time. He achieved his aim with a large – both in terms of wing area and span – but lightweight airframe. This permitted flight at low speed (due to the low wing loading) without requiring lots of power to counter induced drag (due to the low span loading). The technology of the day meant that such a structure was anything but aerodynamically clean, so that high speed flight was impossible. However that was not (yet) a pressing requirement.

The contemporary minimum aeroplane designer has very much the same task as the Edwardian designer, namely to achieve a practical, man-carrying flying machine on modest power and at very light weight. Unencumbered by the requirements of high speed and transport efficiency that most contemporary aeroplane designers are saddled with, the Edwardian solution to the problem – build it large and light, if not particularly clean – fits the bill.



**Figure 2.1: Santos Dumont's Demoiselle.** Generally considered the first minimum aeroplane. Fuselage constructed from bamboo (presumably in lieu of decent aluminium alloy tube!).

### 2.1 The Demoiselle

Santos Dumont's Demoiselle of the late Edwardian period

<sup>3</sup> Generally extended in this context beyond 1910 to 1912, or even the commencement of hostilities in 1914.

is generally considered the first truly light aeroplane [7]. It was of fairly conventional high wing tractor layout but with the engine mounted high above the wing. See figure 2.1.

Although the original Demoiselle's fuselage was a space frame constructed of bamboo, the Demoiselle configuration has been extremely successful for minimum aeroplanes over the years. With the advent of aluminium tubing a very simple fuselage could be built up around a single large diameter fuselage tube to which the engine, wing and empennage all attach. See figures 2.2 and 2.3.



**Figure 2.2: Skycraft Scout.** Early microlight aeroplane clearly showing influence of Demoiselle.

Figure 1.2 shows the contemporary, and highly successful, Comco-Ikarus C42. Despite appearances this aircraft is also built around a single large diameter aluminium fuselage tube, which is hidden by non-structural composite fairings. The fuselage tube is positioned low resulting in a conventional engine location.



**Figure 2.3: Thruster TST.** Highly successful microlight of the late 1980s. Engine, wings and empennage all attach to the single, large diameter, aluminium fuselage tube (Curtis, H).

## 3 UK 'SSDR' CATEGORY

The SSDR (single seat deregulated) or sub-115kg (maximum empty weight) was introduced in the UK in

2007: originally by a general exemption issued by the Civil Aviation Authority; subsequently incorporated into the Air Navigation Order.

At the time of writing the relevant text can be found in Article 16 of the Air Navigation Order [1], which waives the requirement for a Certificate of Airworthiness (or a Permit to Fly) for:

- (g) *a microlight aeroplane which:*
  - (i) *is designed to carry one person only;*
  - (ii) *has a maximum weight without its pilot and fuel of 115kg;*
  - (iii) *has a maximum wing loading without its pilot and fuel of 10kg per square metre; and*
  - (iv) *is flying on a private flight.*

This effectively introduces an experimental category in the UK for minimum aeroplanes.

It should be noted that the fact that it is specifically a *microlight* aeroplane restricts the maximum all up mass to 300kg, and requires the stalling speed, or minimum steady flight speed, not to exceed 35 knots<sup>4</sup>. It also requires compliance with noise legislation [2], although at the time of writing the requirement to hold a noise certificate is waived by a rolling general exemption issued by the Civil Aviation Authority.

Also note that the deregulation only applies to airworthiness. Aircraft registration, insurance, and pilot licensing requirements, for example, remain unaffected.

### 3.1 Assurance of airworthiness

The structural analysis techniques described in this paper are approximate and primarily intended for design purposes. For a (non-SSDR) microlight to qualify for a Permit to Fly use of such analysis techniques alone would not be considered sufficient assurance of airworthiness. Confirmatory load testing and/or independent analyses would be required to validate the design<sup>5</sup>.

Where appropriate, commercial grade materials and components are used in regulated (non-SSDR) microlights. However commercial items are always used with caution; testing programmes are often introduced to ensure that such materials and components consistently exhibit the mechanical properties required by the design.

Although the requirement to have a Permit to Fly has been waived for SSDR microlights, the laws of physics

have not! While a designer of an SSDR microlight may choose to dispense with the above mentioned work, he does so entirely at his own risk.

## 4 MINIMUM AEROPLANE SIZING

In the absence of a rigorous definition for a 'minimum aeroplane', the UK SSDR category definition (see section 3) will be used in the following discussion: empty mass 115kg; wing area 11.5m<sup>2</sup>. Although arbitrary, use of a concrete example permits real numbers to be presented, which are illuminating.

No apology is made for mixing airspeed in miles per hour (mph), climb rate in feet per minute (fpm) and power in horsepower (hp) with SI units!

Symbols are defined in APPENDIX 3. Basic aerodynamic relationships are derived by Houghton [8].

### 4.1 Maximum all up mass

To be considered truly practical, a minimum aeroplane must be able to carry a good range of male adult pilots – say up to 110kg – together with fuel for at least a couple of hours duration. For an aeroplane of 115kg empty mass, a maximum all up mass approaching 250kg is generally appropriate.

This results in a useful load (fuel and payload) fraction somewhat in excess of 50%. This is similar to the useful load fraction of a modern, turbine engined, air transport aeroplane. In other words it does require a reasonably efficient structure.

### 4.2 Stalling speed

Wing lift

$$L = C_L \frac{1}{2} \rho V^2 S$$

Therefore the stalling speed

$$V_{s0} = \sqrt{\frac{Mg}{C_{LMAX} \frac{1}{2} \rho S}}$$

Assuming a maximum lift coefficient of 1.4, which is not untypical for an aeroplane without high-lift devices<sup>6</sup>, a 250kg, 11.5m<sup>2</sup> aeroplane will have a stalling speed of 35mph. Increasing wing area to 16m<sup>2</sup> reduces the stalling speed to 30mph.

### 4.3 Power requirement – induced drag

Induced drag power for elliptic spanwise loading (see APPENDIX 1)

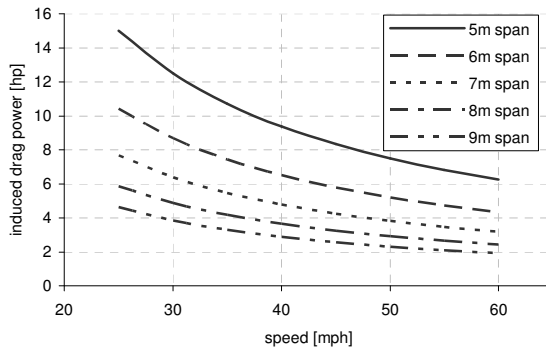
<sup>4</sup> Article 255 of the Air Navigation Order 2010 [1].

<sup>5</sup> In addition to which, the design and the means of assuring airworthiness would be independently reviewed by the certifying body.

<sup>6</sup> Estimated maximum lift coefficient for Raj Hamsa X'Air.

$$P_i = \frac{1}{\frac{1}{2}\rho V \pi} \left( \frac{Mg}{s} \right)^2$$

The induced drag power is a function of speed and span loading. The induced drag power as a function of airspeed and span for a 250kg aeroplane is shown graphically in figure 4.1.



**Figure 4.1: induced drag power at mean sea level as a function of airspeed and span for a 250kg aeroplane (assuming elliptic spanwise loading).**

This clearly shows that, unless power is at a real premium, there is little benefit to be gained from increasing the span much above 8m.

It is interesting to note that, for a wing area of 11.5m<sup>2</sup>, an 8m span corresponds to an aspect ratio of only 5.6. This does not sound high to those used to dealing with more conventional aircraft, and is due to the unusually low wing loading of this type of aircraft. However it is span loading, not aspect ratio, that matters when it comes to induced drag.

#### 4.4 Power requirement – profile drag

The profile drag and profile drag power are, respectively

$$D_0 = C_{D0} \frac{1}{2} \rho V^2 S \text{ and } P_0 = D_0 V$$

Therefore

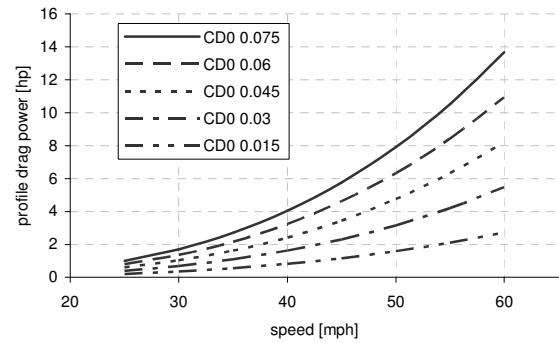
$$P_0 = C_{D0} \frac{1}{2} \rho V^3 S$$

The profile drag power as a function of speed and zero-lift drag coefficient for an 11.5m<sup>2</sup> wing area aeroplane is shown graphically in figure 4.2.

To give some idea of likely zero lift drag coefficient, the Fokker Eindecker, a wire braced monoplane of 1915, had a zero lift drag coefficient of 0.0771 [9]. See figure 4.3.

Although the Fokker Eindecker by no means defines an upper limit on zero-lift drag coefficient, figure 4.2 clearly shows that an even dirtier airframe does not require significant amounts of power (compared to the induced drag power) to pull it along until airspeed reaches 40 to

45mph.



**Figure 4.2: profile drag power at mean sea level as a function of speed and zero-lift drag coefficient for an 11.5m<sup>2</sup> wing area aeroplane.**



**Figure 4.3: Fokker Eindecker. Wire braced mid wing monoplane fighter of WW1. A scale replica is available in the SSDR category.**

#### 4.5 Power requirement – climb

The excess power required to climb (in excess of that required for level flight)

$$P_c = \frac{Mgh}{t} = Mg \frac{h}{t}$$

To climb a 250kg aeroplane at 500fpm requires 8.35hp.

#### 4.6 Power requirement – total

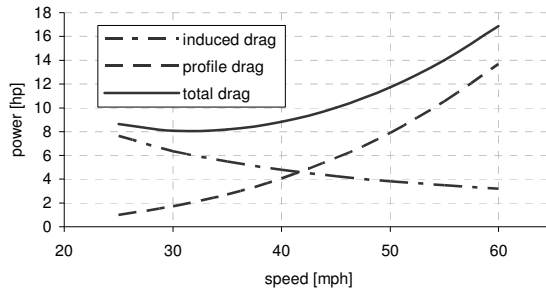
We can now pull together sections 4.3, 4.4 and 4.5.

The drag power curve for a hypothetical wire braced minimum aeroplane – 7m span and 0.075 zero-lift drag coefficient – is shown in figure 4.4. With a further 8+ horsepower required to climb, 20 to 25 horsepower is a practical minimum power requirement.

Note that this hypothetical aeroplane has a theoretical minimum drag power at an airspeed of 32mph, which is below its stalling speed of 35mph (see section 4.2) and is



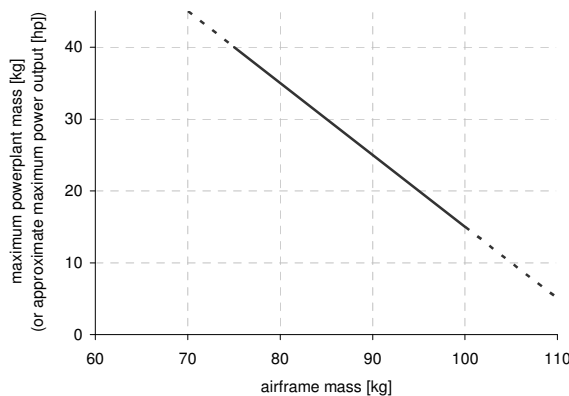
not, therefore, achievable. It is for this reason that many low power minimum aeroplanes have had an even lower wing loading than the maximum required by the UK SSDL requirement to permit them to take advantage of their minimum drag power airspeed.



**Figure 4.4: total drag power at mean sea level as a function of speed for a 250kg, 11.5m<sup>2</sup> aeroplane with a span of 7m and a zero-lift drag coefficient of 0.075 (assuming elliptic spanwise loading).**

#### 4.7 Airframe mass

Figure 4.5 shows a rather trivial result of the SSDL category: the trade off between maximum airframe and powerplant mass. This assumes a specific power output of 1 hp per kg, which is not atypical for a 2-stroke engine of this kind of power output. A power requirement of 20 to 25hp (see section 4.6) puts an upper limit of around 90kg on the mass of the airframe.



**Figure 4.5: maximum powerplant mass (and approximate maximum power output) versus airframe mass. Assumes specific power output of 1 hp per kg.**

#### 4.8 Conclusion

It is, of course, possible to design a highly efficient minimum aeroplane that will fly at relatively high speed on very little power. Bolted aluminium tube construction is unlikely to be appropriate for such an aeroplane however.

Due to the external bracing required, a minimum aeroplane of bolted aluminium tube construction is likely to be relatively draggy. However, as long as the wing loading and span loading are kept low, a practical aeroplane with decent climb performance and an acceptable speed range is possible on relatively little power.

## 5 MATERIALS

It is not uncommon for commercial grade materials and components to be used in this class of aeroplane. If this is being considered please read section 3.1.

### 5.1 Aluminium

6000 series (magnesium and silicon) aluminium alloys are the most commonly used for this type of structure. They are medium strength aluminium alloys, which can be precipitation (age) hardened to an ultimate tensile strength of around 300 MPa. At this strength 6000 series alloys are not as strong as the traditional aerospace 2000 and 7000 series alloys. However, 6000 series alloys have the significant advantages for this application of better corrosion resistance and reduced cost. 6000 series alloys can be used simply anodised. High strength alloys are occasionally used to save weight in high stress areas (such as wing spars).

6000 series alloys are most commonly used in the T6 temper: solution heat-treated and artificially aged. 6061T6 is the traditional North American specification with a minimum ultimate tensile strength of 290MPa [13]. 6082T6 (formerly HT30TF) is the traditional British specification with a minimum ultimate tensile strength of 310MPa [3].

### 5.2 Tubes

Drawn seamless tubes are almost universally used for critical airframe components. Use extruded tube with extreme caution – rumours abound regarding the splitting of extruded tube under bending loads<sup>7</sup>.

In Britain and North America 17 gauge (0.056" or 0.058" wall thickness) tubes with outside diameter increments of 1/8" are commonly used. As the wall thickness is just under half the outside diameter increment these tubes fit snugly within one another. Double, and even triple, sleeving is not uncommon for reinforcement.

### 5.3 Bracing cables

Most bolted aluminium tube airframes are cable braced to some extent. Multi-strand cables of galvanised or stainless steel with swaged fittings are typically used. See figure 8.1.

<sup>7</sup> Presumably due to inconsistent grain structure around the circumference resulting from the extrusion process.

## 5.4 Bolts

Aircraft grade AN [4] bolts are available in  $\frac{3}{16}$ ",  $\frac{1}{4}$ " and  $\frac{5}{16}$ " (and larger) diameters, and  $\frac{1}{8}$ " length increments. These have a minimum tensile strength of 125ksi (862MPa) and a minimum shear strength of 75ksi (517MPa) [12]. Similar metric bolts are also available, but generally not in such a comprehensive range of sizes.

## 6 STRUCTURAL ANALYSIS

Bolted aluminium tube airframes are, essentially, space frames. As such, standard methods of analysing frameworks are applicable when determining the load distribution through the airframe required to react the air, ground and inertia loads seen in operation. These methods are covered in any undergraduate structures course or structures textbook [11], and beyond the scope of this paper.

The analysis techniques described in this section are approximate. Please read section 3.1.

### 6.1 Structural redundancy

Structural redundancy and fail safe structures are important parts of the structural design of larger aeroplanes. However for minimum aeroplanes, where, by necessity, the vast majority of the airframe is structurally critical but (and this is important) readily inspectable, the author would argue that redundancy should be avoided. A simple and largely statically determinate structure, carefully designed so that the load paths through the structure can be determined accurately and straightforwardly, is the best way of ensuring that the resulting airframe is both structurally efficient and safe.

Of course avoiding all redundancy is impractical. There are formal stiffness and energy methods for analysing statically indeterminate structures [11]. However as long as the structure is reasonably straightforward use of these can usually be avoided by estimating the relative stiffness of competing load paths. This often allows one of the load paths to be shown to be dominant, or a relative split between the competing load paths to be estimated.

### 6.2 Elastic stability

Many of the tubes subject to compressive loads in a bolted aluminium tube airframe are 'slender', and as such will fail due to Euler buckling before their material limit is reached. Often such tubes are braced to increase their buckling load. However, due to the nature of such a lightweight structure, it is not always safe to assume that this bracing is infinitely stiff. The author has had success with energy methods to estimate the effect of elastic supports in such cases [11].

Note that local buckling failure is not usually a problem

with the dimensions of the tubes used in these airframes [10].

### 6.3 Transverse loading

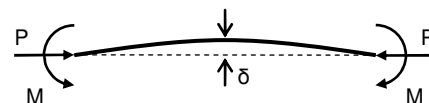
In an ideal framework all external loads are applied at nodes and all structural elements in the framework carry compressive or tensile loads only. This ideal is not achievable in a bolted aluminium tube airframe as the wing spars, stabilising surface spars and control surface spars have to react aerodynamic loads distributed along their length. Therefore these elements in the framework will carry bending loads (often in addition to compressive or tensile loads from their bracing – see section 6.4).

In fact, as thin wall aluminium tubes are reasonably efficient at reacting bending moments it is common to design parts of the airframe to utilise this, and not to fully triangulate the airframe. A common example is the use of a relatively large diameter thin wall aluminium tube as a fuselage tube. Although often partially braced for structural efficiency, the fuselage structure is not fully triangulated, and aerodynamic loads on the empennage are at least partially reacted by bending and torsion of the fuselage tube. See the aeroplane in figure 2.3 where the inclined bracing tubes meet the fuselage tube some distance short of the empennage.

### 6.4 Simultaneous axial and transverse loading

A beam (in this case a tube) subjected to simultaneous axial and transverse loading cannot be analysed by simple superposition of the effects the axial and transverse loading would have in isolation. This is due to bending moments – in addition to those due to the transverse loading – resulting from the deflection due to the transverse loading and the axial loading. See figure 6.1.

This problem is amenable to straightforward analytical analysis [11]. Although solutions to axial and transverse loadings applied independently cannot be superimposed, solutions to various transverse loadings applied simultaneously with a particular axial loading, can be superimposed [11][15]. This allows an externally braced wing, for example, to be analysed accurately. See section 7.2.



**Figure 6.1: beam under simultaneous transverse (end moments  $M$ ) and axial (compressive force  $P$ ) loading. The deflection of the beam  $\delta$  in combination with  $P$  causes an additional bending moment at the centre of the beam  $\delta P$ .  $\delta$  is a function of the bending moment along the beam, not just the applied end moments, and therefore a function of  $P$  as well as  $M$ .**

## 6.5 Stress analysis

In general the stress analysis of a tube can be separated into two distinct, and independent, exercises. The first of these is a uniaxial stress analysis considering the stress parallel to the major axis of the tube caused by the axial loading (tension or compression) and transverse loading (bending moment) to which the tube is subject<sup>8</sup> – see section 6.6. The second of these is the stress local to a bolt hole caused by the bearing of the bolt on the edge of a hole in the tube – see section 6.7. Although these exercises can generally be treated independently there are certain cases where this is not a safe assumption to make – see section 6.8.

In general it is acceptable to ignore stress concentrations, such as those that occur around bolt holes, in a *strength* analysis in a ductile material. Limited local yielding effectively removes the stress concentration as the average stress level approaches the yield strength of the material. However in a *fatigue* analysis stress concentrations cannot be ignored – see section 6.9.

## 6.6 Longitudinal stress analysis

Once the axial and transverse load distributions along a tube have been determined – in terms of axial load P and bending moment M – the longitudinal stress can be calculated.

$$\sigma = \sigma(P) + \sigma(M) = \frac{P}{A} + \frac{My}{I}$$

A is the cross-sectional area of the tube, I the second moment of area, and y the distance from the neutral axis. For a tube of outside diameter  $D_o$  and inside diameter  $D_i$

$$A = \frac{\pi}{4}(D_o^2 - D_i^2) \text{ and } I = \frac{\pi}{64}(D_o^4 - D_i^4) \text{ and}$$

$$y_{MAX} = \pm \frac{D_o}{2} \text{ (and wall thickness } t = (D_o - D_i)/2 \text{)}.$$

This analysis can be extended for use at bolted joints by using reduced values of A and I that take into account the bolt holes. For a tube with a pair of holes, diameter  $D_B$ , drilled opposite each other, the cross sectional area of the tube is reduced to

$$A \approx \frac{\pi}{4}(D_o^2 - D_i^2) - 2D_B t$$

For a tube subject to significant bending it is good practice to locate the bolt holes on the neutral axis. This both minimises the reduction in bending strength and ensures that the holes are in an area of the tube subject to low bending stress – see section 6.8.

$$I \approx \frac{\pi}{64}(D_o^4 - D_i^4) - \frac{1}{6}D_B^3 t$$

If the holes are not on the neutral axis but are located at the point of maximum bending stress

<sup>8</sup> Combined with the shear stress due to any torsion (if this is significant).

$$I \approx \frac{\pi}{64}(D_o^4 - D_i^4) - \frac{1}{2}(D_o - t)^2 D_B t$$

To demonstrate the difference between locating holes on and away from the neutral axis consider a 1" diameter tube of 0.056" wall thickness containing a pair of  $\frac{3}{16}$ " diameter holes. The second moment of area away from the holes is 7727 mm<sup>4</sup>. With the holes on the neutral axis the second moment of area is reduced to 7702 mm<sup>4</sup>, a reduction of only 0.3%. However, with the holes away from the neutral axis the second moment of area is 5780 mm<sup>4</sup>, a reduction of 25%.

If a hole contains a bolt then the bolt is able to carry compressive stress across the hole. This means that, when filled with a bolt, a hole in a compression surface does not weaken the tube and can be ignored for stress analysis purposes. Therefore under axial compression both holes can be ignored and the full cross sectional area of the tube used, while under bending the hole on the compression surface can be ignored and an intermediate second moment of area used<sup>9</sup>.

Some longitudinal stress analysis examples are shown in APPENDIX 2.

## 6.7 Bearing stress analysis

The stress analysis in section 6.5 considers the weakening effect of holes in tubes, and (by their effect on the axial and transverse load distributions along the tube) the macroscopic effect of any loads applied to the tube through bolts in those holes. However it does not fully consider the ability of the tube to locally react the loads entered by the bolt.

The primary failure mode is bearing failure. For a load F on a single hole of diameter  $D_B$  in a tube of wall thickness t the bearing stress

$$\sigma = \frac{F}{D_B t}$$

A possible secondary failure mode is shear-out failure. This is shown by the dotted lines<sup>10</sup> in figure 6.2a (the dashed line is the critical tension line). For a load F on a single hole distance X from an edge, the shear stress

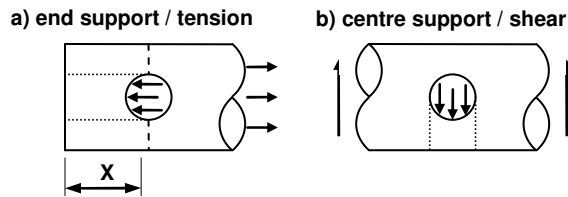
$$\sigma = \frac{F}{2Xt}$$

A shear-out failure in the transverse loading case of figure 6.2b is a possibility. However the shear-out area is usually an order of magnitude larger than the bearing

<sup>9</sup> Note that the reduction in bending strength is not quite halved by filling the hole in the compression surface. This is due to the movement of the neutral axis towards the compression surface, which adversely affects the second moment of area as well as increasing  $y_{MAX}$  (to the tension surface).

<sup>10</sup> Using the edge distance for X (the end of the tube to the edge of the hole) is very conservative. Unfortunately using the distance from the end of the tube to the hole centreline for X is not quite conservative [6].

area, so the bearing stress is generally critical.

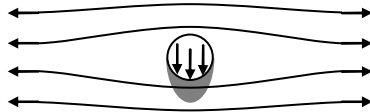


**Figure 6.2: bearing failure and shear out failure.**

## 6.8 Combined stress

If a hole is located in an area of high longitudinal stress, and the bolt is exerting a load normal to the direction of the longitudinal stress, it is not safe to treat the longitudinal and bearing stresses independently.

Figure 6.3 shows an example in which the material in the highlighted area is subject to high tensile stress and high compressive stress acting perpendicular to each other. This condition can be analysed using the von Mises yield criterion, for example, and will result in an effective bearing strength significantly lower than the bearing strength of the tube material. Note that, unlike most strength analyses, the stress concentrating effect of the hole on the longitudinal stress cannot be ignored.



**Figure 6.3: combined stress.**

By careful design, such as positioning holes close to the neutral axis, such problems can be avoided.

## 6.9 Fatigue

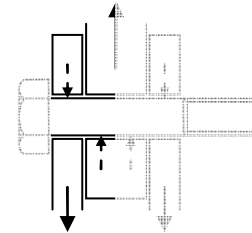
It is standard practice in the design (and certification) of microlight aeroplanes not to undertake a fatigue analysis of the airframe. Although the reason for this is primarily historical, accident statistics appear to show that it is not an unreasonable shortcut for this class of aeroplane. In applicable design codes [14] emphasis is placed on airframe inspectability so that, rather than designing fatigue problems out, they are caught before they become catastrophic.

In bolted aluminium tube airframes the majority of fatigue problems occur at joints due to the stress concentrations inherent in these areas. It is not impossible that fatigue could occur in a highly loaded section of plain tube, but it rarely occurs in practice. Therefore good design practice is key in avoiding fatigue problems: ensuring that likely problem areas are easily inspectable, and ensuring that margins at joints are not cut down.

## 6.10 Bolts

The bolts used in aircraft structures are usually loaded in shear. They are effectively used as shear pins, with the nut to retain them in position rather than to take any significant load. The bolts used have a plain shank with only a small threaded portion at the end. No significant bearing load should be applied to the thread.

By only loading the plain shank, not the threaded portion of the bolt, the risk of fatigue cracks being initiated under varying load conditions is minimised. Bolts can be loaded in tension, but aircraft structures are generally not robust enough to permit large bolt preloads to be used<sup>11</sup>. Therefore fatigue cracks being initiated due to the stress concentrations occurring in the threaded portion of the bolt is a real risk. The designer should ensure that bolts used in tension are over engineered to keep stresses below the fatigue limit.



**Figure 6.4: bolt loaded in double shear with associated bending due to load offset. A single-shear couple is highlighted.**

When loading a bolt in shear it is impossible to avoid applying bending loads as well. These are due to the necessary offset between the opposing loads as shown in figure 6.4. These bending loads can be analysed (approximately but conservatively) by decomposing the loading into single-shear couples and assuming that the loads act at the centre of each bearing surface.

## 6.11 Tube deformation

If a bolt in a tube is loaded in shear it is applying its load parallel to the surface of the tube adjacent to the bolt hole as shown in figure 6.5a. This loading does not attempt to deform the cross section of the tube and a large load can be transferred into the tube (generally limited by bearing failure).

If a bolt in a tube is loaded in tension it is applying its load normal to the surface of the tube adjacent to the bolt hole as shown in figure 6.5b. This loading tends to crush the tube and severely limits the magnitude of load that can be transferred this way. (The crushing load can be conservatively estimated by analysing a short length of the tube as a ring in compression [15].) To transfer a large load into a tube through a bolt in tension generally

<sup>11</sup> In mechanical engineering bolts are often 'torqued up' so that they carry a tensile preload in excess of the tensile load they are required to carry in operation (often over the yield strength of the bolt!). Under varying load conditions the stresses in the bolt therefore remain constant and the fatigue driver is removed.



requires the tube to be plugged in some way to stabilise the cross section.

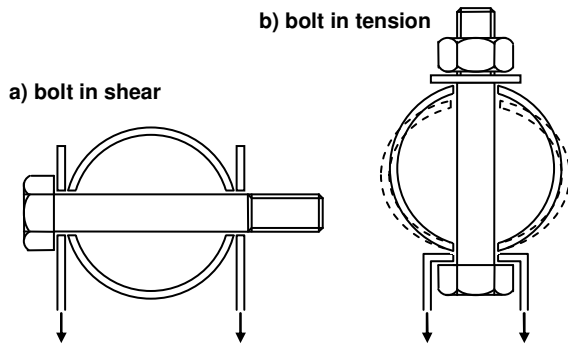


Figure 6.5: load entry.

## 7 WING STRUCTURE

A structurally efficient cantilever wing, which is required to achieve high bending strength from a minimum of material, cannot be achieved with a *simple* tubular structure. This is for two reasons. Firstly, an annulus is not a particularly efficient section in pure bending (at least not without significant modification). And secondly, although sleeving can be used to achieve modest changes in strength along a wing, it is not a practical way of achieving the large changes in strength (and corresponding weight savings) required along the span of an efficient cantilever wing.

Therefore aeroplanes made from simple tubular structures tend to have externally braced wings. This significantly reduces the bending moments required to be reacted, albeit at the expense of the wing spars having to react axial – often compressive – loads. However, an annulus is an efficient section at reacting combined compression and bending loads (at least as long as the bending loads are not too high).

### 7.1 Bending moment control

Figure 7.1 shows the bending moment along the span of a simplified wing: a beam subjected to uniform loading. Two cases are shown: simply supported at the root plus one additional support (2 supports); simply supported at the root plus two additional supports (3 supports).

The bending moment has been normalised and is shown as a percentage of the root bending moment of an equivalent cantilever wing: fully fixed at the root; no additional supports. Therefore a single additional support reduces the maximum bending moment by an order of magnitude, and a further support halves the maximum bending moment again.

In a real wing the loading is not uniform but biased towards the root. Therefore the supports will be located somewhat inboard of those in this example. In addition, the bending moments in figure 7.1 have been calculated assuming the supports apply vertical reactions only:

normal to the plane of the wing. However in most practical situations the bracing is inclined to the vertical and, in reacting the lift, will apply an axial load to the wing. The spars inboard of the bracing are therefore subject to simultaneous axial and transverse loading. This is discussed at length in section 6.4. For present purposes it is only necessary to be aware that, if the axial loading is compressive, the bending to which the spars are subject will be in excess of that to which they would be subject under transverse loading alone.

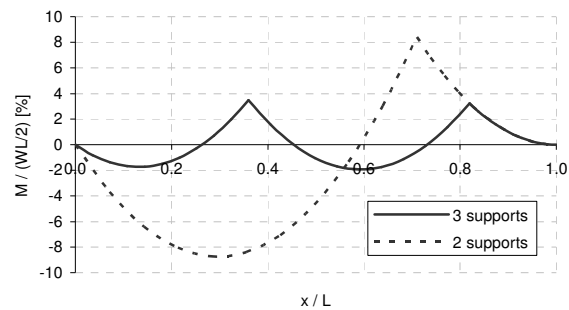


Figure 7.1: normalised bending moment along a beam subjected to uniform distributed loading. 2 support (root + 1) case: simple supports at 0% and 71% length. 3 support (root + 2) case: simple supports at 0%, 36% and 82% length.

Due to the extra support in the three support (root + 2) case – and the consequent reduction in spar length between supports – the increase in bending moment due to simultaneous compressive and transverse loading is less significant than in the two support (root + 1) case. This increases the benefit of the three support case over the two support case.

Note that the supports (in both three support and two support cases) may be located further inboard than if there was no compressive load. This reduces the angle of the bracing, which reduces the compressive load, and reduces the spar length between supports, which reduces the increase in bending moment due to the simultaneous compressive and transverse loading.

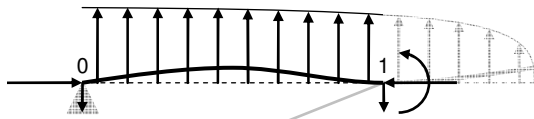
### 7.2 Spar structural analysis

Figure 7.2 shows the bending moment along the span of the 2 support (root + 1) and 3 support (root + 2) cases. A single section of spar between two supports and the loading on that section is highlighted in each case.

The 2 support (root + 1) case of figures 7.2a is statically determinate. The moment applied by the wing tip at point 1 can be determined from the lift distribution over the tip. Because point 0 is simply supported the vertical reaction at point 1 can be determined from the lift distribution over the wing. The compression in the wing between points 0 and 1 can be determined from the vertical reaction at point 1 and the angle of the bracing. The tip moment, compression and lift distribution fully define the external loading on the wing between points 0 and 1. The

bending moment distribution is calculated as described in section 6.4.

a) 2 support (root + 1) case



b) 3 support (root + 2) case

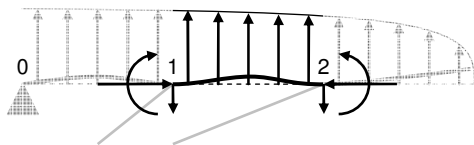


Figure 7.2: spar structural analysis.

The 3 support (root + 2) case of figures 7.2b is statically indeterminate. The moment at point 1 cannot be determined from the external loading on the wing. The other boundary condition required is the slope of the wing at point 1, which must be continuous. Note that the distribution between the vertical reactions at points 1, 2 and 3 is a function of the moment at point 1. The author has had success solving this problem using a spreadsheet in which the moment at point 1 can be varied until the slope at point 1 of the solution for the wing between points 0 and 1 equals the slope at point 1 of the solution for the wing between points 1 and 2.

### 7.3 Bracing types

Figure 7.3 shows typical types of external bracing. Wire bracing requires bracing above the wing – ‘landing wires’ – in addition to the ‘flying wires’ below the wing. Despite their name, the critical design case for the landing wires tends to be negative flight loads.

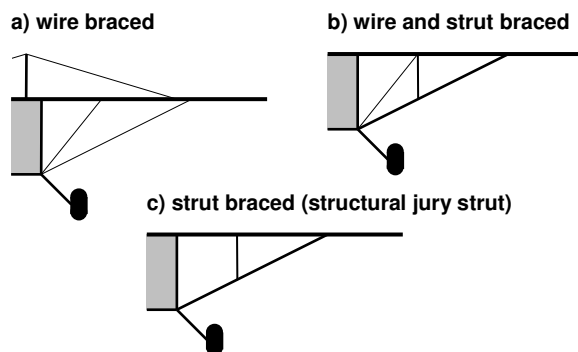


Figure 7.3: solutions to the 3 support (root + 2) problem.

Replacing the outboard flying wires with a strut allows the landing wires to be dispensed with. A jury strut is often used to stabilise the lift strut against buckling.

In modern designs the inboard wire bracing is often

deleted to reduce drag. However this does not necessarily mean that it reverts to the 2 support case. The spar – under transverse loads and compressive load from the lift strut – may well be less stiff than the lift strut in tension. Therefore the lift strut, via the jury strut, can help support the spar inboard of the lift strut attachment point.

### 7.4 Anti-drag bracing

Figure 7.4 shows the movement of the centre of pressure, and the direction of the lift force (normal to the local freestream) with angle of attack. At zero angle of attack (the chord line parallel to the local freestream) the lift is purely due to camber and acts at the  $\frac{1}{2}$  chord point. As the angle of attack is increased the proportion of lift due to angle of attack increases and the centre of pressure moves forwards towards the  $\frac{1}{4}$  chord point.

The lift force always acts through a point X, which is always located below the  $\frac{1}{2}$  chord point. If the external bracing is attached to the fuselage close to X, the external bracing reaction will tend to balance the lift acting parallel to the chord line, and the internal anti-drag bracing can be minimised.

Often, for practical reasons, the external bracing is attached well forward of X, and forward of the  $\frac{1}{4}$  chord point. In this case the external bracing reaction to lift loads will always provide an anti-drag load to be reacted by the internal anti-drag bracing. This is in addition to the anti-drag component of the lift.

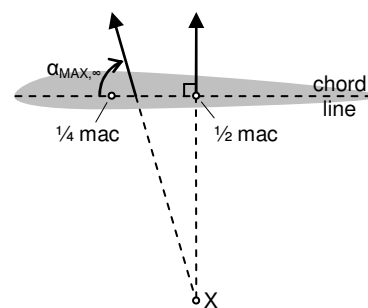


Figure 7.4: anti-drag. The lift force always acts through a point X located below the  $\frac{1}{2}$  chord point.

### 7.5 Two spar, or ladder frame, wing

Most common is the two spar, or ladder frame, wing, which has a front spar that also provides the leading edge, and a rear spar that doubles as the aileron / flap / flapron attachment. External bracing is provided as per section 7.3. As spar bending is the critical design case, 3 supports (root + 2) results in the most structurally efficient design. See figure 7.5 for an example: the Sky Ranger.

Drag / anti-drag bracing is normally provided by internal wire bracing.



**Figure 7.5: Sky Ranger minus covers. Note the two spar, or ladder frame, wing, two lift struts and structural jury struts. The wing's aerofoil shape is achieved by shaped, tubular battens that stiffen the sailcloth covers (Flylight Airsports).**

## 7.6 Single spar wing

There have been a number of single spar designs, particularly Mike Whittaker's MW range of aircraft. See figure 7.6. By contrast to two spar designs, in which torsional stiffness is achieved by external bracing (in combination with the spars' bending stiffness), single spar designs achieve torsional stiffness by using a much larger diameter thin wall tube for the spar, and reacting the torque at the wing root.

The large diameter required for torsional stiffness results in bending strength being less critical than in a two spar design, such that a single lift strut (two supports; root + 1), and a single internal drag strut, are generally sufficient.



**Figure 7.6: Mike Whittaker MW5. An example of a tubular single spar wing.**

Although the wing's primary structure is very simple – a spar, a lift strut and a drag strut – it is not particularly light. Also, unlike a two spar wing in which the leading edge and trailing edge are provided for 'free', a single spar wing's aerodynamic surface needs to be built up from scratch.

## 8 JOINT DESIGN

Probably every bolted aluminium tube airframe ever designed uses novel – to a greater or lesser extent – means of attaching tubes together. Therefore any kind of

comprehensive review is impractical and has not been attempted. Instead this section contains a discussion of joint and bracket design techniques followed by a few, fairly generic, examples.

The analysis techniques described in this section are approximate. Please read section 3.1.

### 8.1 Secondary loads

When analysing a framework it is usually assumed that the centreline of structural elements – the tubes in this case – intersect where those elements are joined. In the detail design of a bolted aluminium tube airframe, for practical reasons this ideal is not always achieved. This will introduce secondary bending or torsion loads, which are in addition to the primary loads being carried. These secondary loads must be assessed, although they only need to be analysed approximately if that confirms that they are not significant.

### 8.2 Joint fixation

When analysing a framework it is also usually assumed that the fixation of the joints conforms to some ideal such as simply supported, fully fixed or guided. In reality many joints are none of these; in particular, joints that are nominally fully fixed generally have a degree of flexibility. Rather than attempt to accurately determine the real degree of fixation, which is both time consuming and unlikely to be accurate, it is usually more satisfactory to estimate a conservative range of fixation, and calculate accordingly. For example, consider a wing spar that has a root attachment of indeterminate stiffness. The root attachment is not articulated, so an assumption of simply supported is invalid. However, by inspection, the root attachment bracket is not particularly stiff, so an assumption of fully fixed is also unlikely to be valid. The easiest way of analysing this is to perform two calculations: the first assuming that the root attachment is simply supported; the second assuming that the root attachment is fully fixed. If the loads are satisfactory either way then problem solved. If not (or if a more accurate solution is required to optimise the structure) then the stiffness of the bracket does need to be estimated. However, rather than calculating the stiffness accurately, it is generally more satisfactory to estimate the stiffness and again calculate over a conservative range of stiffness, albeit a reduced range than previously.

### 8.3 Bracket design

For a one-off minimum aeroplane, it is likely that the amateur designer will want to keep the number of machined end fittings and brackets to a minimum (or avoid machining altogether). The use of simple, 'off the shelf', aluminium extrusions, such as angle, channel and box sections, for brackets is very common, as is the use of folded stainless steel.

## 8.4 Bracket analysis

The loads that brackets carry can usually be defined reasonably precisely. If designed carefully it is usually possible to deconstruct the bracket into simple structural elements such as struts, ties and beams. To assist in this material may be 'theoretically' removed from the bracket, as long as the material removed does not significantly change the load path through the bracket, which would invalidate the analysis.

## 8.5 Example 1 – the tang

A bracing cable is commonly terminated using a tang, such as shown in figure 8.1. A tang allows the load in the cable to be conveniently transferred to a bolt, which is then attached, and conveniently transfers the load, to a tube or other structural element. Tangs are commonly made from stainless steel.

Cables are most commonly attached to the tang using a swaged fitting as shown in figure 8.1. These swaged fittings normally allow the full strength of the cable to be achieved<sup>12</sup>. The cable loop is formed around a thimble, which stops the cable being damaged by the tang.



**Figure 8.1: bracing cable termination on a Thruster T600N. The Thruster wing is strut and cable braced; this is the front spar, jury strut, inner flying wire connection point (as per figure 7.3b).**

The stress analysis techniques described in section 6 are applicable to analysing the tang. The possible failure modes are bearing failure, shear out failure and tension failure. All of these three failure modes must be assessed at both ends of the tang (the bolt end and the cable end). The tang applies the same bearing stress to the bolt and thimble as they apply to the tang. Therefore bearing failure of the bolt and thimble must also be assessed as part of the tang analysis.

## 8.6 Example 2 – the end sleeve

When transferring a load to a thin wall aluminium tube via

<sup>12</sup> Note that although this is normally the case it should not be assumed. It is normal practice to test swaged fittings to ensure that they are providing the required strength.

a bolt, the bearing stress applied by the bolt to the tube wall is often critical. This bearing stress can be reduced by increasing the diameter of the hole and transferring the load from the bolt to the tube via a bush. However this solution reduces the amount of metal in the tube cross-section, locally reducing the strength of the tube (with respect to axial or bending loads). An alternative solution is to locally sleeve the tube as shown in figure 8.2 and feed the proportion of the bolt load reacted by the sleeve into the tube using rivets. Although this requires additional holes to be drilled in the tube, they are located away from the bolt holes so that the minimum cross section – and therefore the strength – of the tube is not reduced.



**Figure 8.2: engine mount support strut on a Thruster T600N. The strut has a short inner sleeve riveted into the end. This increases the bearing strength of the bolt hole. The strut is bolted to a 'U' shaped bracket folded from stainless steel.**

## 8.7 Example 3 – the 'U' bracket

The 'U' bracket, examples of which are shown in figures 8.2 and 8.3, is a very common means of terminating a tube. Although these examples both terminate struts, 'U' brackets are also commonly used as spar root connections.



**Figure 8.3: front strut (small diameter) to monopole (large diameter) attachment on a Pegasus XL-Q. This 'U' shaped bracket is cut from an aluminium extrusion.**

When a 'U' bracket is loaded in tension the sides of the 'U' can be analysed in a similar way to a tang. When



loaded in compression, buckling of the sides of the 'U' must be considered. When in tension (and in compression if poorly supported) bending of the base of the 'U' is a possible failure mode. Another tension failure mode is shear out of the head of the bolt through the base of the 'U'. The shear out distance is the circumference of the bolt head (or washer).

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<sup>13</sup> Available for download from [www.everyspec.com](http://www.everyspec.com).

## APPENDIX 1 INDUCED DRAG POWER<sup>14</sup>

The induced drag and induced drag power are, respectively

$$D_i = C_{Di} \frac{1}{2} \rho V^2 S \text{ and } P_i = D_i V$$

Therefore

$$P_i = C_{Di} \frac{1}{2} \rho V^3 S \quad (1)$$

For elliptic loading the induced drag coefficient

$$C_{Di} = \frac{C_L^2}{\pi A} \quad (2)$$

Where, with  $s$  as the span, the aspect ratio

$$A = \frac{s^2}{S} \quad (3)$$

The lift coefficient

$$C_L = \frac{Mg}{\frac{1}{2} \rho V^2 S} \quad (4)$$

Inserting equations 3 and 4 into 2

$$C_{Di} = \frac{(Mg)^2}{\left(\frac{1}{2} \rho V^2 S\right)^2} \frac{S}{\pi s^2} = \frac{(Mg)^2}{\left(\frac{1}{2} \rho V^2\right)^2} \frac{1}{\pi s^2 S}$$

And inserting into equation 1

$$P_i = C_{Di} \frac{1}{2} \rho V^3 S = \frac{(Mg)^2}{\frac{1}{2} \rho V \pi s^2} = \frac{1}{\frac{1}{2} \rho V \pi} \left(\frac{Mg}{s}\right)^2$$

## APPENDIX 2 STRESS ANALYSIS EXAMPLES

Figure A2.1 shows a number of typical tube loading scenarios.

Figure A2.1a shows the bolted end support of a tube in compression. The tube carries the full compression load to the right of the dashed line. Therefore the critical cross sectional area is the gross cross sectional area of the tube.

By contrast figure A2.1b shows the bolted end support of a tube in tension. The tube carries the full tension load to the right of the dashed line. Therefore the critical cross sectional area is the gross cross sectional area of the tube minus the area removed for the bolt holes. Note that shear-out is a possible failure mode in this case.

Figures A2.1c and d show the effect of unloaded bolt holes in a tube in compression and tension respectively. If the holes are unfilled (there is not a bolt through the tube) the critical cross sectional area passes through the centre of the bolt hole in both cases. However, if the holes are filled (contain a bolt) the capacity of the tube to

<sup>14</sup> Symbols are defined in APPENDIX 3. Basic aerodynamic relationships are derived by Houghton [8].

carry the compression is unaffected by the bolt holes.

Figures A2.1e is an example of a loaded bolt hole in an axially loaded tube. In this case the tube is in compression to the right of the right hand dashed line and in tension to the left of that line. The tube carries the full tension load from, and to the left, of the left hand dashed line. Therefore the critical tension cross sectional area is the gross cross sectional area of the tube minus the area removed for the bolt holes. Other, general cases can be treated similarly.

Figures A2.1f shows a bolted support of a tube in bending. The dashed line shows the critical second moment of area. In this case the bolt holes are located on the neutral axis of bending. Therefore the reduction in second moment of area, and bending strength, due to the bolt holes is not large. Additionally, because the bending stresses are not large close to the neutral axis, the bearing stress due to the load exerted on the tube by the bolt can be analysed independently of the bending stress.

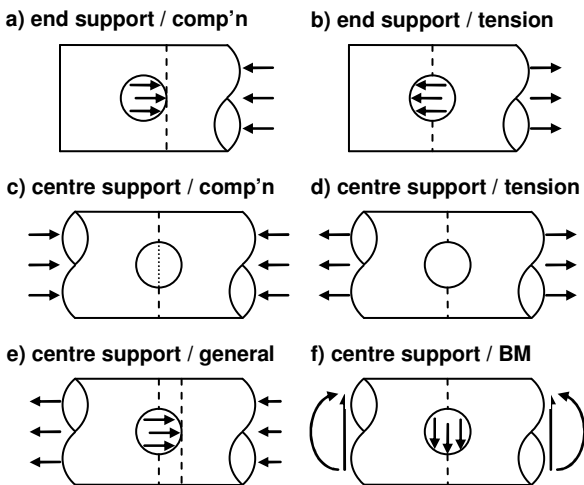


Figure A2.1: typical tube loading scenarios.

### APPENDIX 3 AERODYNAMIC SYMBOLS

$\rho$	air density
$C_D$	drag coefficient
$C_{D0}$	profile drag coefficient
$C_{Di}$	induced drag coefficient
$C_L$	lift coefficient
$C_{LMAX}$	maximum lift coefficient
$D$	drag
$g$	acceleration due to gravity
$h$	height
$L$	lift
$M$	aircraft mass
$P$	power
$s$	wing span
$S$	wing area
$V$	airspeed
$V_{S0}$	stall speed