

**TALAT Lecture 2302**

# **Design of Joints**

126 pages, 123 figures

Advanced Level

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**Objectives:**

- to provide a view of types of joints in aluminium structures and how to design and calculate frequently used joints

**Prerequisites/Target Group:**

- Basic structural mechanics and knowledge of design philosophy, structural aluminium alloys and product forms

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# 2302 Design of Joints

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## 2302.01 Types of Joints

- Introduction
- Joints in primary structures
  - Welding
  - Screws and bolts
  - Riveting
  - Solid state welding
  - Special mechanical joints
- Joints in thin-walled structures
  - Thread forming screws
  - Blind rivets
  - Cartridge fired pin connections
  - Spot welding

### Introduction


### Importance of Joining Technology

For the design of light-weight aluminium structures it is required

- to know about the plentitude of available joining techniques
- to know how to design and calculate connections

in order to achieve optimum service performance at low costs.


Joining is a key technology in aluminium structural engineering

 Training in Aluminium Application Technologies	Importance of Joining Technology	2302.01.01
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Well designed joints are essential to ensure the satisfactory performances of any structure. In aluminium frameworks with riveted or bolted gusset plates it has been estimated that the weight of the joints is about 10% of the weight of the structure; in cost terms, the ratio is probably larger. A significant weight advantage results from the use of welding which reduces this ratio to about 4%. Welding may also be preferred for general engineering purposes because it simplifies fabrication and assembly, which reduces cost. However, where site assembly is required, or when the structure is

subjected to fatigue loading, joints with mechanical fasteners - bolts or rivets - may be necessary. Furthermore, such joints provide useful system damping which is virtually absent in continuous welded structures.

The behaviour of structural joints has not attracted the research interest that its importance in structural performance would seem to merit. The bulk of research effort for the construction industry has been concerned with steel joints, comparatively little having been directed to problems peculiar to aluminium joints. However, the change from permissible stress to limit state design methods during the last decade, and the consequent need to revise codes of practice, has revived research interest in joint behaviour. Although limit state design, by definition, requires plastic (non-linear) analysis of structural behaviour, elastic analysis is still needed for the calculation of deformations in the serviceability limit state and in fatigue life estimations.

Types of Joints		
<ul style="list-style-type: none"><li>• Joints in Primary Structures<ul style="list-style-type: none"><li>- Welded Connections</li><li>- Bolted Connections</li><li>- Riveted Connections</li><li>- Adhesive Joints</li></ul></li><li>• Joints in Thin-Walled Structures<ul style="list-style-type: none"><li>- Thread Forming and Self-Drilling Screws</li><li>- Blind Rivets (Rivets with Break Mandrel)</li><li>- Cartridge Fired Pin Connection</li><li>- Resistance Spot Welding, MIG and TIG</li></ul></li><li>• Special Joints in Aluminium Structures<ul style="list-style-type: none"><li>- Solid State Welding</li><li>- Joints with Cast Connection Parts</li><li>- Snap Joints, Rolled Joints etc.</li></ul></li></ul>		
	Types of Joints	2302.01.02

## Joints in Primary Structures

Joints in structures with element thickness larger than 5 mm are made as

- welded connections
- bolted connections
- riveted connections

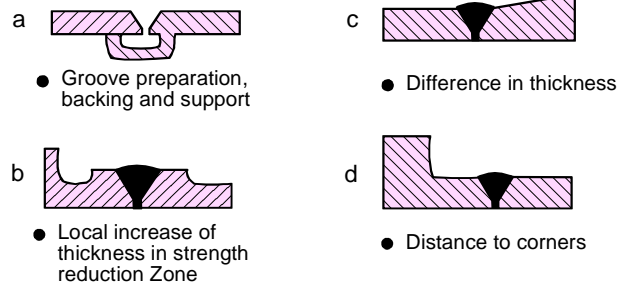
In aluminium structures sometimes special connections are used such as

- solid state welding
- joints with cast connection parts
- snap joints, rolled joints.

Examples of specifically aluminium welded joints are shown in [Figure 2302.01.03](#).

### Advantages of Welded Connection:

- Saving of work and material
- Absence of drilling and overlap
- Tight joints
- No crevice corrosion
- Joint Preparation in extruded sections, e.g.



Advantages of welded connections is saving of work and material, absence of drilling and overlap, tight joints and no projection of crevice corrosion. By the extrusion technique groove preparation and backing (**Figure 2302.01.03 a**), can be integrated in the profile, strength reduction in heat affected zones can be compensated by locally increasing the thickness (**Figure 2302.01.03 b**) and difference in thickness can be levelled out (**Figure 2302.01.03 c** and **Figure 2302.01.03 d**). Butt-welded joints are preferable in most cases. It gives a favourable state of stress in members in bending and tension. More about details of welded connections are given in section 2302.05.

### *Welding*

Welding is defined as the joining of materials by the use of heat and/or force, with or without a filler material. The welding of aluminium is widely established and has been developed into an important method of joining (see also **Figure 2302.01.04**). Inert gas shielded arc welding processes have considerably extended the possibilities for welding aluminium, and are even used in ordinary workshops.

The aluminium welding processes commonly used in workshop practice are the following:

- Gas welding (autogenous welding)
- Metallic arc welding
- Inert gas arc welding with a non-consumable tungsten electrode (TIG), or with a consumable metal electrode (MIG)
- Stud welding

## Welding

- Gas Welding
- Metal Arc Welding
- Inert Gas Arc Welding with non-consumable tungsten electrode, TIG
- Inert Gas Welding with consumable metal electrode, MIG
- Stud Welding
- Electric Resistance Welding
  - Spot Welding
  - Flush-Butt Welding
  - Seam Welding
  - Projection Welding
- Solid State Welding
  - Cold and Hot Pressure Welding
  - Explosion Welding
  - Ultrasonic Welding
  - High-Frequency Welding
  - Electron Beam Welding
  - Friction Welding



Welding

2302.01.04

The following welding processes are also common in industry: electric resistance welding (spot welding, flash-butt welding, seam welding and projection welding), cold and hot pressure welding, explosion welding, ultrasonic welding, high-frequency welding, electron beam welding, and friction welding. The choice between the different welding processes is decided by a number of criteria (**Figure 2302.01.05**).

	Inert Gas Shielded Arc Welding		Metal Arc Welding	Gas Welding
	MIG	TIG		
<b>Quality of the Welded Joint</b>				
Strength	1	4	2	4
Elongation	1	2	1	4
Chemical Stability	1	4	2	4
Weld Defects	2	4	1	4
Penetration	1	4	3	2
Distortion	1	4	2	2
<b>Suitability for Use</b>				
Welding Thin Sheet (s<1mm)	-	2	1	-
Sheet Welding (s>3mm)	1	4	2	3
Welding AlMg Alloys	1	4	1	-
Overhead Welding	1	-	2	-
Variable Material Thickness	2	4	1	3
Variable Welding Speed	4	2	1	3
Welding of Castings	2	-	1	-
Joining Cast to Wrought Alloys	1	-	2	-
Repair Welds on Castings	2	4	1	3
<b>Suitability for Automation</b>				
with Filler	1	-	2	-
without Filler	-	-	1	-
Butt Weldings s < 3mm	2	-	1	-
s > 3mm	1	-	2	-
<b>Suitability for Fillet Joints</b>				
	1	--	2	-
<b>Economic Aspects</b>				
Equipment Costs	4	1	3	2
Maintenance Costs	3	2	3	1
Labour Costs	1	3	2	4
Welder's Training Time	1	4	2	3

Scale of Values:  
1 = Best  
4 = Worst  
- = Not Practised



Welding Process Selection

2302.01.05

In **gas welding**, the relatively low concentration of heat, together with the good thermal conductivity of aluminium, result in the fact that welding can only be carried out slowly; considerable shrinkage occurs and the stresses resulting from this lead to distortion of the workpiece. The heat affected zone (HAZ) is very wide and work-hardened or age-hardened alloys are reduced to the soft condition within it. The removal of the flux is also difficult.

Though **metallic arc welding** with a flux-coated electrode allows a more rapid welding rate, marked porosity is observed in the weld seam, caused by "frozen-in" gas blowholes produced by the flux. The removal of flux residues is as troublesome as in the case of gas welding.

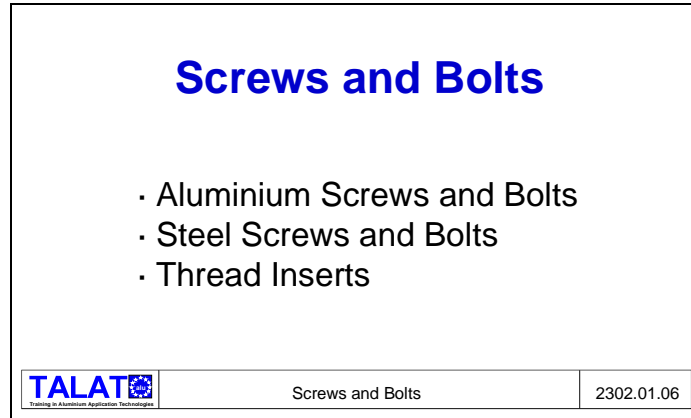
**Inert gas shielded arc welding** allows one to take advantage of the high heat concentration of the arc while avoiding the disadvantage of having to use a flux. The HAZ, in which the properties of the material deteriorate, is narrow in arc welding.

Unalloyed aluminium and most aluminium alloys are entirely suitable for welding. Increases in strength by work hardening or age hardening are partially or fully lost under the action of the welding heat. As with any type of welding, undesirable distortions of shape or weld cracks can arise. Assuming that the component to be welded has been correctly designed for this purpose, these risks can be met, but only by appropriate handling and welding procedures, the selection of a suitable filler material, and by a welding method suited to the job. In this connection, some of the properties of the material itself are significant for welding technology: its thermal expansion, tendency to shrinkage, modulus of elasticity, and its melting point.

The coefficient of the thermal expansion of aluminium is  $0.000024 \text{ mm/mm} \cdot ^\circ\text{C}$  (steel:  $0.00012 \text{ mm/mm} \cdot ^\circ\text{C}$ ). When an aluminium rod 1 m long is heated by  $1^\circ\text{C}$ , it expands by 0.024 mm; a temperature rise of  $100^\circ\text{C}$  increases its length by 2.40 mm. It should be borne in mind that if a workpiece is at  $100^\circ\text{C}$  its temperature rise compared to room temperature (about  $20^\circ\text{C}$ ) is only  $80^\circ\text{C}$ .

During welding and the subsequent cooling, these properties may result in changes in shape due to distortion, and produce stresses. However, the widespread use of welding with aluminium shows that their effect cannot be too grave a disadvantage, and this is because aluminium has a modulus of elasticity only about one-third that of steel. Hence, the material can absorb a large proportion of the stresses without damage, by elastic deformation. Unalloyed aluminium has a fixed melting point. In contrast, most aluminium alloys have a melting range. The tendency to form weld cracks is the greater, the wider the melting range of the material and the lower the content of alloying additions are. In such cases, selection of an appropriate filler can largely oppose the tendency towards crack formation. In this respect, the alloy AlSi5 behaves particularly well. This alloy is capable of filling heat cracks that appear during the solidification of the weld pool, because the silicon diffuses rapidly into the crack region and increases the fluidity of the molten metal. However, if the surface is subsequently to be decoratively treated by anodizing, the use of AlSi5 is excluded since this would give a dark colour. The introductory remarks presented above apply to all the fusion welding processes.

(Figure 2302.01.06)



**Aluminium Screws and Bolts:** Screw connections are commonly used with aluminium in machine and vehicle building, and also in the assembly of load-bearing structures, for forming joints that can be undone. Compared to welded joints they have the advantage that there is no softening of the material due to the influence of heat. High-strength alloys of the AlCuMg type (2024), and also the freecutting alloys and the AlZnMgCu type (7075) are not suitable for welding, and components made from these materials, especially those of greater thickness, are usually held together by screw joints.


Aluminium screws, bolts and nuts offer the advantage that changes in the tightness of the screw joints due to large differences in thermal expansion (as can occur when aluminium is joined with steel screws and bolts) are avoided. The screw material is chosen to match the material forming the components to be joined. **Figure 2302.01.07** gives a number of recommendations. Aluminium bolts with a rolled thread are always to be preferred. The mechanical connecting devices covered by EC9 are bolts, friction grip fasteners, solid and hollow rivets, but not screw. For this reason it is to be thought that screws are to be used for not relevant structural purposes. The minimum guaranteed values of the 0.2% proof strength  $f_{0.2}$  and the ultimate strength  $f_u$  for bolts and rivets are shown in **EC9-tab. 3.4** (see [appendix](#)). All bolts, rivets, washer and nuts must conform with existing ENs, prENs and ISO standards, a list of which is given in EC9 Section 1.3. The corrosion resistance and wear resistance of aluminium screws and bolts can be improved by anodic oxidation. Aluminium screws and bolts are available in many varieties, in standardized form as regards their strength properties and delivery conditions.

Aluminium woodscrews are made from the alloys AlCuMg (2024;L98), AlMgSi (6082;H30, age hardened), and AlMg5 (5056A;Nr6). Provided that the head slot is deep enough or the screws are of the cross-head type, with a smooth thread surface, and provided they are used in the correct way, they suffice for normal applications. Screws which are anodized to give the same colour as the components to be held together, for example in architectural applications, should be handled with particular care since if the head slots are damaged their colour will be affected. Apart from the general-purpose standard screws, nuts and bolts, there are many special varieties (many of them

patented) suitable for forming screw joints that are not highly loaded, are seldom or never undone (mainly in sheet metalwork), or for joining metals to non-metallic materials. In most cases the parts being joined or the fasteners themselves undergo some plastic or elastic deformation, and this also provides a degree of security against spontaneous loosening of the joint. Sheet metal screws (self-tapping screws) are also made from high-strength aluminium alloys.

Recommended Materials for Aluminium Screws and Bolts	
Component Material	Recommended Screw Material (+ Tensile Strength $R_m$ in N/mm <sup>2</sup> )
AlMg3 (5754)	AlMg5 (255)
AlMg2Mn0.8 (5154)	as above
AlMg5 (5056)	as above or AlMgSi1 (315)
AlMgSi1 (6063) Age-Hardened	AlMgSi1 (315)
AlMgSiPb (2011)	as above
AlCuMg (2017A), AlCuMgPb	AlCuMg (395 or 440)

	Recommended Materials for Aluminium Screws and Bolts	2302.01.07
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The following general points should be borne in mind when forming screw-type joints:

- Excessively high pressure on the surface of the aluminium when the fastener is tightened can be avoided by fitting hard aluminium washers under the head of the bolt or screw, and the nut (the outer diameter of the washers should be three times the thread diameter). This also spreads the loading more favourably.
- Serrated washers and spring washers made of steel should not be used as means of locking the screws in aluminium structures. Loosening of the screws can be prevented by applying an adhesive to the screws and washers before tightening.
- When bolts are loosened and done up again frequently, the thread in the aluminium component or on the bolt itself can quickly become worn. In such cases it is recommended to use screw inserts (see below), or anodized screws dipped in a molten mixture of wax and paraffin at 130 °C.
- For joints exposed to moisture the aluminium screw fasteners should be sealed with a sealing compound.

**Female Threads in Aluminium Components:** Recent investigations have shown that when the threads in components made of wrought aluminium alloys have been cut or grooved cleanly, the bolts can be undone and tightened up again many times without damaging the thread. The nominal values of minimum screw depth for withstanding a breaking load equivalent to that of steel bolts are as follows:

with AlMg3 (5754),                      hard drawn                      2.5 d

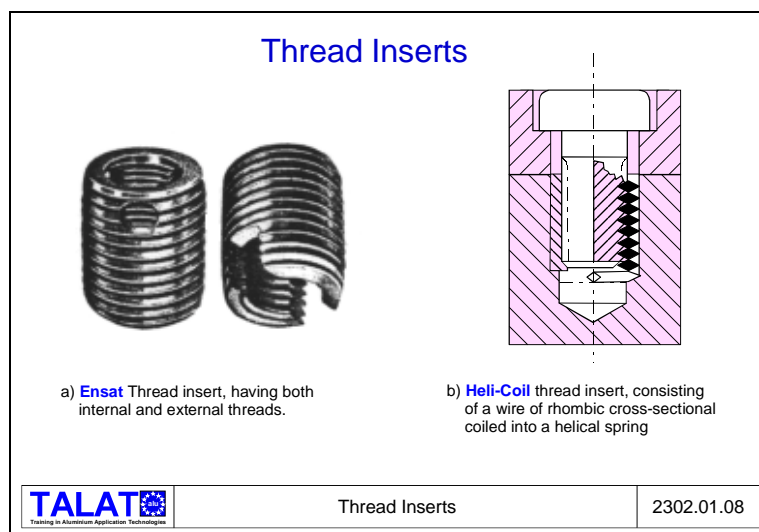
with AlMg4.5Mn (5083;N8)	hard drawn	2.0 d
with AlMgSi1 (6082;H15)	age-hardened	1.5 d
with AlCuMg (2024;L98),	naturally aged	1.5 d
with AlZnMgCu (7075;2L88),	artificially aged	1.0 d

(d = nominal thread diameter)

**Steel Screws and Bolts:** Steel screws and bolts used in aluminium structures exposed to weathering or other corrosive environments must be protected against corrosion (for example be galvanized). However, it is becoming increasingly common to use screws made of stainless austenitic chromium-nickel steels (covered by the BS Aerospace A series). To avoid excessive surface pressure, steel through-bolts are also fitted, under both the head and the nut, with galvanized or cadmium-plated washers of diameter three times that of the thread diameter, so that the load will be more evenly distributed. Before fitting, steel screws and bolts should always be coated with a suitable sealing compound which will prevent the access of moisture to the fastener and thus prevent the formation of a bimetallic couple.

- Aluminium structures should only be held together with steel screws when these will not rust under the prevailing service conditions.

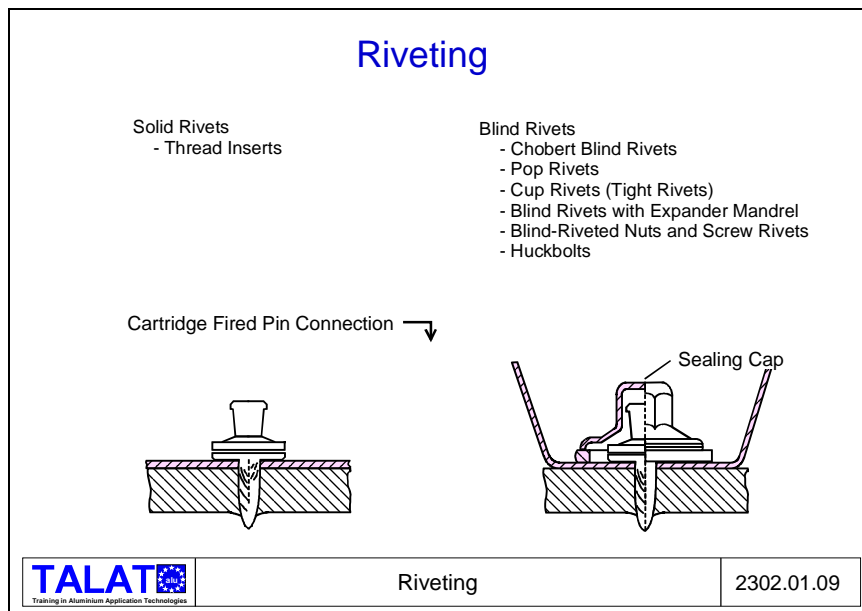
**Thread Inserts:** Thread inserts serve to increase the pull-out force of female threads in materials of low shear stress. The load-bearing capacity of a joint formed between a bolt and a machined thread depends not only on the strength of the material but also on the form of the thread and the area of the mating surfaces. Thread inserts increase the load-bearing capacity of screw joints, and have significant applications in connection with unalloyed aluminium and aluminium castings. Thread inserts are available in two forms: **Ensart** inserts and **Heli-coil** inserts (**Figure 2302.01.08**).



## Riveting

(Figure 2302.01.09)

**Riveting with Solid Rivets:** Aluminium rivets are driven while cold. However, cold-driven rivets transfer the load in a different way from hot-driven rivets. Steel rivets, which are driven hot, shrink on cooling and press the riveted sheets tightly together. The load transfer takes place mainly due to the frictional force between the tightly mating sheet surfaces and the rivet itself is thus mainly under a tensile load. Cold-driven aluminium rivets are not under tensile stress since there is no shrinkage. Thus, the friction between the sheets riveted together is not sufficiently great to assume the load transfer. This means that the rivet is subjected to shear stress, and the sheet to radial hole-expanding forces. For this reason, riveted joints in aluminium must be made even more carefully than those in steel.



The head cups and riveting dies chosen for driving aluminium rivets differ somewhat from those familiar from working with steel. The head cup must be heavier than is usual with steel rivets, to cater for the greater springback of aluminium. The cup must fit closely over the rivet head (Figure 2302.01.10).

**Rivet Materials and Types of Rivet:** Basically, the same material should be used for the rivet and for the parts to be held together. However, exceptions to this rule are possible. Rivets made of the heavy non-ferrous metals should not be used. In the relevant standards (e.g. BS 641; see also the BS SP series) the following materials are specified:

- |    |                              |    |                       |
|----|------------------------------|----|-----------------------|
| a) | non heat-treatable materials | b) | heat-treatable alloys |
|    | Al99.9 (1080A;S1a)           |    | AlMgSi1 (6082;H30)    |

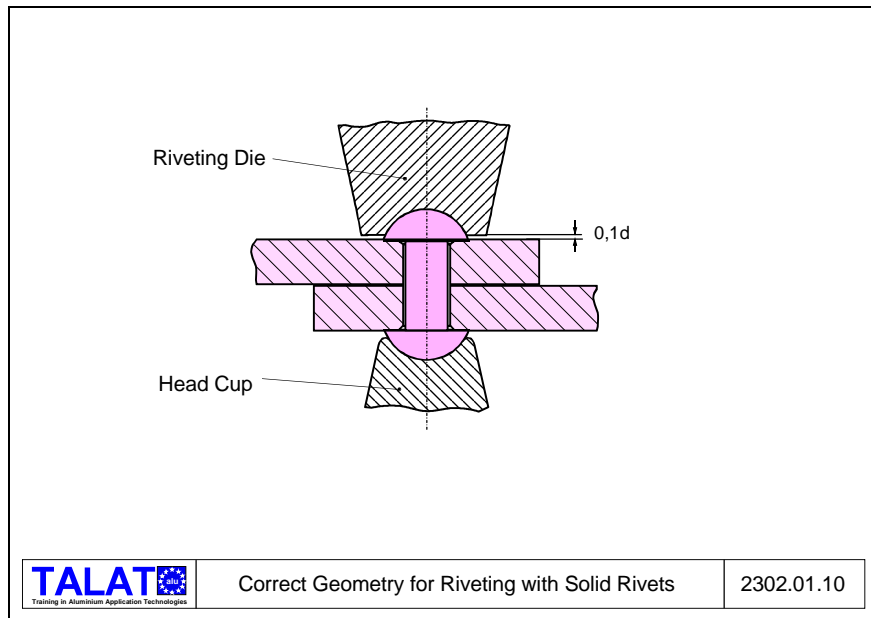
Al99.5 (1050A;S1B)  
 AlMg3 (5754)  
 AlMg5 (5056A;NR6)

AlCuMg0.5 (2117)  
 AlCuMg1 (2017A)  
 AlCuMg2 (2024;L98)

Like steel rivets, aluminium rivets are denoted and standardized according to their head shapes:

Half-round rivets	1 - 9 mm diameter, or 10 - 36 mm diameter
Flat-head rivets	3 - 8 mm diameter
Mushroom head rivets	1.7 - 8 mm diameter
Countersunk head rivets	1 - 9 mm diameter, or 10 - 36 mm diameter

In EC9 materials for rivets are listed in **tab. 3.4** (see **appendix**).



### *Solid State Welding*

Solid state welding (SSW) refers to a group of welding processes that are so classed because coalescence is achieved without melting either the base metals or any filler metals added to facilitate coalescence. All the processes in this group require intimate contact between the mating joint surfaces to produce a weld. Each has a means to remove or disperse the aluminium oxide films and to prevent their reformation during welding. While none of the processes are general purpose methods, each has advantages which make it superior for certain joining applications.

The following procedures are briefly described

- Explosion welding
- Ultrasonic welding
- Diffusion welding
- Pressure welding
- Cold welding
- Hot pressure welding
- Friction welding

The **explosion welding process (EXW)** uses a controlled detonation to cause the components of a joint to move together at very high speed, and to produce coalescence upon impact. It is the unique ability of the metal deformation from an explosion shock wave to remove the oxide from the mating surfaces that makes this process viable. It can be applied to making lap joints in a wide range of metals and is especially effective on aluminium and aluminium alloys.

Explosion welding can be used to join a range of metals. One of its more important applications is in joining aluminium to other metals, such as copper, steel, stainless steel and others, to make bimetallic products. These are used for transition pieces in chemical plants, for attaching aluminium deck houses to steel decks on ships and for joining aluminium to steel and to copper in electrical bus systems. In almost all cases, the joining of aluminium to other metals is done in large plates, by specialist companies, and the resulting bimetallic material is cut to size for the sale to users.

**Ultrasonic welding (USW)** is a solid state welding process which produces coalescence by pressing the workpieces together and applying high-frequency vibratory energy to disperse the interface oxide films and allow a metallurgical bond to form. Frequencies are normally in the range of 15 to 20 KHz. Ultrasonic welding is a true solid state welding process in that the heat generated by the vibratory energy is minimal and not sufficient to cause even localized melting.

Ultrasonic welding systems are available in a range of power ratings from 25 watts to 8 kilowatts. They can be used to make five types of weld arrangements: spot welds, ring welds, line welds, area welds and seam welds. The most common application is for spot welds, but the others fill special needs. Ring welds are often used to seal containers. Line and area welds are used to make connections to mesh and other similar materials. Seam welding is important for joining coil to coil in the manufacture of aluminium foil.

Aluminium can also be welded to a wide range of other metals. Many of the combinations are very difficult, or even impossible, to weld by other methods. Copper is easily welded by this process and is the most common metal to be welded ultrasonically to aluminium. Joints between these two metals find important applications in such products as solid state ignition systems, automotive starters and small electric motors.

The principal advantages for ultrasonic welding as a joining method for aluminium are:

- It generally requires less surface preparation than other methods
- No melting of the metal is necessary

- Surface deformation is minimal
- Once set to procedure, the process is controlled automatically
- Weld times are very short, generally less than a second
- Joint strengths approach parent metal strengths
- It is easily be adapted to automation

In general, the same joint designs used for resistance welding can also be applied to ultrasonic welding. However, unlike resistance welding, such factors as edge distance, spot spacing and thickness ratio of component parts, are not critical with ultrasonic welding. Welds can be positioned close to each other or close to an edge. They may be overlapping to produce a seam or area weld without affecting metal properties. Less allowance need be made for overall deformation of the weld area than for other solid state methods. Typical ultrasonic spot weld strength in aluminium and aluminium alloys are given in the table below ([Figure 2302.01.11](#)).

Aluminium Alloy	Steel Thickness mm	Strength of Spot Welds *)	
		N	±ΔN
1100-H14	0.8	1557	±0
	1.0	2090	±0
	1.3	2535	±133
	1.6	3025	±133
	0.8	3469	±222
2014-T6	1.0	3914	±267
	1.3	4626	±178
	1.6	5827	±534
2024-T3 (Bare)	0.8	4537	±178
	1.0	5338	±222
	1.3	5782	±222
	1.6	6116	±222
2024-T3 (Alclad)	0.8	5160	±222
	1.0	5338	±222
	1.3	7784	±534
	1.6	8229	±934
	1.8	8851	±756
	2.3	9252	±845
5086-H34	1.0	3425	±178
6061-T6	0.8	3870	±44
7075-T6 (Alclad)	1.3	6850	±400

\* 90% confidence interval; 90% of all welds made will be in this range

<b>TALAT</b> Training in Aluminium Application Technologies	Typical Strength of Ultrasonic Spot Welds in Aluminium	2302.01.11
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**Diffusion welding (DFW)** is a solid state process where pressure, heat and time are used to cause atomic diffusion to take place across the joint interface and produce coalescence. The welding operation is usually performed in a vacuum or in inert gas.

Under correct conditions, diffusion occurs at temperatures well below the melting points of the component members. Temperatures for aluminium are usually in the range of 850-1000 °F (454-538 °C). Pressures may be as high as the tensile yield strengths of the alloy. Only local surface deformation is necessary to ensure the required intimacy between the member faces. Aluminium may be welded in as little as one minute but somewhat longer times are needed to weld it to other metals. The resultant weld may be as strong as the weaker of the two metals.

Diffusion welding requires that the mating surfaces be flat, smooth and clean. Also the oxide film on aluminium must be reduced to a minimum why welding is sometimes done in a vacuum to inhibit oxide film growth and to improve diffusibility.

The principal application for diffusion welding of aluminium has been to join dissimilar alloys and to join aluminium to other metals without fusion. The process does not lend itself easily to high production, and thus has been mainly limited to special applications where the cost is justified by the very high weld quality and integrity possible with this process.

Aluminium has been diffusion welded to other metals such as copper, zirconium, uranium, nickel and stainless steel.

**Pressure welding** is a term applied to solid state processes in which pressure is applied to the joint to cause localized plastic flow to fracture and disperse the oxide films and other contaminants; this permits intimate contact between clean metal surfaces and results in coalescence. When it is accomplished at room temperature, it is termed **cold welding**, and when at an elevated temperature, **hot pressure welding**.

**Cold welding (CW)** is a solid state welding process in which coalescence is produced by the deformation caused by external mechanical force at room temperature. It makes welds which may be as strong as, but less ductile than the base metal. In the case of lap welds, a reduction of thickness also results. Diffusion is minimized and there is no melting to produce cast structures or heat-affected zones. Cold welds have excellent corrosion resistance. They permit the welding of aluminium to other metals such as copper and steel.

Cold welding can be used with butt or lap joints. Butt welds can be made in most aluminium alloys. The metal surfaces must be clean and not heavily oxidized, but no wire brushing is necessary for butt welding.

**Butt welds** are usually stronger than the base metal, i.e. they have 100% joint efficiency, due to the work hardening the metal undergoes. Because there is no severe notch, as there is in lap welds, they are excellent for tension, bending and cyclic loadings. Butt welds can be made in wire, rod, tubing and simple extruded shapes. Commercial equipment is available for welding wire and rod from sizes as small as 0.4 mm up to 9.5 mm diameter.

**Lap welds** have been made in thicknesses from foil gauges 6 mm plate. The metal must be clean and not heavily oxidized. Lap welds have good strength in shear and tension but low strength in bending. They have poor fatigue strength because of the severe notch represented by the weld.

**Hot pressure welding (HPW)** is a solid state welding process in which coalescence is produced by the application of external mechanical force at elevated temperatures. The use of heat reduces the pressure required to initiate plastic flow, especially with the harder aluminium alloys and tempers. It also can reduce the pretreatment requirements.

Heat must be confined to a thin layer on each mating surface, otherwise the drop in base metal yield strength reduces the interface pressure to the point where it is no longer high enough to produce coalescence. Aluminium's high coefficient of thermal conductivity means that very rapid and localized heating is necessary if its effect is to be limited to

the mating surfaces. The process must control both peak temperature, and time at temperature, very precisely if it is to be viable.

High-frequency resistance welding is a form of hot pressure welding which uses the resistance to flow of electrical current in the joint faces to generate the necessary heat. The high-frequency current limits the heating effect to shallow depths on the joint faces. The process is widely used for making tubular products.

**Friction welding (FRW)** is a hot pressure welding process where the heat is generated by the friction of the component parts moving relative to each other, under applied pressure. This process requires enough heat and pressure to cause the contacting surfaces to flow plastically to remove the oxide films and other contaminants from the joint. When this has been accomplished, the relative motion of the component parts is suddenly stopped, and a weld is formed. The operation is performed in air and no inert gas shielding is necessary. The process is very adaptable to repetitive joining and can be automated if production quantities justify.

Two types of friction welding are available. The first type directly controls relative speed, pressure and time and is called friction welding. The other is a stored energy process called inertia welding. In the latter the rotating member is connected to a flywheel, raised to a specified speed, brought into contact with the other member under pressure and the stored energy allowed to make the weld. Both of these processes have had proponents but with the continuing development of new applications for this type of welding, and the need for more precise control of weld parameters, friction welding appears to be gaining in acceptance over inertia welding.

Friction welding is used to join cylindrical products of either equal or unequal cross sections. Cylindrical parts can be welded to other shapes. Tubular joints, as for automotive drive shaft components, are commonly welded. Pipe has been joined by rotation a collar between the pipe ends so that two welds are made simultaneously to make one pipe joint. Friction welding requires specialized machinery and controls to ensure that welding parameters are precisely controlled. This machinery is usually designed for a specific application and can be quite costly. Friction welding has a number of advantages over other methods: no special preparation of the mating surfaces is necessary, the process is a natural for repetitive welding and can be automated without affecting the welding operation and aluminium can be welded to itself and also to a number of other metals.

### *Special Mechanical Joints*

#### **Profile to Profile Joints**

It is often an advantage to design products with large cross sections, such as component boxes, panels etc., as built up of smaller profiles. This results in thinner parts, smaller tolerances and lower die costs. In some cases, it is easier to work small profiles than a complete structure (**Figure 2302.01.12**).

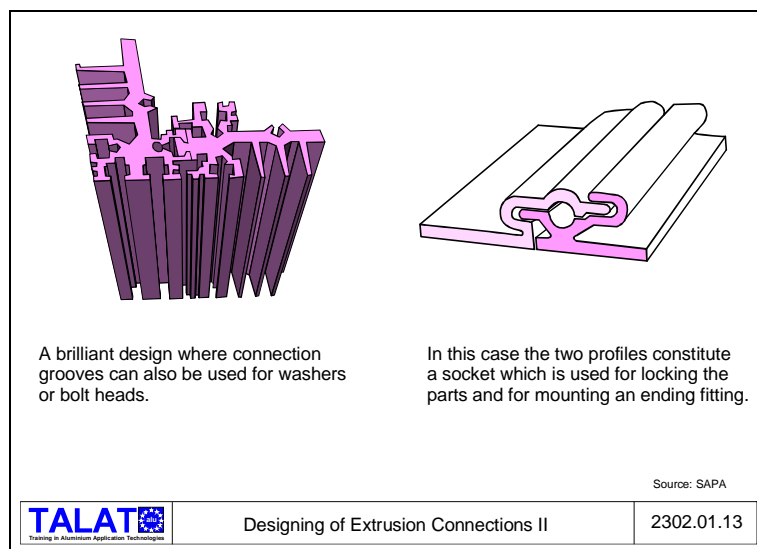
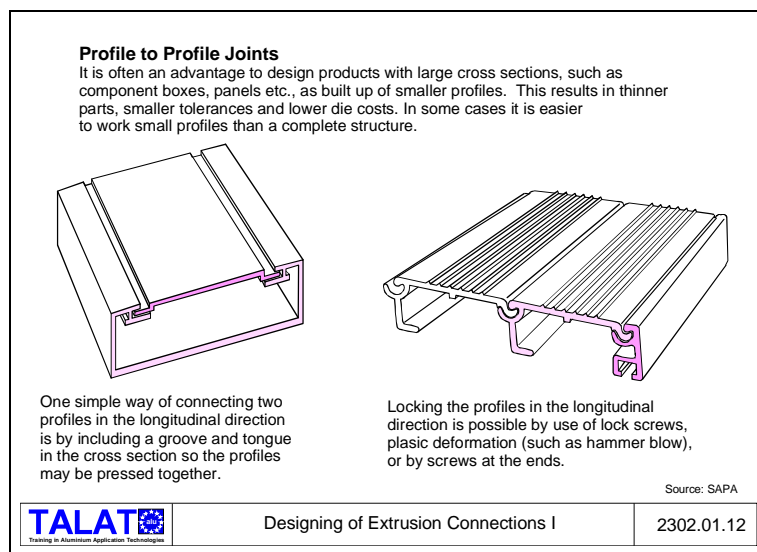
One simple way of connecting two profiles in the longitudinal direction is by including a groove and tongue in the cross section so the profiles may be pressed together.

Locking the profiles in the longitudinal direction is possible by use of lock screws, plastic deformation (such as hammer blow), or by screws at the ends.

A brilliant design where connection grooves can also be used for washers or bolt heads (Figure 2302.01.13).

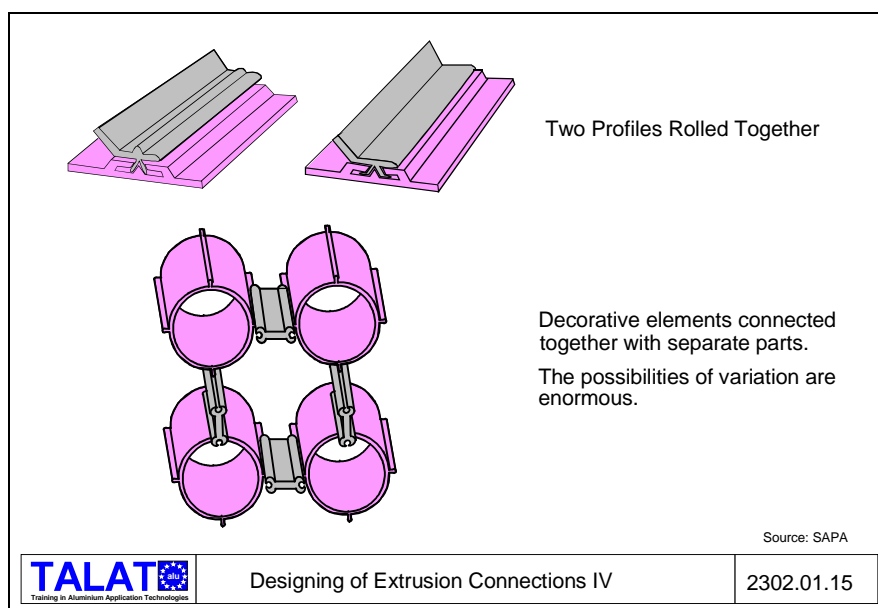
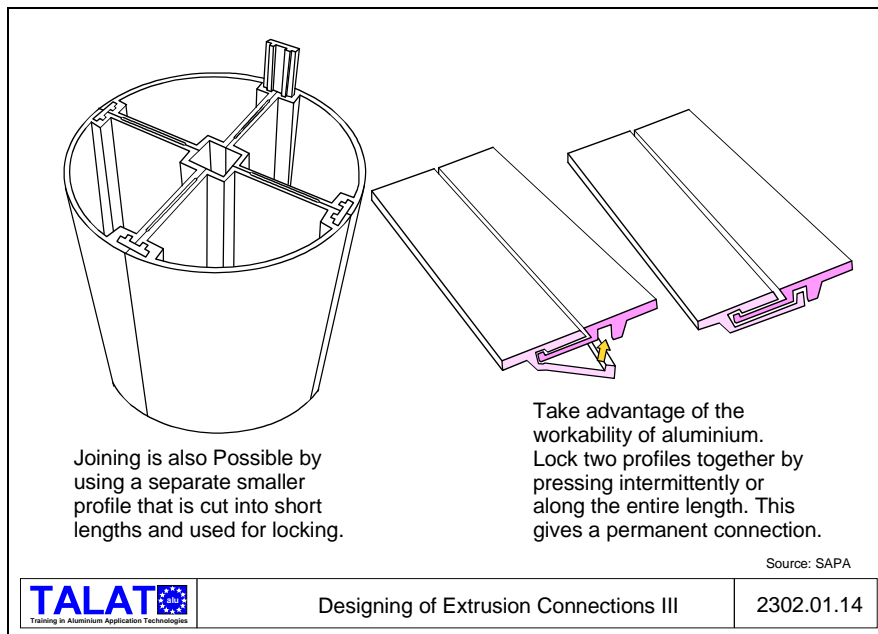
In this case (Figure 2302.01.13 b) the two profiles constitute a socket which is used for locking the parts and for mounting an ending fitting.

Joining is also possible by using a separate smaller profile that is cut into short lengths and used for locking (Figure 2302.01.14).



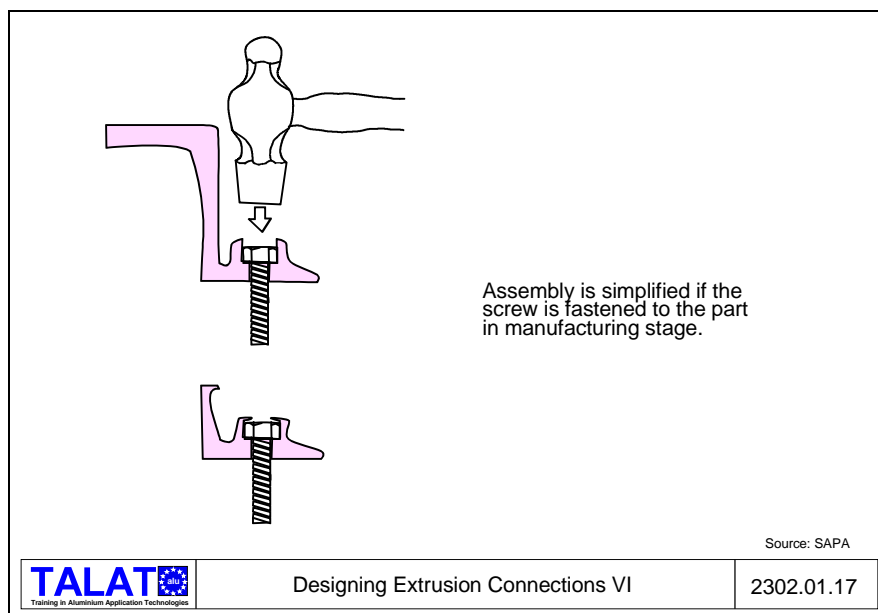
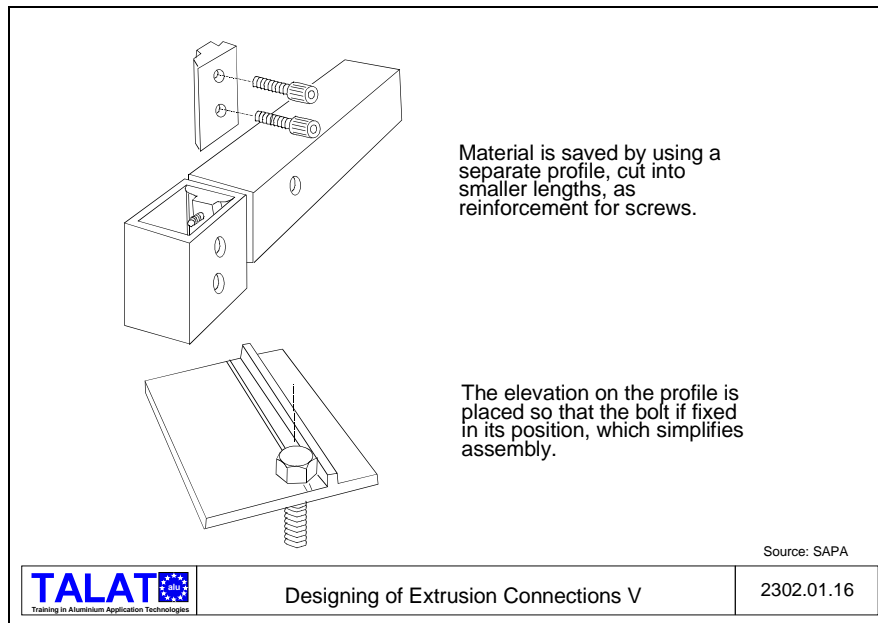
Take advantage of the workability of aluminium. Lock two profiles together by pressing intermittently or along the entire length. This gives a permanent connection.

Here two profiles are rolled together (**Figure 2302.01.15**). Decorative elements connected together with separate parts. The possibilities of variation are enormous.

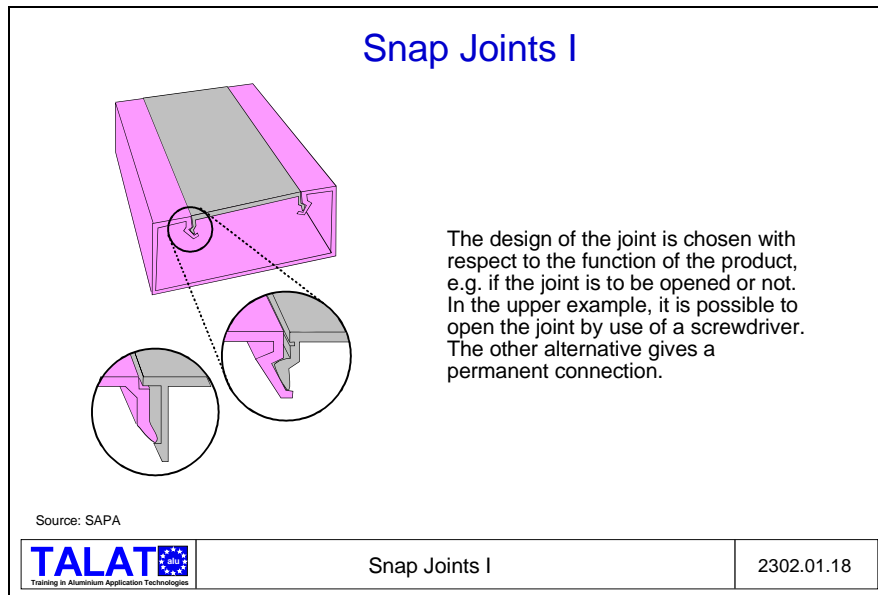


Material is saved by using a separate profile, cut into smaller lengths, as reinforcement for screws (Figure 2302.01.16). The elevation on the profile is placed so that the bolt is fixed in its position, which simplifies assembly.

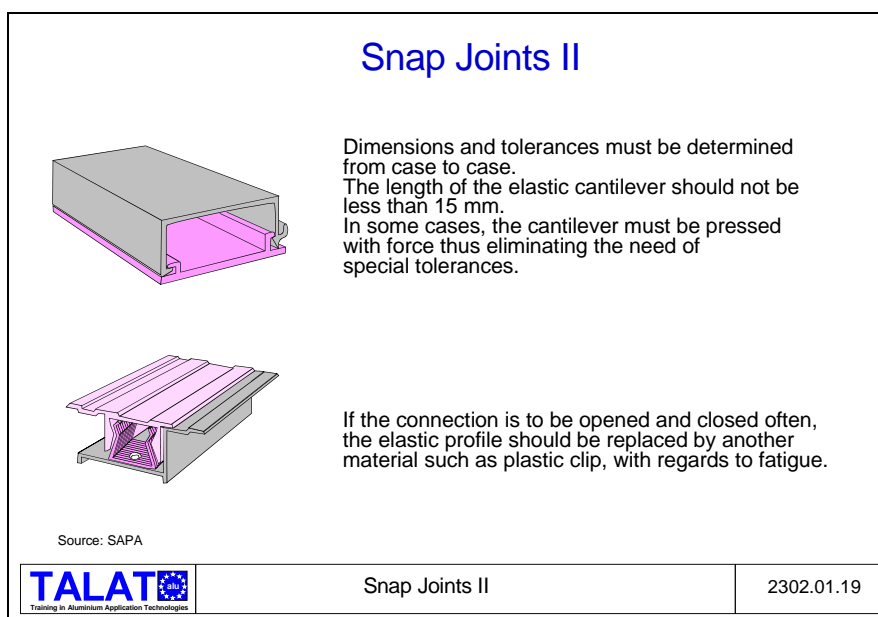
The assembly is simplified if the screw is fastened to the part in manufacturing stage (Figure 2302.01.17).



**Snap Joints:** The elasticity of aluminium and absence of attachments make snap joints much faster than welded or bolted joints. Snap joints are used in windows and side panels on trucks (**Figure 2302.01.18**). The design of the joint is chosen with respect to the function of the product; e.g. if the joint is to be opened or not. In the upper example, it is possible to open the joint by use of a screwdriver. The other alternative gives a permanent connection.

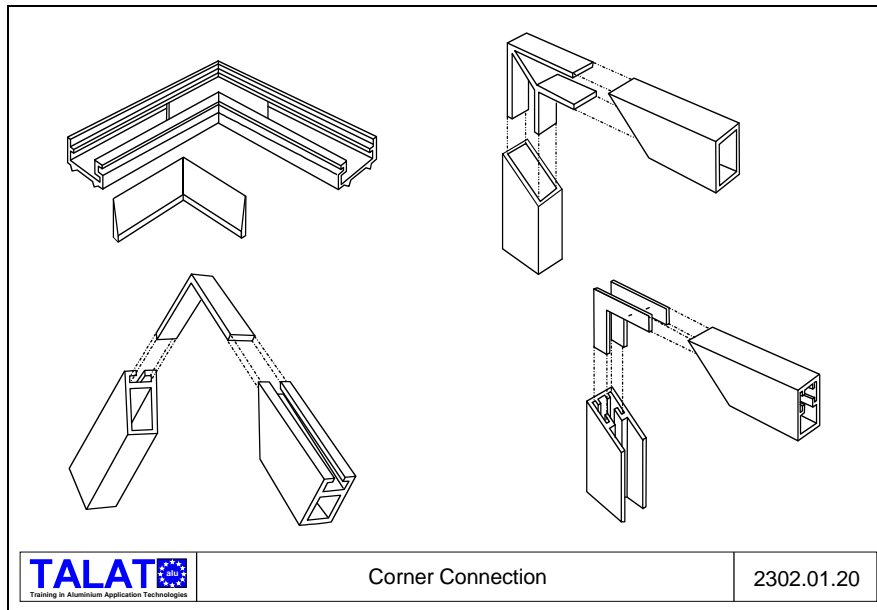


**Figure 2302.01.19** illustrates another type of joint that may be opened and closed. The outer groove gives support for a screwdriver.



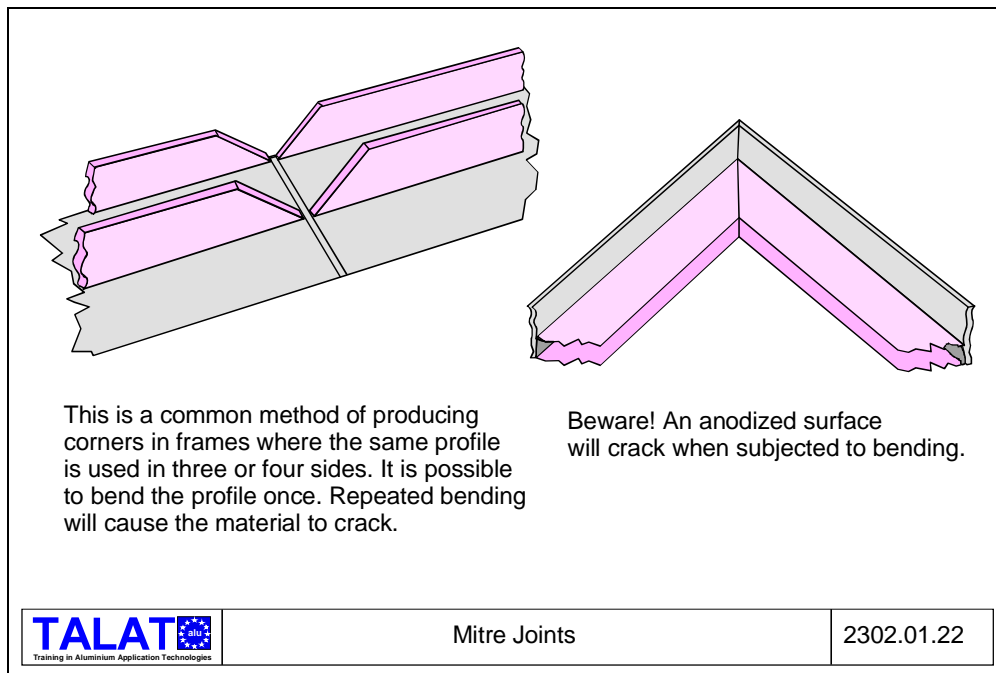
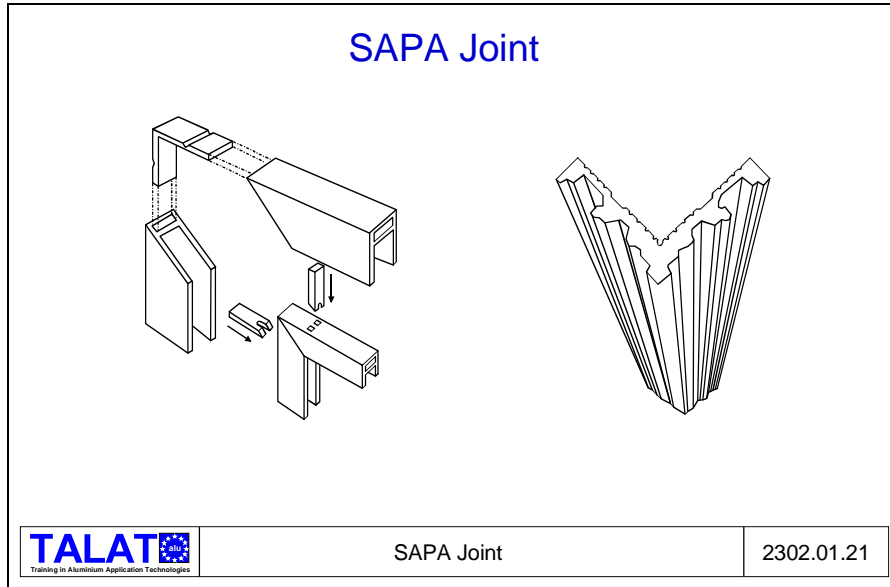
Dimensions and tolerances must be determined from case to case. The length of the elastic cantilever should not be less than 15 mm. In some cases, the cantilever must be pressed with force thus eliminating the need of special tolerances. If the connection is to be opened and closed often, the elastic profile should be replaced by another material such as a plastic clip with regards to fatigue.

**Corner Connections:** Corner blocks are used in corner joints that demand strength and stiffness. The block itself, which can be cast, or as in most cases a profile cut into short lengths, is fastened by pressing or by screws into both profiles ([Figure 2302.01.20](#)).



In frames and other light structures, the corner blocks consist of a pressed steel angle. The **SAPA Joint** ([Figure 2302.01.21](#)) is an example of a corner joint. The width of the joint profile can be cut to fit a hollow section regardless of its width.

**Mitre Joints** ([Figure 2302.01.22](#)) are a common method of producing corners in frames where the same profile is used in three or four sides. It is possible to bend the profile once. Repeated bending will cause the material to crack. Beware! An anodized surface will crack when subjected to bending.



## **Joints in Thin-Walled Structures**

Special mechanical fasteners and welding procedures are often used in thin-walled structures and thin sheet structures. Examples of fasteners and procedures are

- Thread forming and self-drilling screws
- Blind rivets (rivets with mandrel)

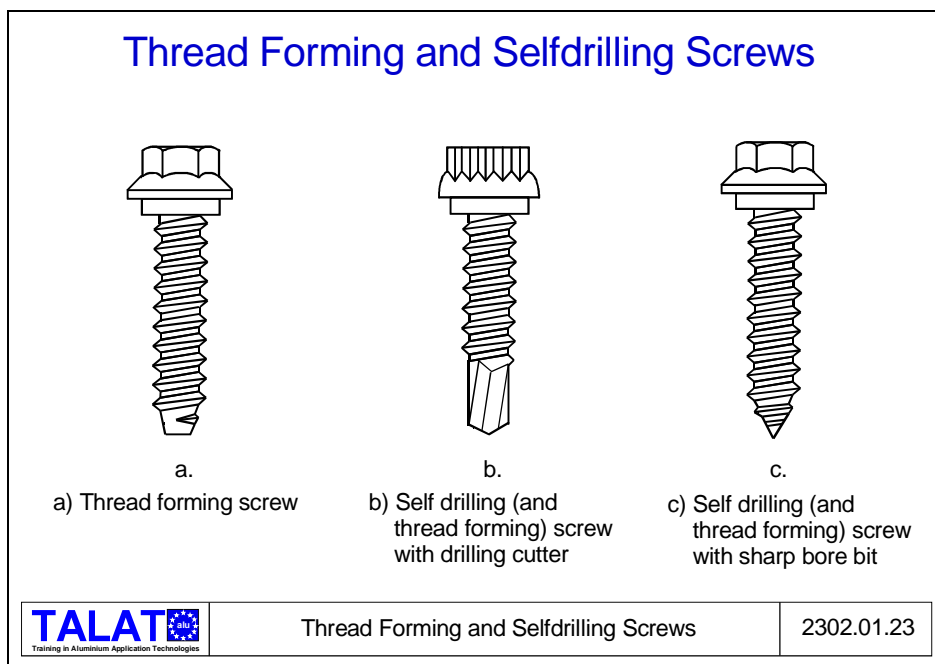
- Cartridge fired pin connections
- Resistance spot welding, MIG and TIG

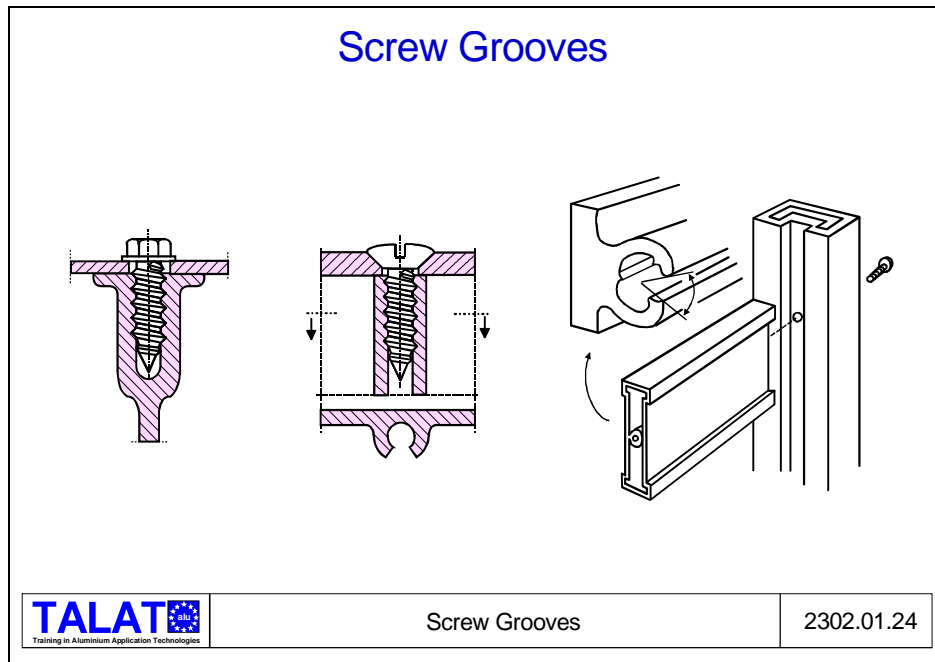
There is no distinct thickness limit defining thin- and thick-walled structures. E.g. bolts with nuts are used in thin-walled as well as in thick-walled structures.

### *Thread Forming Screws*

The most usual application of screws is the fastening of thin to thin material and thin to thick material.

Thread forming or thread cutting screws are installed in predrilled or punched holes (**Figure 2302.01.2**) or screw grooves (**Figure 2302.01.24**). Selfdrilling screws are provided with a drilling cutter or a sharp bore bit to drill the hole.

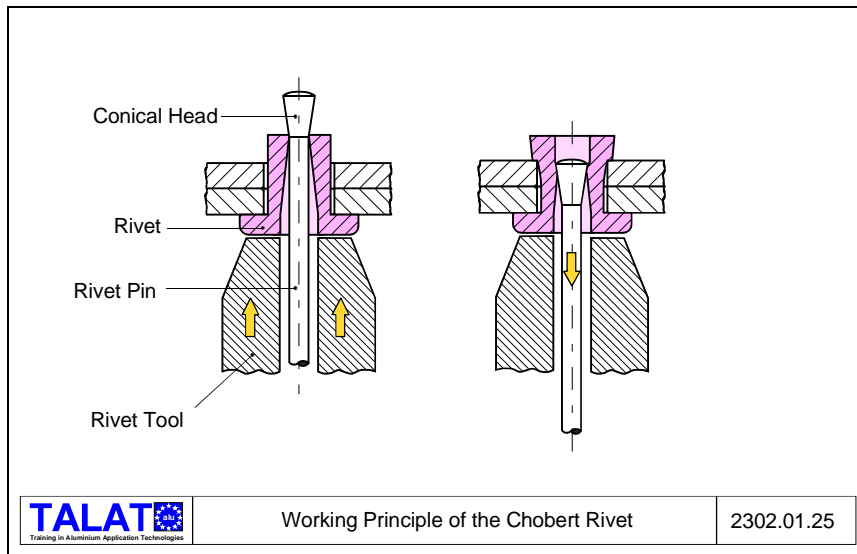




### *Blind Rivets*

When components have to be riveted together in situations where the rivet is not accessible from both sides (e.g. in hollow sections), blind riveting systems provide a solution to the problem. Using a suitable tool the rivets are inserted from one side and a closing head is formed. Blind rivets are always hollow, but may be provided with filler pins. The various systems available have proved themselves over a long time, and are nowadays often used for applications where solid rivets would formerly have been employed.

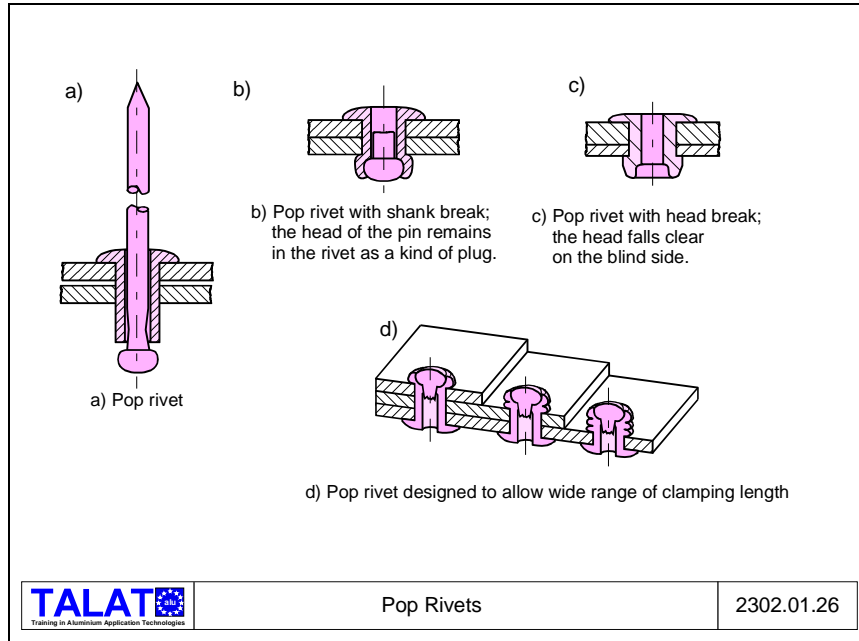
**Chobert Blind Rivet.** One type of hollow-shanked rivet, known as the Chobert rivet, is made from steel or aluminium alloys. [Figure 2302.01.25](#) shows a conical rivet hole tapering from die head side to the shank end. The closing head is formed by gathering up the material at the end of the rivet shank. In the riveting process itself, the projecting mouthpiece of the riveting tool presses the rivet firmly into its hole, while the riveting pin closes the rivet by moving back outwards through it; the conical head of the pin expands the shank end projecting beyond the sheet assembly into a bulbous closing head. As the riveting pin moves further back, the rivet is pressed tight against the hole walls along its entire contact length. The rivet is seated so tightly that it can be drilled out along its entire length, whereas a looser rivet frustrates this by beginning to rotate.



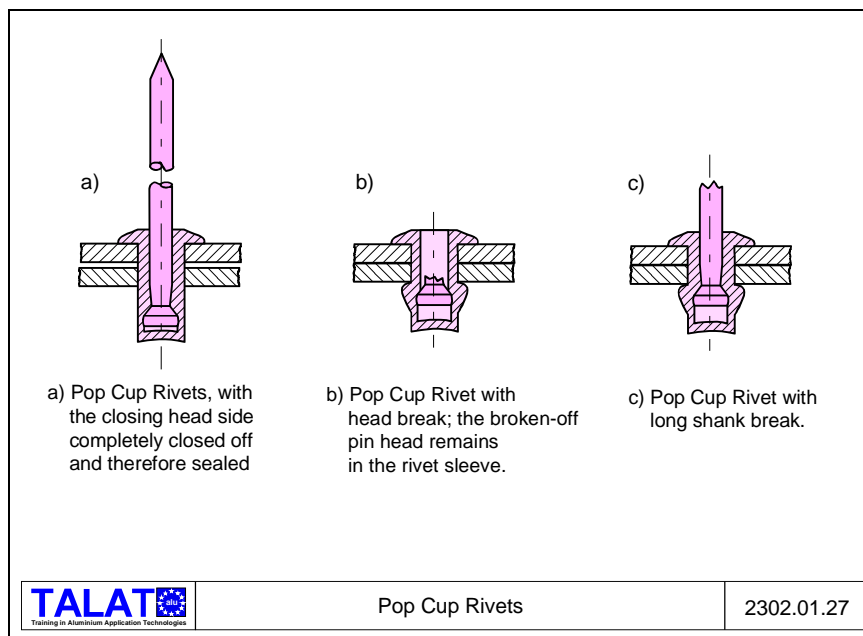
In sealed joints, or to increase the shear strength, the hollow shank can be closed by a filler pin. A rivet with its filler pin in place can be regarded as almost equivalent to a solid rivet; tests of the shear strength have shown values 85% of those for a driven solid rivet. In view of the design and mode of use of Chobert rivets, a riveting device has been produced that can be charged from a magazine. The aluminium rivets are made of AlMg5 (5056A;NR6); the filler pins, of AlCuMg (2017A), cadmium-plated steel, or plastics.

**Pop rivets** consist of a riveting pin and a rivet sleeve with a flat or countersunk head (Figure 2302.01.26). In the riveting process the tool first pulls the sheets tightly together and then forms the closing head. Finally, the pin breaks off at a predetermined point. In some types the pin breaks at a point within the rivet shank, and its head then remains as a sort of sealing plug.

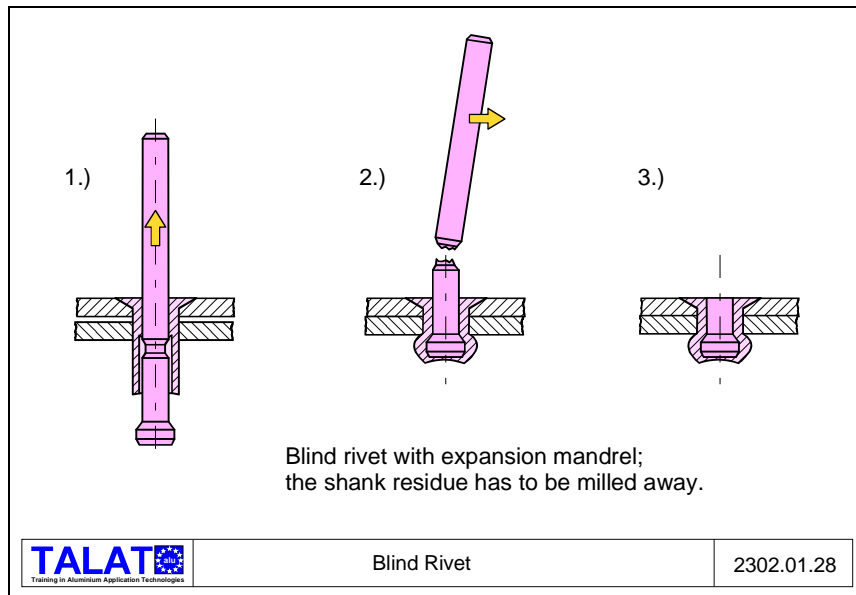
In other types the head breaks off and falls clear on the blind side (Figure 2302.01.26c). In this case, too, the hollow shank can be closed off by a metal or plastic filler pin, or by an aluminium cap. The version shown in Figure 2302.01.26 can clamp joints in a wide range of thicknesses, making it unnecessary to store rivets with a variety of different lengths.



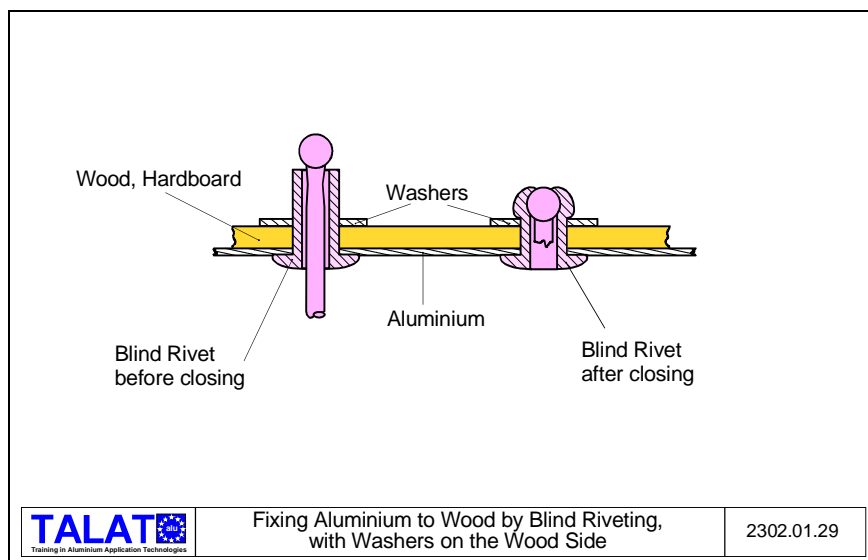
**Cup Rivets** are blind rivets and a variant of the pop rivet. The riveting procedure and the tool are just the same, but the closing head side of the rivet is completely closed (Figure 2302.01.27) and thus perfectly sealed. The broken off head of the pin remains in the rivet sleeve. Cup rivets are available in "head break" or in "shank break" versions.



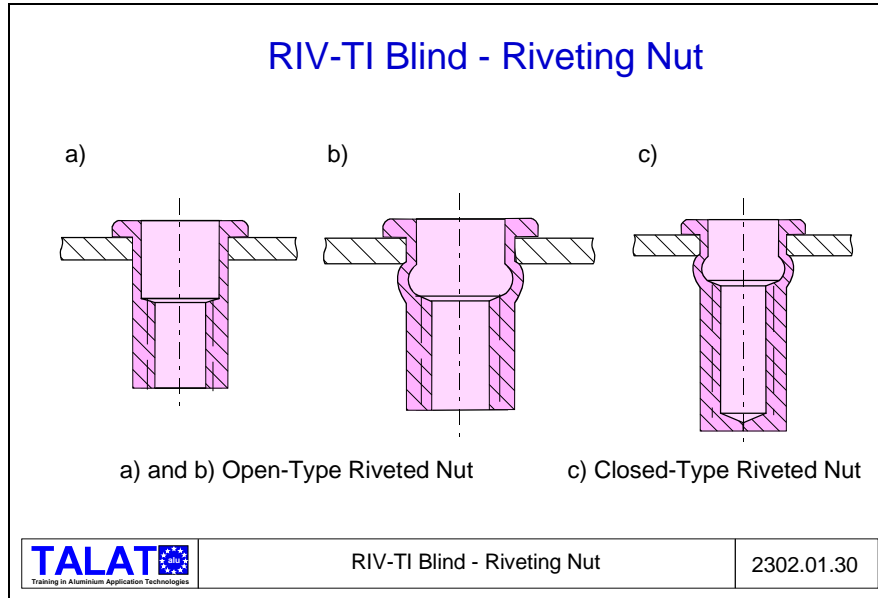
**Blind Rivets with Expander Mandrels**, see Figure 2302.01.28, which shows a type of rivet with a mandrel which, when pulled through, first expands the rivet sleeve and then forms the closing head. The fracture point of the mandrel is so chosen that the part left behind projects far out of the rivet sleeve, and must be milled flush to the surface.



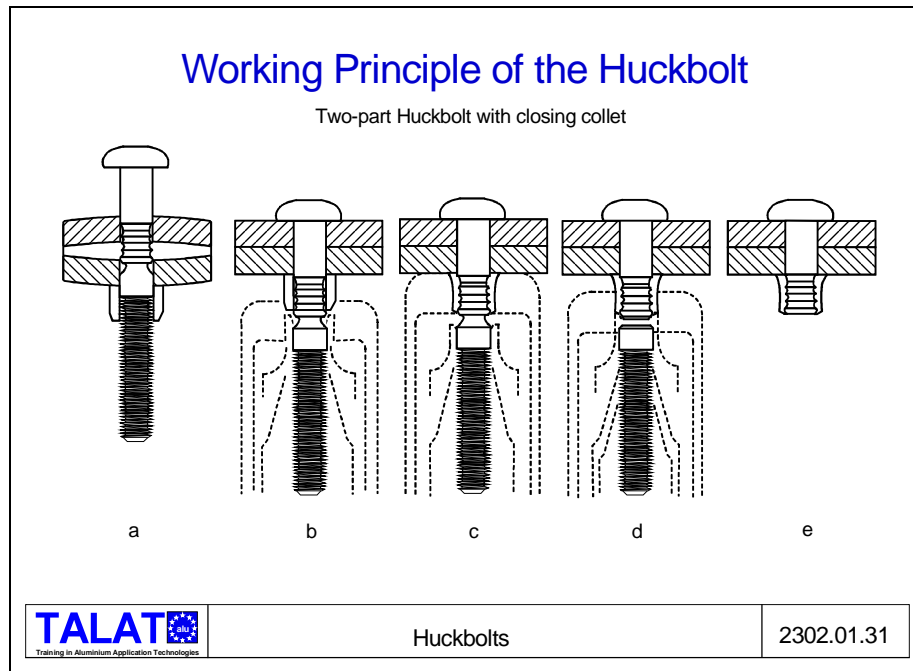
**Riveting of Aluminium Sheet to Soft Material.** In practice, soft materials (wood, cardboard, hardboard) are often clad with aluminium sheet. A rapid and durable joint can be formed by passing a washer of the corresponding size over the shank of the blind rivet and closing the rivet over this ([Figure 2302.01.29](#)).



**Blind-Riveted Nuts and Screw Rivets.** The catalogue of blind rivets will be completed by mentioning various blind-riveted nuts and screw rivets. The RIV-TI blind-riveted nuts and screw Happich riveted nut ([Figure 2302.01.30](#)) are inserted like ordinary blind rivets. There are two versions: the open type (Figure 2302.01.30 a and b) and the closed type (Figure 2302.01.30 c). Other products are the Champion blind-riveted nut, the Nutsert (a two-sided riveted nut), the Pressti hammer nut, and the Jo-Bolt screw rivet. Apart from these, a number of firms supply different types of driven fasteners.



**Huckbolts** are not blind rivets in the strict sense of the term, since the bolts are introduced from the rear, while the closing operation is performed on the working side. The particular advantage of this method is that the rivet bolt itself is not deformed. The bolts are made of steel or aluminium (AlMg5, 5056A;NR6). The joint can withstand very high shear and tensile stresses. Huckbolts are fasteners consisting of two parts (**Figure 2302.01.31**), the rivet bolt itself, with a mushroom or countersunk head, and a closing collet. The bolt has a smooth, cylindrical shank to withstand shear stresses. This is extended by a conical constriction to a shank section provided with ring grooves; this in turn ends in a deep annular groove beyond which the shank has a final portion, at first plainly cylindrical and then grooved so that it can be well gripped by the jaws of the riveting tool specially developed for this type of fitting.



The closing collet passes easily over the shank of the rivet bolt; it consists of a sleeve with a cylindrical internal bore, and is also cylindrical on the outside, except that the end facing the riveting tool is formed into a truncated cone.

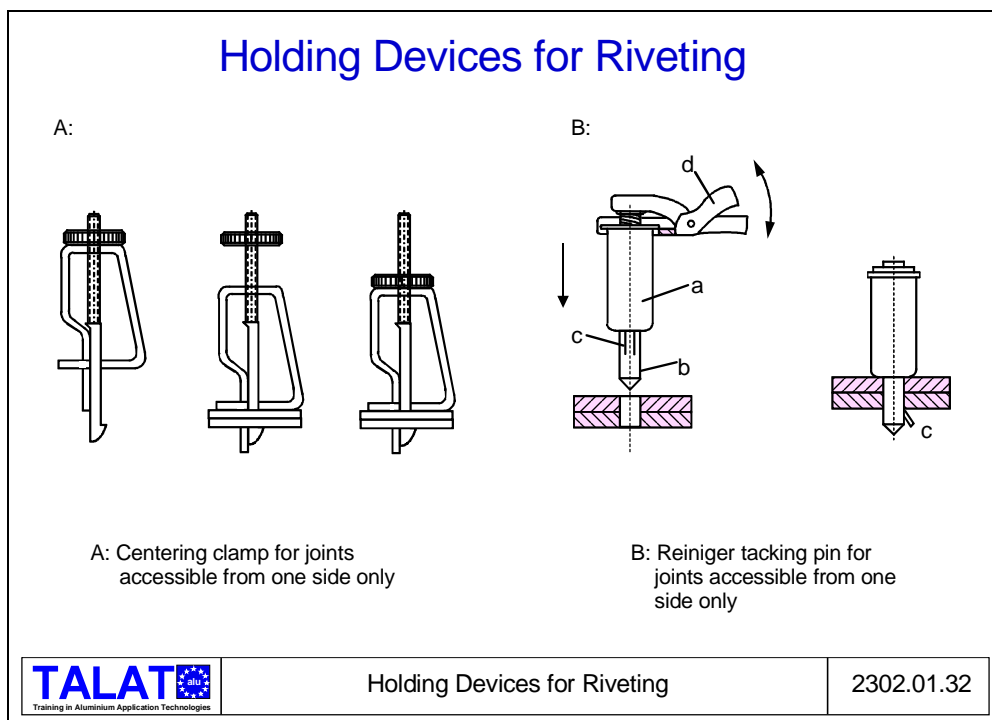
For riveting, the bolt is introduced into the prepared hole from the rear and the closing collet is slipped over the projecting end of the bolt shank (Figure 2302.01.31 b). The riveting tool, which is held like a pistol, is then pushed over the shank as far as the end-stop. When the pulling trigger is operated the jaws of the tool grip the shank and pull it backwards into the tool, bringing the mouth of the pistol hard up against the collet. The axial pull draws the parts to be joined tightly together, giving a tight sheet-to-sheet seal (Figure 2302.01.31 c). The mouthpiece then moves up over the collet and compresses it into the ring grooves of the bolt so that the bolt and collet now form a tightly closed unit (Figure 2302.01.31 d). Finally, the excess force breaks off the end piece of the bolt at the predetermined point (the deep groove) just outside the collet (Figure 2302.01.31 e).

The riveting process itself takes place fully automatically at a high rate (up to 1000 rivets per hour), and is almost noiseless. A further advantage is that the automation makes life easy for the operator, while every joint is uniformly accurate.

The special features of the huckbolt fastening method can be summarized as follows:

- Largely automatic working and simple operations that can be carried out by unskilled personnel.
- A high rate of riveting can be achieved.
- The process is not tiring, and is quiet.
- The closing heads are of constant and uniform circular shape and exert a constant clamping force.
- The joints have high shear, tensile and fatigue strengths.
- The joints are self-locking and unaffected by vibrations.
- The joints are gas-tight and fluid-tight.

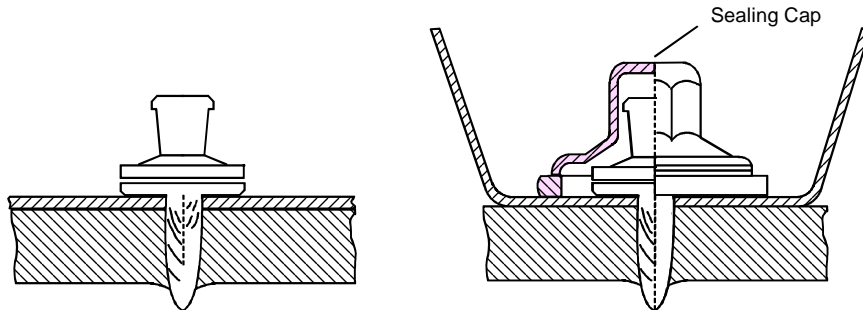
**Holding Devices for Riveting.** Riveted joints can be made more easily with the aid of suitable holding devices ([Figure 2302.01.32](#)). These can be obtained from the manufacturers of blind rivets. Moreover, there are other, virtually essential aids such as centering clamps, tacking pins or tacking screws. It should, however, be mentioned that such aids are mostly intended for use with lighter sheetwork (holes up to about 6 mm diameter). For heavier work the use of ordinary screws and bolts with washers is almost unavoidable. Other special holding devices are available for rational mass production in thin sheet-metalwork, bodywork and railway stock construction, and other related fields.



### *Cartridge Fired Pin Connections.*

Cartridge fired pins, see [Figure 2302.01.33](#), are normally used to fix aluminium sheeting to underlying members of steel. The pins are made of high strength steel why the risk of corrosion must be considered. The shear force of a cartridge fired pin connection is carried by friction and as the prestressing force is large the shear strength is high.

## Cartridge Fired Pin Connection

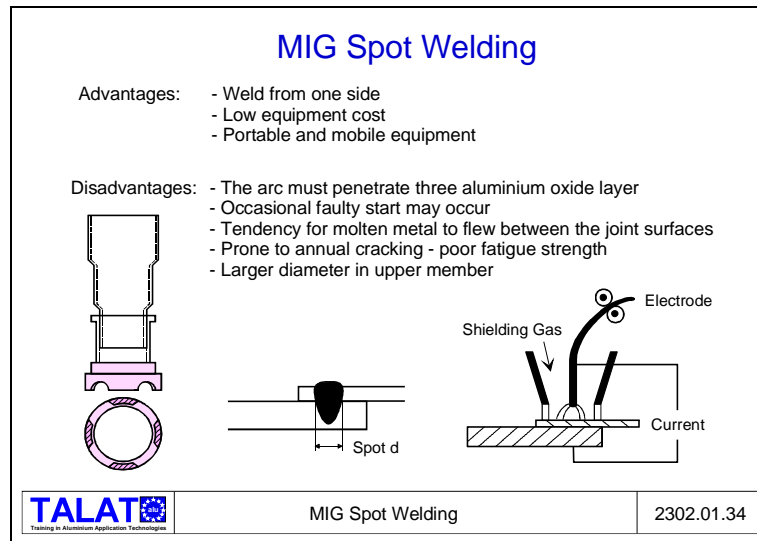


### *Spot Welding*

Two main groups of spot welding procedures are available:

- arc spot welding and
- resistance spot welding.

The main advantage of **arc spot welding** is the ability to weld from one side only of the joint, a very much lower equipment cost than for resistance spot welding, and the portability and mobility of a TIG or MIG gun. Of the two processes, MIG spot welding found the greatest application. Arc spot welding ([Figure 2302.01.34](#)) uses a timed arc. The gun is fitted with a special gas nozzle designed to allow the gun to be pressed against the upper member which acts to set the gun-to-work distance and helps to press the joint members tightly against each other. The nozzle is notched at its outer end to permit shielding gas to escape. The timer is usually a solid state device which "times in" when welding current begins and "times out" after a preselected interval.



**TIG spot welding** has not found much application on aluminium, because it is really only useful on very thin non heat-treatable alloys. The arc does not create enough turbulence in the pool to break up the oxide films at the joint interface. No filler is added and thus welds tend to be underfilled. Arc times have to be relatively long to ensure penetration; this makes larger welds than necessary and also affects the economics of the process.

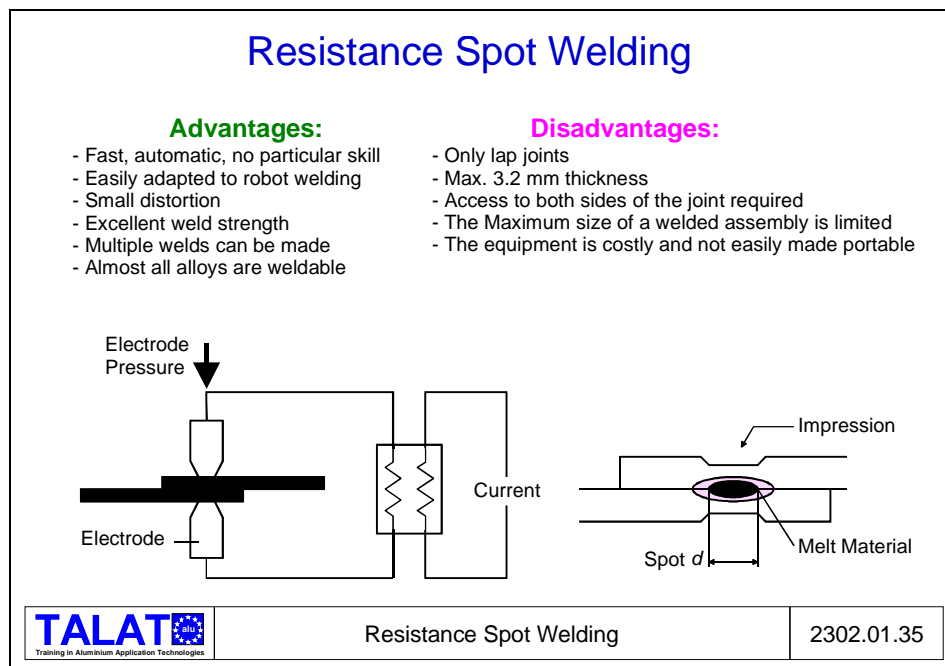
**MIG spot welding** was, for a time, quite widely applied, but it, too, proved to have shortcomings for aluminium and has been largely supplanted by other more reliable joining methods. The factors preventing greater success of MIG spot welding on aluminium are as follows:

- The arc must penetrate through three thicknesses of aluminium oxide in order to fuse the two members together. The MIG arc has adequate penetrating power to do this but in doing so, it is inclined to over penetrate the joint.
- The arc must initiate smoothly and consistently for each weld. Even with the best operating equipment an occasional faulty start will occur.
- If the gun pressure is not sufficient to bring the two members into intimate contact there is a tendency for molten metal to flow between the joint surfaces and a defective weld to result.
- The welds are very prone to annular cracking, usually in the base metal heat affected zones. This cracking contributes to poor fatigue strengths for MIG spot welds.
- The welds are much larger in diameter in the upper member than in the lower and as a result can cause distortion, especially if there are multiple welds in close spacing.

Reference should be made to an unusual application of MIG spot welding, i.e. for joining aluminium to other metals. By using a special joint configuration which leaves the weld in compression, the effect of the presence of brittle intermetallic compounds is

minimized. Welds have been made to copper, to aluminized steel and to titanium. The principal application for this technique is for electrical connections.

**Resistance spot welding (RSW)** is the general name for a group of processes which rely on the resistance of a metal to the flow of electrical current to produce the heat needed for coalescence. Both solid state and fusion welding processes are included in this grouping. Because of aluminium's high coefficient of electrical conductivity, current levels for welding aluminium must be much higher than for a low conductivity metal, like steel. Consequently, while aluminium can be welded by all the usual resistance welding methods, some special care is needed to achieve the desired results.



Resistance spot welding produces a local weld "spot" by clamping two (or sometimes more) thicknesses of metal between two electrodes for a brief interval, with the metal under pressure (**Figure 2302.01.35**). The heat required for coalescence is generated by the bulk electrical resistance of the metal and also by the interface resistance between metal thicknesses. It is a fusion welding process because melting must occur at the interface between the joint members to cause coalescence, form a cast nugget and join the members together.

Resistance spot welding is a high production joining method for fabricating sheet structures ranging from aircraft to cooking utensils. In addition to welding wrought metal, it may also be used for joints to permanent mold castings and sand castings. It has a number of advantages over other methods:

- Welds are usually completed in a fraction of a second and weld-to-weld times are often less than one second.
- The process is automatic and requires no particular skills.
- It is easily adapted to robotic welding.

- Distortion is minimal and weld appearance is consistent.
- Weld strengths are excellent.
- Multiple welds can be made in a joint to give the desired strength.
- Almost all alloys are weldable.

It also has some disadvantages:

- It is limited to lap joints.
- It is limited to about 3.2 mm maximum thickness.
- It requires access to both sides of the joint.
- The maximum size of a welded assembly is not unlimited.
- The equipment is costly.
- The process is not easily made portable.

Aluminium is somewhat more difficult to resistance weld than other metals, like steel. This means that the performance of the welding machine, the welding schedule and the metal preparation are more demanding than for other metals. However, once these differences are understood and taken into account, excellent welds can be made. The four main characteristics of aluminium which cause these differences are:

Aluminium has a high electrical and thermal conductivity. The high electrical conductivity (or the corresponding low resistivity) mean that higher currents are needed to produce the same amount of heat. The high thermal conductivity means that welds must be made very quickly, before the heat can diffuse into the surrounding metal.

- The natural oxide film on aluminium acts as a high and quite variable electrical resistance. For best welding it is necessary to prepare the surfaces of aluminium to produce a uniform and consistent surface resistance.
- Aluminium is quite soft, with a very narrow plastic range, at welding temperatures. Thus the welding process must be able to complete the weld without overheating the metal to the point where excessive deformation occurs.
- Aluminium more readily alloys to the copper electrodes than steel does. This causes greater electrode tip pickup and a consequent change in welding conditions.

Aluminium thicknesses from foil gauges up to about 3.2 mm are considered most suitable for resistance spot welding. However, under special conditions and with special equipment, somewhat thicker metal has been welded. Equal thicknesses in a joint are preferred but ratios as high as 1:3 can be welded.

For resistance spot welding aluminium requires more overlap than steel. A weld too close to an edge can extrude or bulge the metal. In extreme cases, metal can be expelled, and sometimes surface cracking can result. A commonly used rule of thumb is to make minimum flange widths equal to 6 mm plus 8 times metal thickness.

There must be enough space between spots so that any shunting of welding current through existing welds will not rob subsequent welds of enough current to produce acceptable welds. A rule of thumb is to make minimum spacings to 6 mm plus 7 times metal thickness.

The minimum distance to edge is about 4 mm + 3 times metal thickness.

**Resistance roll spot welding** is similar to resistance spot welding, except that the conventional electrodes are replaced by rotating wheel electrodes. Welds are made repetitively, usually at uniform spacing. If the welds are spaced, it is termed intermittent seam welding. If the welds are overlapped, it is termed seam welding. The latter is often used to make gas- or liquid-tight joints. The welds may be made while the rolls are in motion, or the rolls may be momentarily stopped for each weld. The latter produces better weld quality and surface appearance.

**High-frequency resistance welding** is a group of resistance welding process variations that use high-frequency welding current to concentrate the welding heat at the desired location. While there are quite a number of applications, and more continue to be developed, high-frequency resistance welding as applied to aluminium is limited mainly to the seam welding of butt joints in tubular products.

### **Adhesive bonded connections**

Some provisions on the use of adhesive bonded connections are supplied in EC9. Such connections should be used to transmit shear only. Tensile forces, in particular peeling or other actions tending to open the joint, should be avoided or transmitted by complementary structural elements. For this reason, adhesive bonded joints can be used in conjunction with other types of connections designed to transmit tension. An uniform distribution of stresses and a sufficient deformation capacity should be guaranteed in order to enable a ductile type of failure. Such kind of failure is attained when, for example, the design strength of the joint is greater than the yield strength of the connected member.

As far as the mechanical properties are concerned high strength adhesives should be used for structural application. However, also the toughness should be sufficient to overcome stress/strain concentrations and to enable a ductile type of failure. The influence of the E-modulus on the strength and stiffness of the joint is not significant, but low E-modulus adhesives are more sensitive to creep. Concerning other adhesive properties it is noted that in temperature range  $-20^{\circ}\text{C}$  up to  $+60^{\circ}\text{C}$  the adhesive properties do not vary too much as long as the glass transition temperature is not exceeded.


Pre-treatments of the surfaces to be bonded have to be chosen such that the bonded joint meets the design requirements during the service life of the structure. Some, simply degreasing will suffice, but often additional mechanical (brushing) or chemical pre-treatment (etching, anodising, chromate conversion of the surface) should be considered with joints in highly stressed components.

## 2302.02 Principles of Design

- Introduction
- Mechanical properties of fastenings (qualitative)
- Forces in connections
- Calculation of forces in a group of fasteners
- Friction type bolt joints

### Introduction

Connections are an important part of every structure not only from the point of view of structural behaviour, but also in relation to the cost of production. As mentioned in chapter 1 a variety of joining methods are available for aluminium structures. Correct selection is governed by a large number of factors, see [Figure 2302.02.01](#). This chapter focuses attention on structural requirements, but this does not mean that structural behaviour is the most important factor. As mentioned in [Figure 2302.02.01](#), there are two types of requirements. When on the basis of all relevant criteria the optimal type of fastener is selected, the number of fasteners is determined by the structural requirements.

Requirements of Joints		
Structural Requirements	Non-Structural Requirements	
✓ Strength	✓ Economic aspects	
✓ Stiffness	♦ Total number of fasteners	
✓ Deformation capacity	♦ Skill required	
	♦ Ability to be dismantled	
	♦ Design life	
	♦ Installed cost of fastening	
	✓ Durability	
	✓ Watertightness	
	✓ Aesthetics	
	Requirements of Joints	2302.02.01

For the design of a connection, an engineer has to compare two quantities:  $F_{Ed}$ , the force in connection caused by design load and  $F_{Rd}$ , the design strength (resistance) of connection, see [Figure 2302.02.02](#). According to EC9, the partial safety factor  $\gamma_M$  for connections subjected to static loading is to be assumed equal to:

- resistance of bolted connections  $\gamma_{Mb} = 1.25$ ;
- resistance of riveted connections  $\gamma_{Mr} = 1.25$ ;
- resistance of pinned connections  $\gamma_{Mp} = 1.25$ ;

- resistance of welded connections  $\gamma_{Mw} = 1.25$ ;
- slip resistance connections  $\gamma_{Ms} = 1.10$  u.l.s, 1.25 s.l.s;
- adhesive bonded connections  $\gamma_{Ma} = 3.00$ ;

Connections subjected to fatigue should comply with the rules provided in EC9 Part 1.2.

The forces in connections are dependent on:

- loads on the jointed elements
- stiffness of the jointed elements
- stiffness and deformation capacity of the fastenings.

In addition, such forces should take into account:

- second order effects;
- the effect of structural imperfections;
- the effects of connection flexibility.

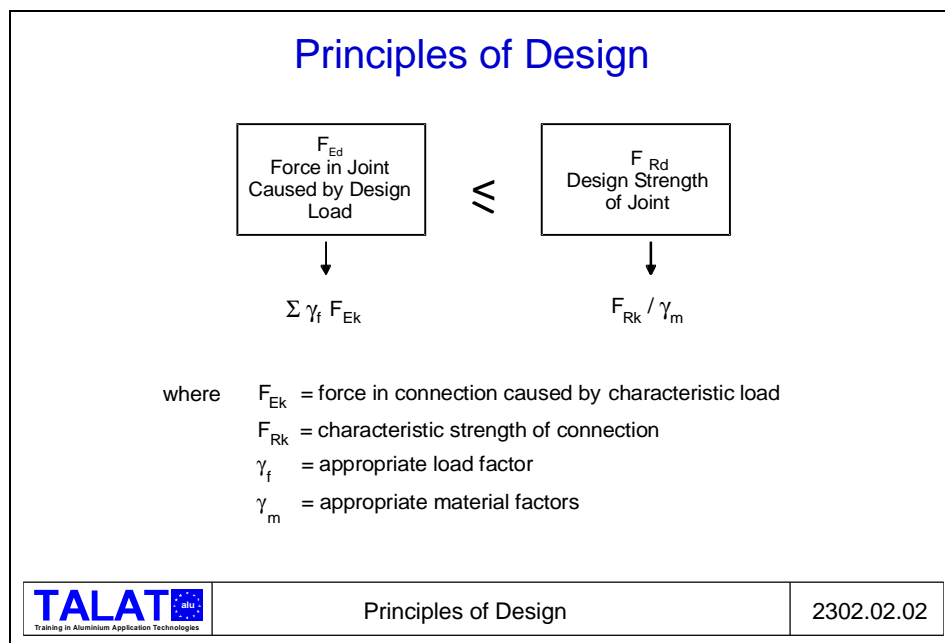
For a more detailed treatment of “forces in connections” see the appropriate subchapter below.

The strength of connections is dependent on:

- type of fastener
- properties of jointed elements (thickness, yield stress)

According to EC9, linear elastic structural analysis can be used in the design of connections. When non-linear analysis is used, the load deformation characteristics of all the components of the connection should be taken into account.

In section 2302.04 the subject of strength will be treated in detail.

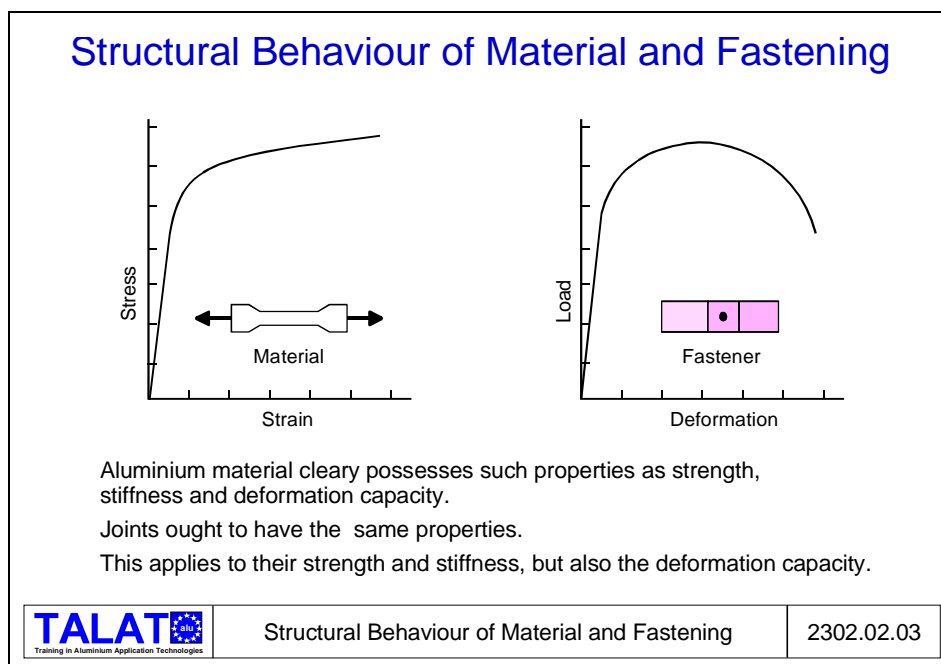


## Mechanical Properties of Fastenings (Qualitative)

Thick-walled structural aluminium and also the light gauge aluminium sheet clearly possesses such properties as strength, stiffness and deformation capacity (Figure 2302.02.03). Therefore, this material is suitable for use in structures. Ancillary parts of structures, e.g. fastenings, ought to have the same properties (Figure 2302.02.04). Evidently, this applies to their strength and stiffness. It is less well known, however, that their deformation capacity should also meet certain requirements.

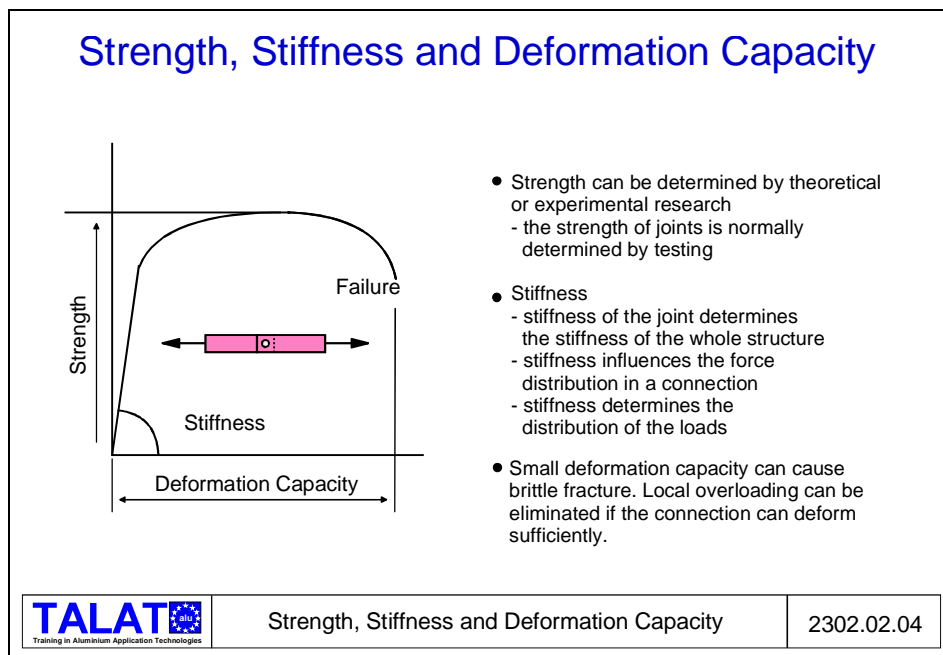
For each type of fastening, a characteristic **strength** can be determined by theoretical or experimental research. This strength can be influenced by the choice of the section, and by the type of fastener.

**Stiffness** of a connection is important because it determines the stiffness of the whole structure or of its components. Moreover stiffness can also influence the forces in a connection. This is, for instance, the case for connections of lateral bracings to purlins and bracings in nonsway frames. The stiffness of a connection also determines the distribution of the loads.



The **deformation capacity** of a connection is also important. A connection with no deformation capacity can cause a brittle fracture of a structure or element. This primarily applies to a continuous construction, where such influences as settlements and fluctuating temperatures are normally not included in a design calculation. Local overloading can be eliminated if the connection can deform sufficiently. In the case of simply supported

structures, the deformation capacity of the separate fasteners can be important if more fasteners are used.



**Figure 2302.02.05** gives two examples which demonstrate the importance of this requirement:

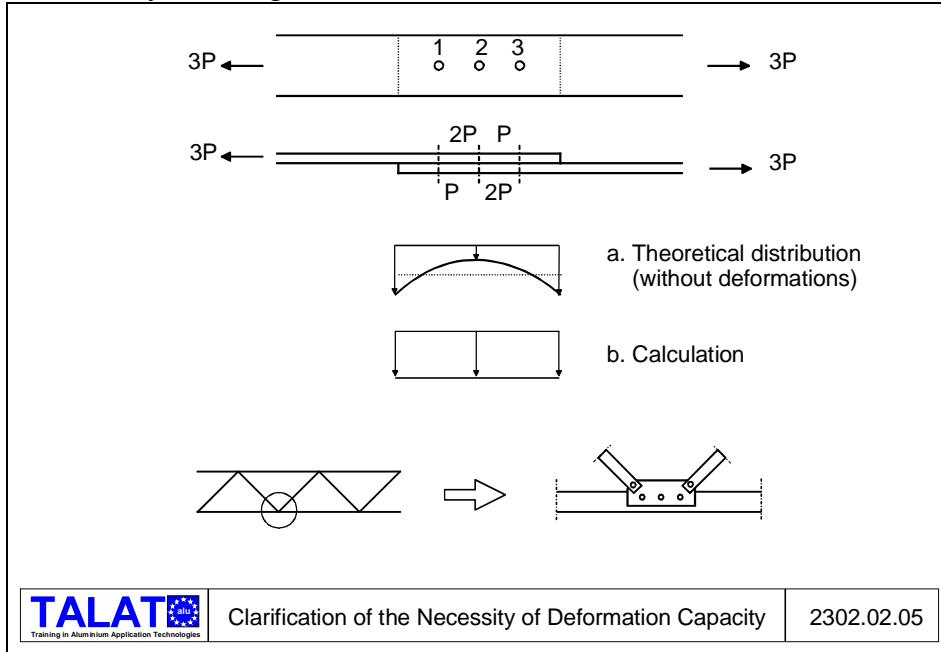
1. A failure mode with little strain capacity has disadvantages if many fasteners have been placed in a row in the direction of load. In calculation, the force is divided into equal parts and applied to each fastener. Theoretically this is not correct. However, this assumption may be used if plastic redistribution can take place.
2. The same requirement is necessary for connections in trusses which are calculated as trusses with pin-ended joints. It is well-known that secondary stresses are always introduced. A simplified design method is, therefore, permitted if the connections can deform plastically in order to limit the influence of the secondary stresses.

### Classification of connections

In EC9 Chapter 6.4 a distinction between “joint” and “connection” is made, the first meaning the system composed by the connection itself plus the corresponding interaction zone between the connected members (see **figure 6.1** of EC9 in the **appendix**). A suitable classification system is provided in EC9 for connections, according to their capability to restore the behavioural properties (rigidity, strength and ductility) of the connected member. Referring to the global behaviour of the connected

member, expressed in terms of generalised force  $F$  and corresponding deformation  $D$ , two main classes are defined in EC9 (see **figure 6.2a** of EC9 in the **appendix**):

- Fully restoring connections;
- Partially restoring connections.



Fully restoring connections are designed so that all behavioural properties are always not lower than those of the connected member. As a consequence the existence of the connection itself may be ignored in the structural analysis.

Partially restoring connections have properties which do not reach those of the connected member in terms of either elastic rigidity, ultimate strength or ductility. The connection must therefore be kept into account in the structural analysis.

In addition, connections are also classified in EC9 by (see **figure 6.2b-d** in the **appendix**):

- Rigidity;
- Strength;
- Ductility.

With respect to rigidity connections can be:

- Rigidity restoring (rigid) connections ,
- Rigidity non-restoring (semi-rigid) connections,

depending on whether the initial stiffness of the connected member is restored or not, regardless of strength and ductility.

With respect to strength connections can be:

- Strength restoring (full strength) connections,
- Strength non-restoring (partial strength) connections,

depending on whether the ultimate strength of the connected member is restored or not, regardless of rigidity and ductility.

With respect to ductility connections can be:

- Ductility restoring (ductile) connections,
- Ductility non-restoring (semi-ductile or brittle) connections,

depending on whether the ductility of the connection is higher or lower than that of the connected member, regardless of rigidity and strength.

In particular, ductile connections have a ductility equal or higher than that of the connected member; deformation limitations may be ignored in structural analysis. Semi-ductile connections have a ductility lower than the one of the connected member, but higher than its deformation at elastic limit; deformation limitations must be considered in inelastic analysis. Brittle connections have a ductility lower than the deformation of the connected member at the elastic limit; as a consequence, deformation limitations must be considered in both elastic and inelastic analysis.

The relevant combinations of the main behavioural properties of connection are shown in **figure 6.3** of EC9 (see **appendix**). In **table 6.1** of EC9 (see **appendix**), the corresponding requirements for the methods of global analysis are given.

As far as connections for framed structures are concerned, a distinction with respect to moment-curvature relationship is provided in EC9 between:

- Nominally pinned connections;
- Built-in connections.

Nominally pinned connections are designed in such a way to transmit the design axial and shear forces without developing significant values of resisting moment. They should be able to develop the required deformation capacity in both elastic and plastic analysis.

Built-in connections allow for the transmission of bending moment between connected members, together with axial and shear forces. They can be classified according to rigidity and strength in the following way:

- Rigid connections;
- Semi-rigid connections;
- Full strength connections;
- Partial strength connections.

Rigid connections must be designed in such a way that the effect of their deformation on the global frame behaviour in terms of strength and deformability is negligible (not higher than 5%).

Semi-rigid connections should provide a predictable degree of interaction between members, based on the design moment-rotation characteristic of the joints. Both rigid and semi-rigid connections should be designed in such a way that the rotations at the necessary plastic hinges do not exceed their rotation capacity. At the same time, the rotation capacity of partial strength connections must be not less than that required for the development of the complete plastic mechanism.

## Forces in Connections

The **forces in connections** are dependent on the external loading on the structure and on the static properties of the structure. In general, the external loads have to be taken in accordance with national standards. Indication about the values of the external actions to be assumed in structural analysis are provided in EC1. The loads will cause shear, tension or a combination of these in the fastenings.

Distinction has to be made between continuous construction and simply supported structures. For simply supported structures the force on a connection follows from equilibrium (**Figure 2302.02.06**). The distribution of the forces over the fastenings depends in principal on the stiffness per fastening. A **simplified** calculation leads to the following conservative maximum force per fastening:

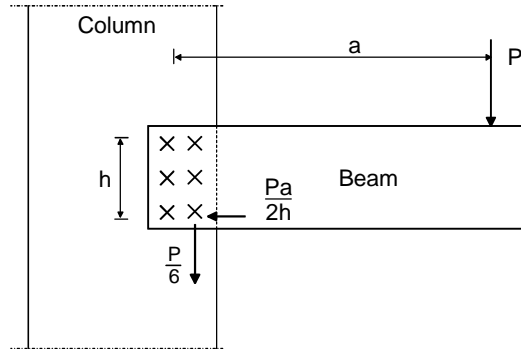
$$F = \sqrt{\left(\frac{P a}{2 h}\right)^2 + \left(\frac{P}{6}\right)^2}$$

where

F is the force per fastening.

Methods of calculations of forces in joints are discussed later.

## Force on Connection in Staticy Determined Structure



For continuous construction the design philosophy will be treated for the example shown in [Figure 2302.02.07](#).

When designing the splice connection the procedure now described has to be followed:

### Semi-rigid joint:

Determine the rotation  $\vartheta_c$  of the connection as a function of the stiffness per fastening and a moment  $M$ .

$$\vartheta_c = f(M, \text{fastening stiffness})$$

Determine the inclinations  $\vartheta_b$  of the beam over the support as a function of the support moment, beam stiffness and load (see [Figure 2302.02.08](#)).

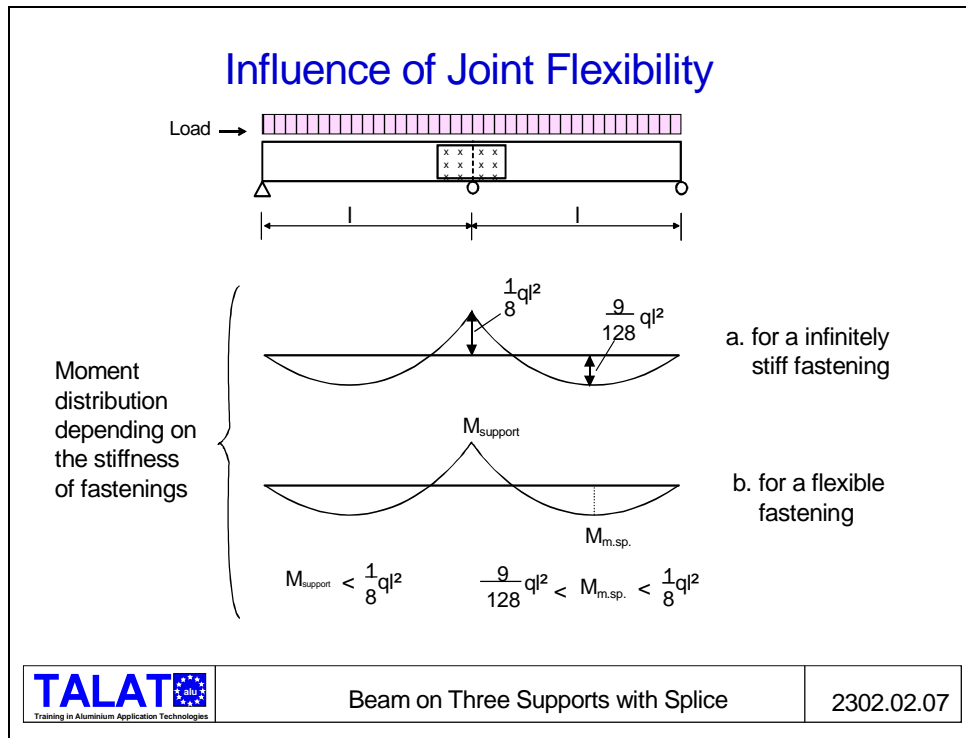
$$\vartheta_b = f(M, l, EI, q)$$

Compatibility requirement:

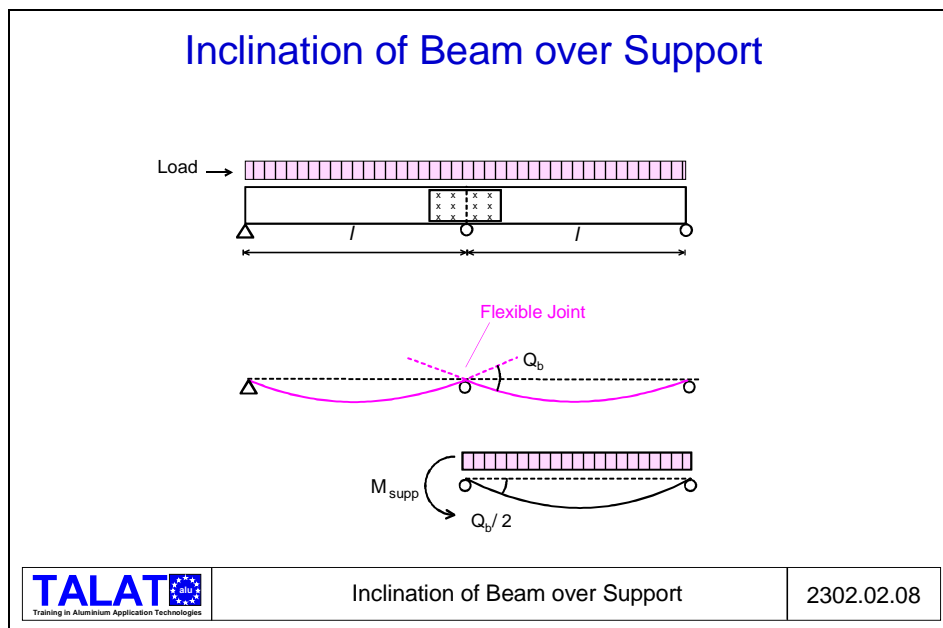
$$\vartheta_c = \vartheta_b$$

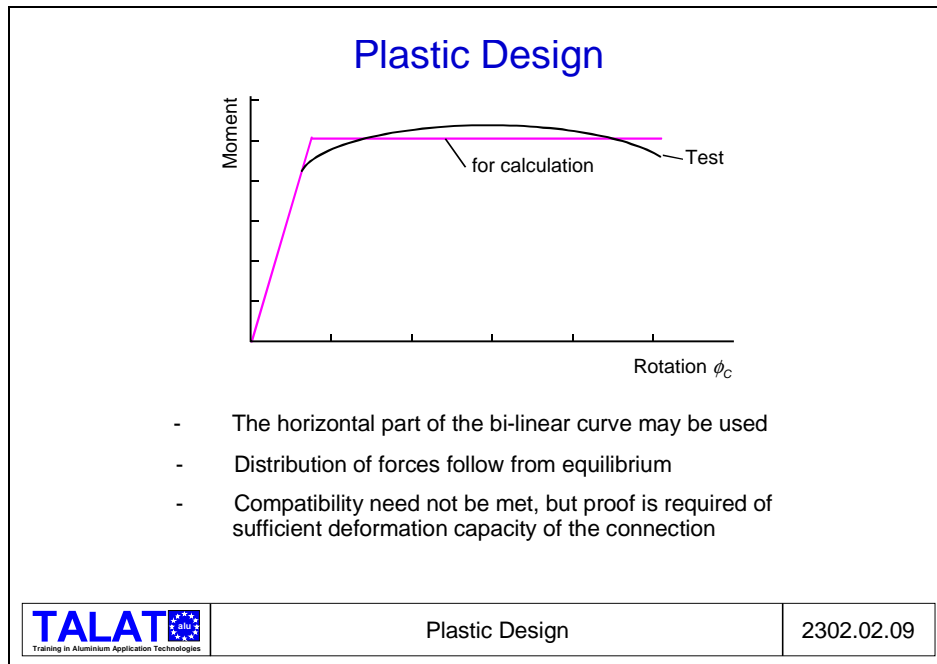
which gives

$$M = M_{\text{support}} \rightarrow \text{force per fastening}$$



**Plastic Design:** In the case of the bi-linear behaviour of the connection ([Figure 2302.02.09](#)), the horizontal part of the curve may be used; then the distribution of forces simply follows from equilibrium. The compatibility requirement need not be met; however, proof is required that the connection possesses sufficient deformation capacity.





**Simple support:** In the case of little stiffness of the connection, the connection shall be regarded as a hinge (two simply supported beams). The connection shall then possess sufficient deformation capacity to follow the inclination of both beams.

As an example of the determination of forces three types of structures in thin-walled sections will be examined:

- a) Composition of a bending member from single sections with connections loaded in shear (see [Figure 2302.02.10](#)):

Shear force in fastenings in a cross-section A:

$$V_h = \frac{V_v S_x}{I_x / a}$$

where

$V_h$  = sum of shear forces in both fastenings in a cross-section A

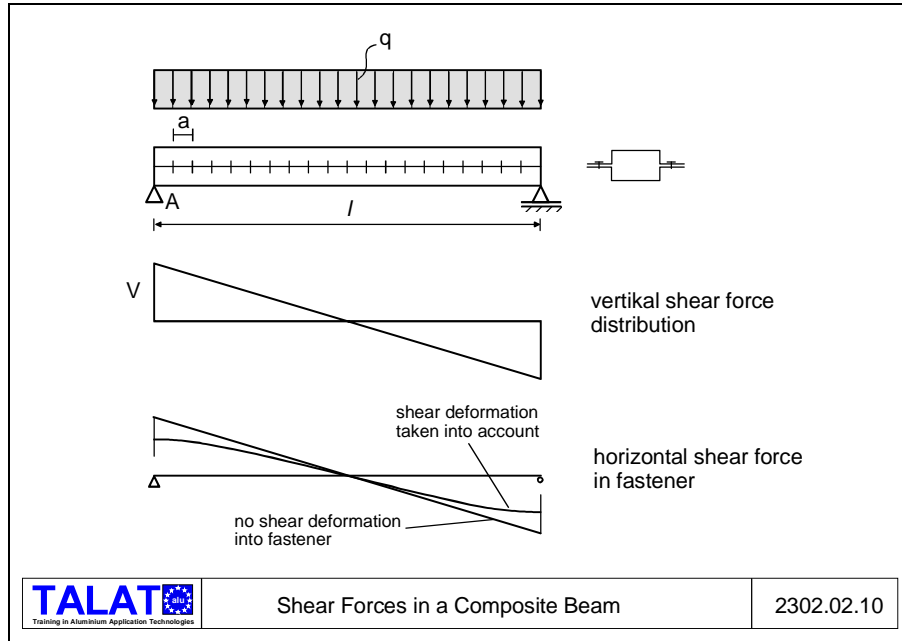
$a$  = distance between fasteners in span direction

$V_v$  = vertical shear force in A equal to  $qL/2$

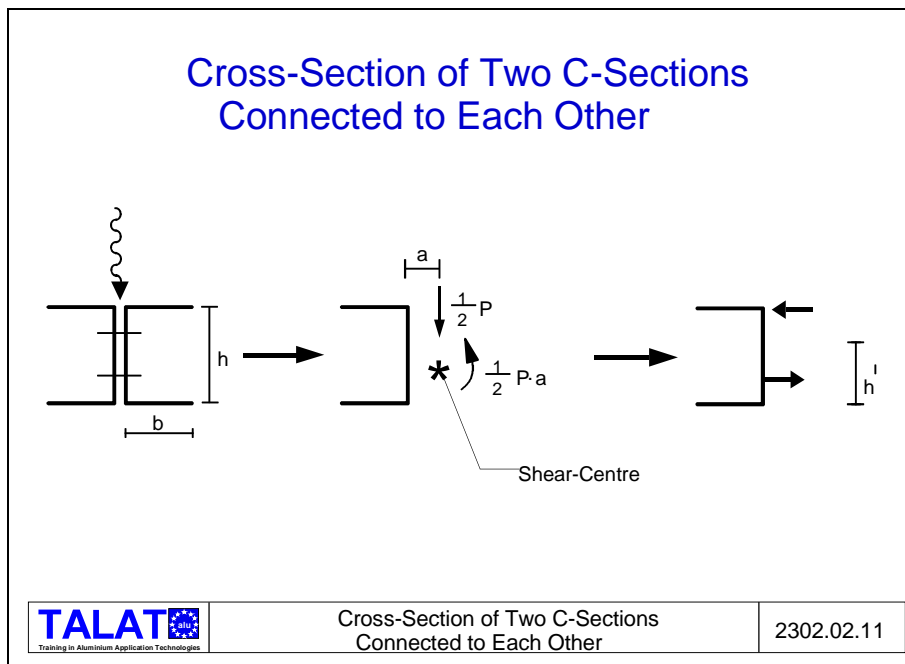
$S_x$  = area of the part which will shear, multiplied with the distance of the centroid of the area which will shear to the neutral axis of the composite beam;

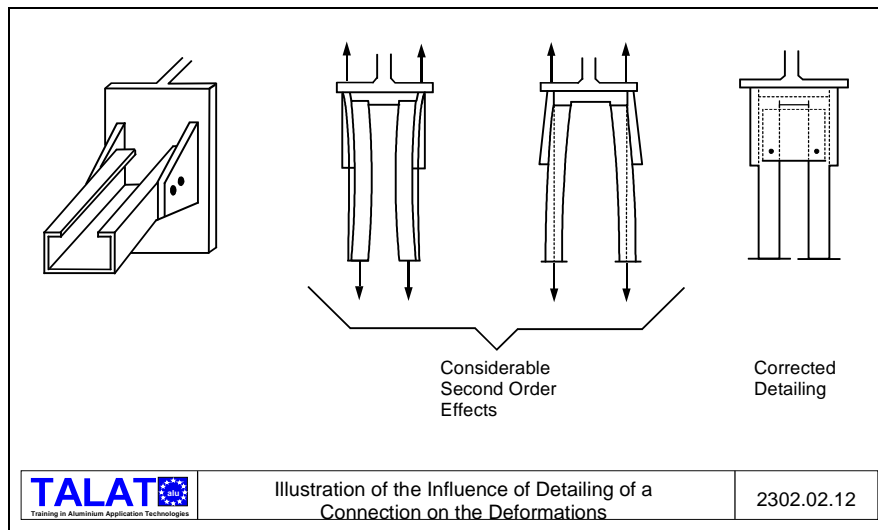
$I_x$  = moment of inertia of the composite beam.

The calculation method shown gives an upper-limit of the shear force in the fastenings A. In reality some slip in the fastenings will occur. This causes a smaller section modulus and moment of inertia of the composite beam and reduces the forces on the fastenings.



- b) Composition of a bending member from single sections with connections loaded in tension: **Figure 2302.02.11** shows the cross-section of two C-sections connected to each other. The method of calculating the forces in the fastenings is described in the figure.
- c) Secondary forces in connections. Care should be taken, by suitable detailing, that second order effects caused by deformation of thin-walled sections will not generate impermissible extra forces in the fastenings. This is illustrated by the example given in **Figure 2302.02.12**.





## Calculation of Forces in a Group of Fasteners

**Eccentrically Loaded Group of Fasteners:** A force applied at a distance,  $e$ , from the centroid of a group of fasteners ([Figure 2302.02.13](#)), causes the connected part to rotate about a point  $C$  lying on the line normal to the direction of the force passing through the group centroid, at a distance,  $c$ , from the centroid, on the side away from the force. The distance  $c$  is given by:

$$c = I_p / (nAe) \quad (2.1)$$

where

$c$  = distance from the centroid to the centre of rotation,  $C$ , of the bolt group

$I_p$  = polar moment of inertia of the group about its centroid

$$= \sum_{i=1}^n Ar_i^2$$

$r_i$  = distance of the  $i$ -th bolt from the centroid

$n$  = total number of fasteners

$A$  = cross-sectional area of fastener

$e$  = eccentricity of the applied load

a) Elastic behaviour ([Figure 2302.02.14](#))

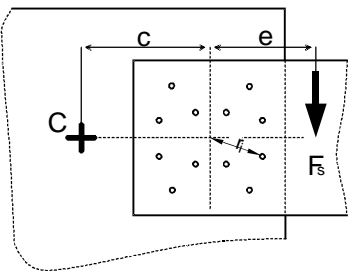
The highest force on a bolt,  $F$ , for elastic behaviour, shall be given by:

$$F = \frac{F_s}{n} \cdot \frac{d_m}{c} \quad (2.2)$$

where

$d_m$  = the distance from the centre of rotation, C, to the furthest fastener  
 $F_s$  = applied force

### Eccentrically Loaded Group of Fasteners




$$c = \frac{I_p}{nAe}$$

$c$  = distance from the centre of the bolt group to the centre of rotation, C  
 $I_p$  = polar moment of inertia of the group about the centroid

$$I_p = \sum_{i=1}^n A r_i^2$$

$r_i$  = distance of the i-th bolt from the centroid  
 $n$  = total number of fastener  
 $A$  = cross-sectional area of fastener  
 $e$  = eccentricity of the applied load  $F_s$



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Eccentrically Loaded Group of Fasteners

2302.02.13

#### b) Plastic behaviour (Figure 2302.02.15)

The same centre of rotation as in elastic behaviour can be assumed at the ultimate resistance, unless the calculated centre lies close to a fastener, in which case the fastener shall be used as the centre of rotation.

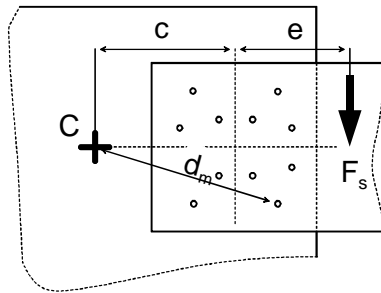
The characteristic resistance  $F_R$  of the eccentrically loaded fastener group shall be obtained from:

$$F_R = F_{v,Rd} \sum_{i=1}^n \frac{d_i}{e + c} \quad (2.3)$$

where

$e+c$  = distance from the force to the centre of rotation  
 $F_{v,Rd}$  = resistance of a single fastener  
 $d_i$  = distance from the centre of rotation, C, to the i -th fastener  
 $n$  = number of fasteners

## Elastic Behaviour



The highest force on a bolt,  $F$ , is given by:

$$F = \frac{F_s d_m}{n c}$$

$d_m$  = distance from the centre of rotation,  $C$ , to the furthest fastener

$F_s$  = applied force

**Centrically Loaded Rows of Fasteners:** In connections containing fasteners of the same dimension which are acted upon by an axial shear force, the force is assumed to be uniformly distributed over all the fasteners if the length  $L_j$  of the connection in the direction of force is less than  $15d$ , where  $d$  is the fastener diameter. If the length of the connection is greater, the greatest force  $F_{v,Ed}$  on a fastener is to be calculated from the formula

$$F_{v,Ed} = \frac{F d}{n} \left( 0.925 + \frac{L_j}{200d} \right) \quad (2.4)$$

where

$n$  = number of fasteners

$L_j$  = length of connection according to [Figure 2302.02.16](#)

$d$  = fastener diameter.

If the shear force acts eccentrically in the shear plane, the force on the fastener due to the moment shall be calculated in accordance with the elastic theory on the assumption of rigid plates and flexible fasteners.

According to EC9 (6.5.10) the formula 2.4 for long joints should be put into the slightly different form:

$$F_{v,Ed} = \frac{F d}{n \beta_{Lf}} \quad \text{with} \quad \beta_{Lf} = 1 - \frac{L_j - 15d}{200d} \quad \text{but} \quad 0.75 \leq \beta_{Lf} \leq 1.0$$

This provision does not apply where there is a uniform distribution of force transfer over the length of the joint, e.g. the transfer of shear force from the web of a section to the flange.

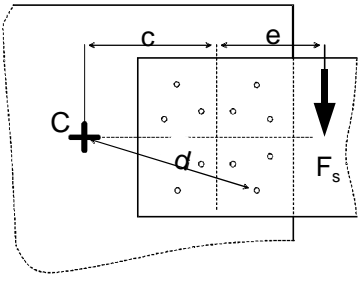
An eccentricity perpendicular to the shear plane which is less than the plate thickness may be disregarded. If a packing plate is used, the effect of this is to be allowed for by increasing the force on the bolts by 1.25% for each mm by which the thickness of the packing plate exceeds 6 mm. This increase in force is not required in high strength friction grip bolted connections if the packing plate is finished in the same way as the other contact surfaces in the connection.

According to EC9 (6.5.12), where bolts or rivets in shear pass through packings of total thickness  $t_p$  greater than one third of the nominal diameter  $d$ , the design shear resistance  $F_{v,Rd}$  is to be reduced by a reduction factor  $\beta_p$  given by:

$$\beta_p = \frac{9d}{8d + 3t_p} \quad \text{but} \quad \beta_p \leq 1$$

For double shear connections with packings on both sides of the splice,  $t_p$  should be taken as the thickness of the thicker packing.

Plastic Behaviour



The same centre of rotation as in elastic behaviour can be assumed at the ultimate resistance, unless the calculated centre lies close to a fastener, in which case that fastener shall be used as the centre of rotation.


The characteristic resistance  $F$  of the eccentrically loaded fastener group is

$$F_R = F_{v,Rd} \sum_{i=1}^n \frac{d_i}{e + c}$$

$e + c$  = distance from the force to the centre of rotation

$F_{v,Rd}$  = resistance of a single fastener

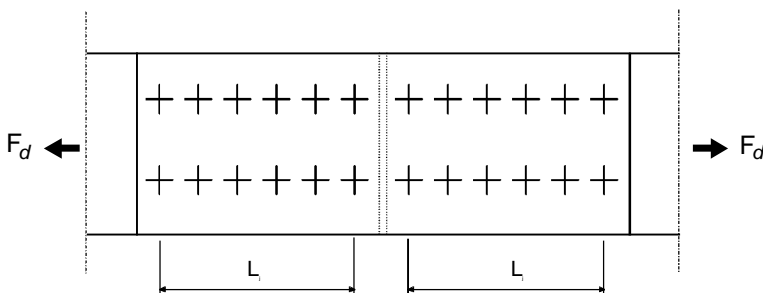
$d_i$  = distance from the centre of rotation, C, to the i-th fastener



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Plastic Behaviour

2302.02.15



Maximum force per fastener:  $F_{V,Ed} = F_d / n (0.925 + L_i / (200d))$

with  $n$  = number of fastener  
 $L$  = length of connection  
 $d$  = fastener diameter

<b>TALAT</b> <small>Training in Aluminium Application Technologies</small>	Centrically Loaded Rows of Fasteners	2302.02.16
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## Friction Type Bolt Joints

Where preloaded high strength bolts are used to create joints that will not slip under service loads, the surface shall be suitably prepared, by means such as sanding, to provide the coefficient of friction adopted.

According to EC9 Chapter 6.5.9, in order for slip-resistant connections with high-strength bolts to be adopted, the proof strength of the material of the connected parts should be higher than  $200 \text{ N/mm}^2$ , otherwise suitable experimental validation should be supplied for the design. At the same time, both the effect of relaxation of the bolt preload due to tension and the effect of strong temperature changes cannot be ignored. The design slip resistance of a preloaded high-strength bolt is given by:

$$F_{s,Rd} = \frac{n\mu}{\gamma_{Ms}} F_{p,Cd}$$

where:

- $F_{p,Cd}$  is the design preloading force;
- $\mu$  is the friction coefficient;
- $n$  is the number of friction interfaces.
- $\gamma_{Ms}$  is the partial safety factor, equal to 1.25 for the ultimate limit state and 1.10 for serviceability limit state.

The design preloading force for high-strength steel bolts  $F_{p,Cd}$  is given by:

$$F_{p,Cd} = 0.65 f_{ub} A_S$$

$$F_{p,Cd} = 0.7 f_{ub} A_S$$

for 8.8 and 10.9 bolts, respectively.

The values of the factor  $\mu$  mainly depend on the surface treatment. EC9 provides values for the lightly shot blasting standard treatment, shown in **table 6.6** in the **appendix**. Rules for the execution of suitable experimental tests for the evaluation of  $\mu$  are supplied in Annex A of EC9.

If a slip-resistant connection is subjected to an applied tensile force  $F_t$  in addition to the shear force  $F_v$  tending to produce slip, the slip resistance is given by:

$$F_{s,Rd} = \frac{n\mu(F_{p,Cd} - 0.8F_{t,Ed})}{\gamma_{Ms}}$$

where  $F_{s,Rd}$ ,  $F_{p,Cd}$  and  $\gamma_{Ms}$  can be referred to both ultimate and serviceability limit state.

Installation procedures for preloaded bolts shall ensure that the required bolt tension is realized.

Bolt holes should exceed the bolt diameter by not more than 10 percent of the bolt diameter.

Washers are required under the turned element.

Slotted holes are not to be used to transmit force in the direction of the slot, unless preloaded bolts develop sufficient resistance by friction to provide the required ultimate resistance.

## 2302.03 Failure Modes and Deformations

- Introduction
- Failure modes of fastenings
  - Failure modes of fastenings loaded in shear
  - Failure modes of fastenings loaded in tension
  - Deformation of connections

### Introduction

For design purposes various formulae have been derived based on experiments. Such formulae are presented in section 2302.04. It should be borne in mind that the design formulae for fastenings are as a consequence of their nature in general conservative. Design values determined by tests will give more realistic values.

The formulae given are valid only for fastenings in which the fastened parts are in direct contact with each other. That means that only small bending moments are acting on the fasteners and the formulae are not valid for the crest fastening of profiled sheeting or the fastening of sandwich elements for example.

### Failure Modes of Fastenings

The strength and flexibility of fastenings is dependent on the failure mode of the fastening. Below the possible failure modes for shear and tension, respectively are demonstrated.

#### *Failure Modes of Fastenings Loaded in Shear*

##### **(Figure 2302.03.01)**

a. Shear of fastener:

This may occur when the sheet is thick with reference to fastener diameter, or when an unsuitable fastener is used.

b. Crushing of fastener:

This may occur with hollow fasteners, and in combination with tilting and yield in bearing.

c. Tilting and pull-out of fastener (inclination failure):

This is the normal mode of failure in thin sheet to thin sheet fastening with either the threads or the site formed rivet head pulling out of the lower sheet. It may occur in combination with yield of both sheets in bearing, and in conjunction with considerable sheet distortion.

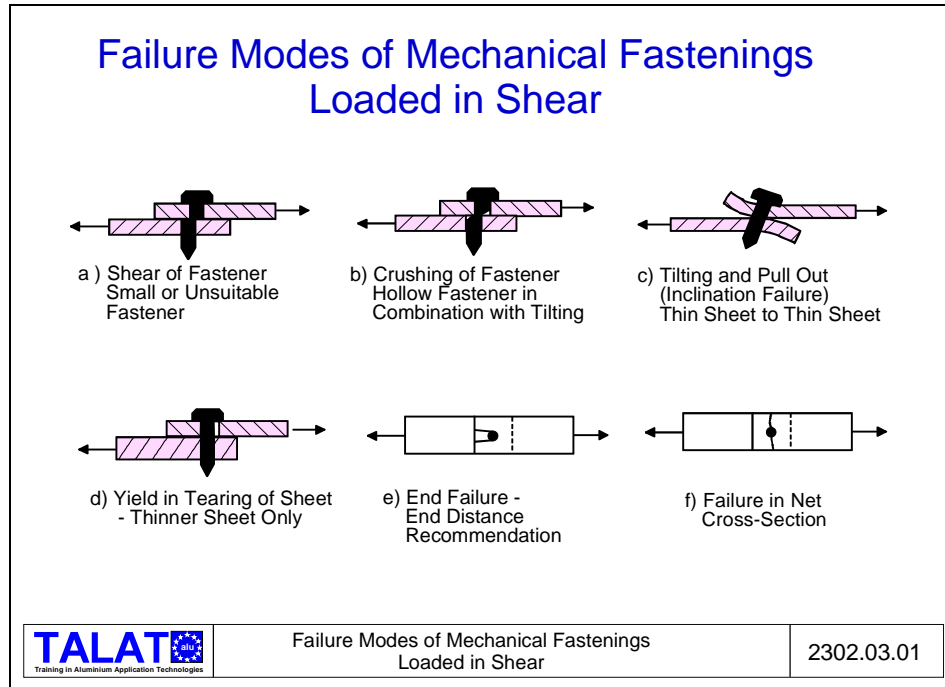
d. Yield in tearing (tearing of sheet):

- Yield of thinner sheet only.
- Yield of both sheets.

e. End failure:

This will not occur if recommended end distances are adhered to.

f. Failure of the net cross-section.



### *Failure Modes of Fastenings Loaded in Tension*

(Figure 2302.03.02)

a. Tension failure of fastener:

This may occur when the sheet is thick with reference to the fastener, or when an unsuitable fastener is used.

b. Pull out:

This may occur when the support member is insufficiently thick, or when there is insufficient anchorage of fastener.

c. Pull over

d. Pull through:

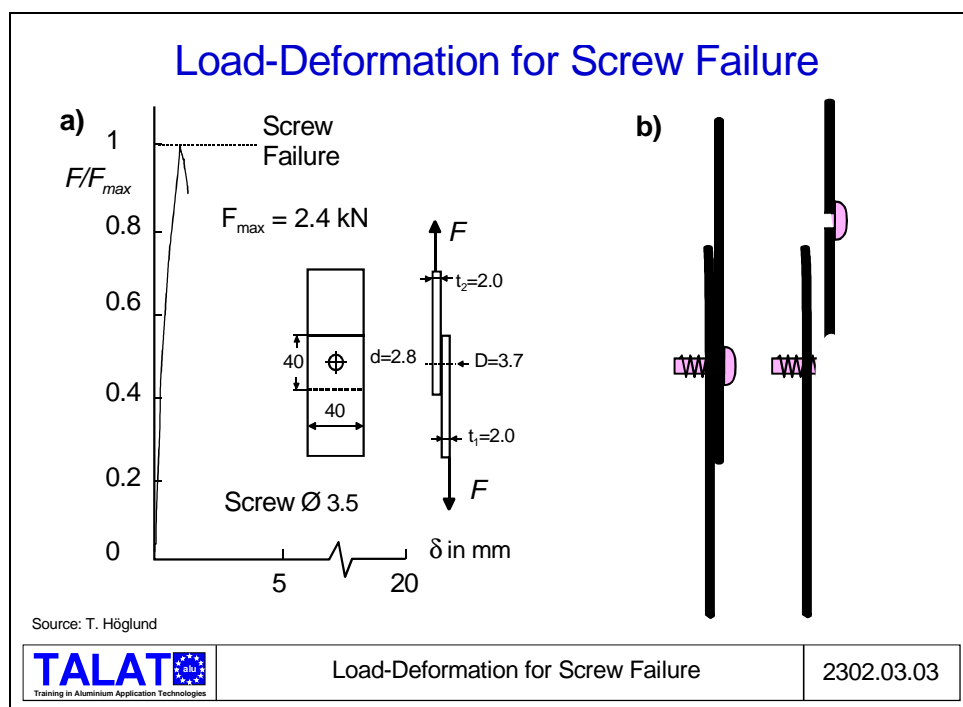
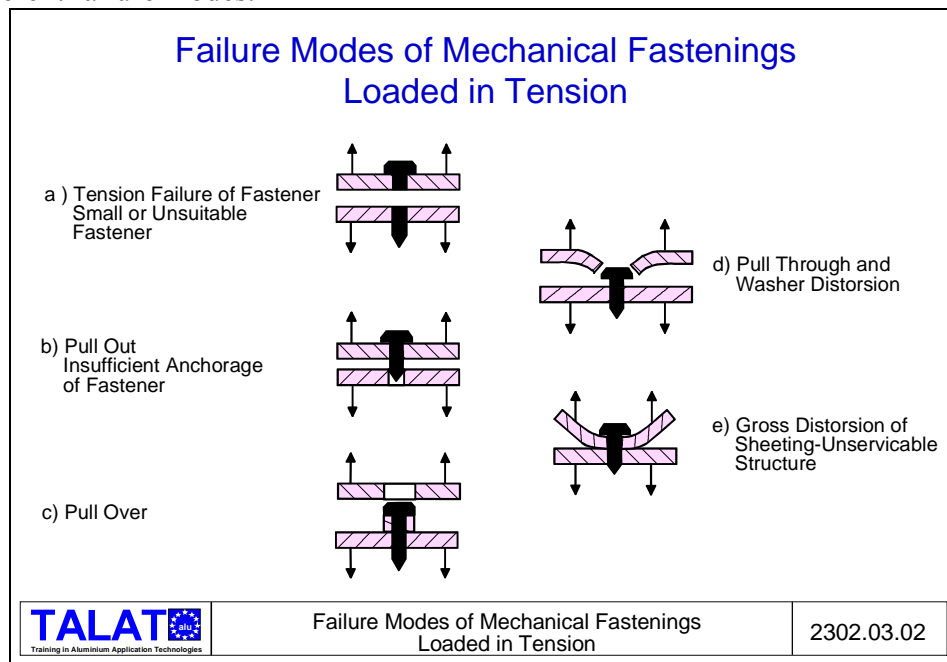
This may be accompanied by washer distortion.

e. Gross distortion of sheeting:

Permanent gross profile distortion may be considered to constitute unserviceability of the structure.

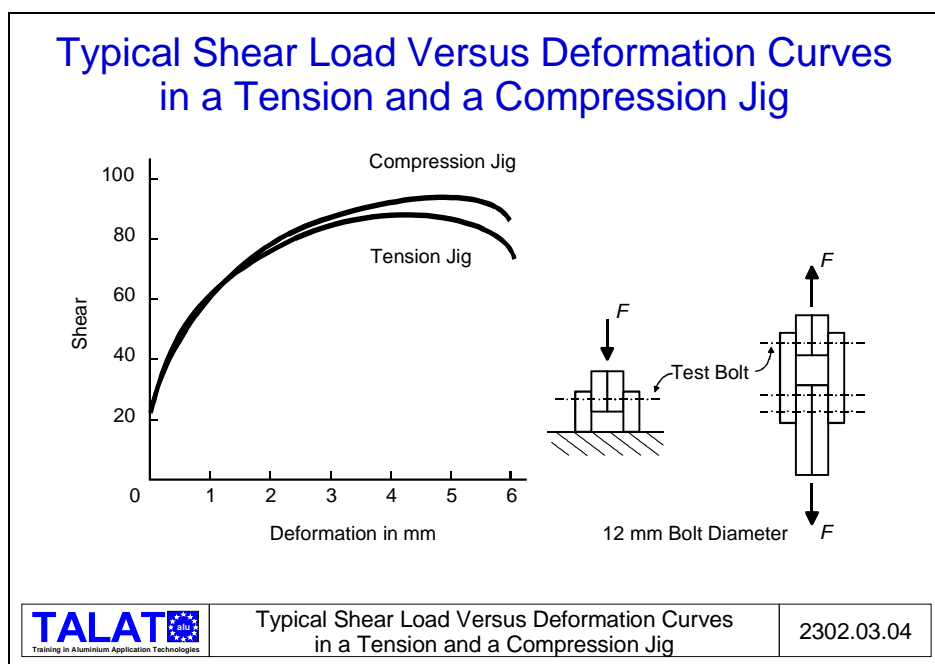
## Deformation of Connections

As already mentioned above the deformation capacity of connections can often be very important. A connection with no deformation capacity can cause a brittle fracture of a structure or element. This primarily applies to hyperstatic structures, e.g. continuous constructions, where influence of settlements and fluctuating temperatures are normally not included in a design calculation. Local overloading can be eliminated if the connection can deform sufficiently. Here some examples of load-deflection curves and deformation stages will be shown to get an impression of the different failure modes.

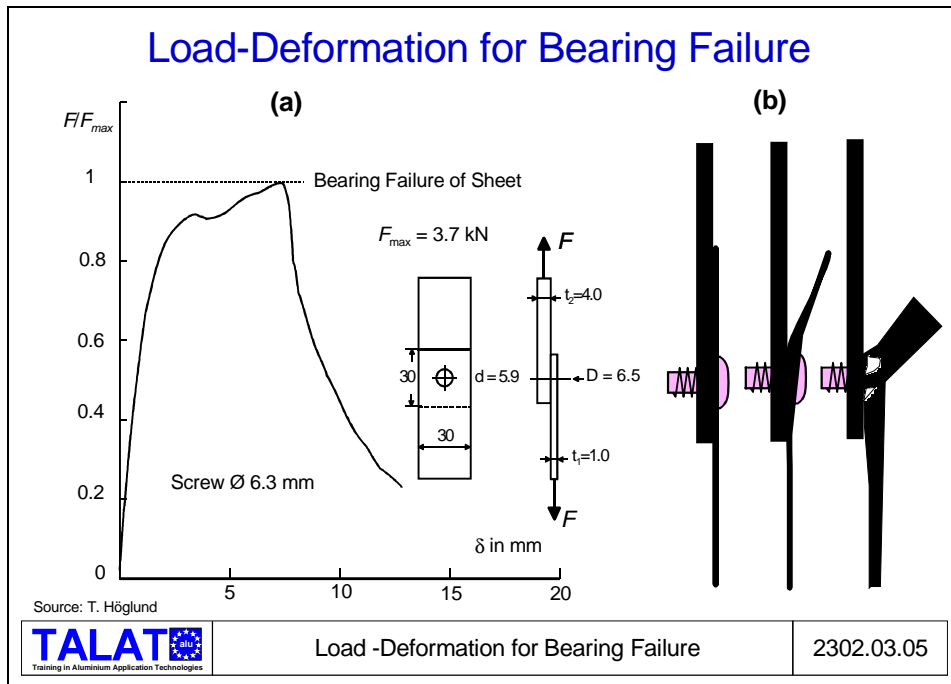


**Shear failure in fastener** occurs with relatively small deformations and is normally not permitted in screw and blind rivet connections. The deformation at failure is of the order of half the fastener diameter. **Figure 2302.03.03 a** shows an example of the load-deformation diagram for shear failure of a screw and **Figure 2302.03.03 b** shows the connection before and after failure.

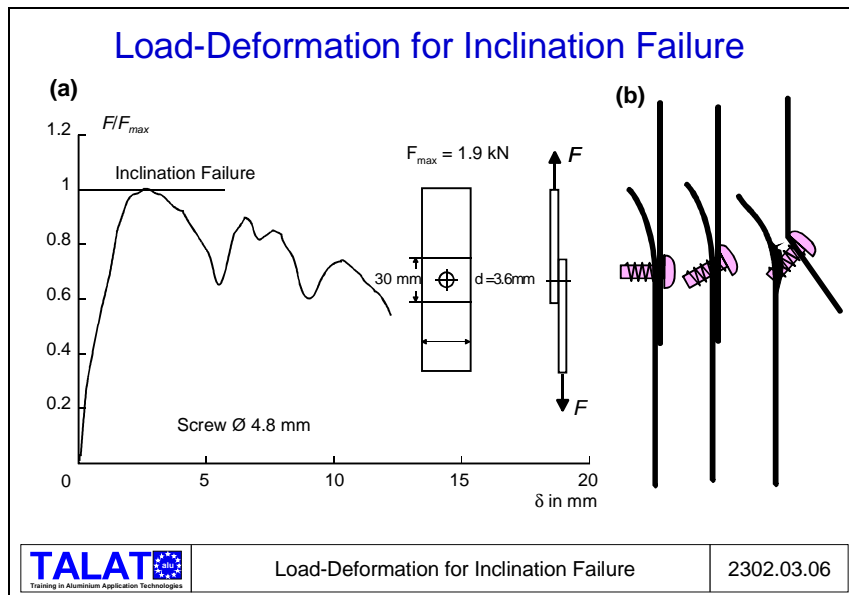
As the diameter of bolts with nuts is normally larger than tapping screws, the deformation at failure is larger, see **Figure 2302.03.04**. Shear deformation in bolts is then normally enough to allow for redistribution of forces e.g. in a connection with several bolts.



**Bearing failure.** An example of the load-deformation diagram for bearing failure of a screw connecting a thin sheet with a thick sheet is shown in **Figure 2302.03.05**. Some stages in the tests are illustrated in **Figure 2302.03.05 (b)**. The deflection at failure is round 10 mm.

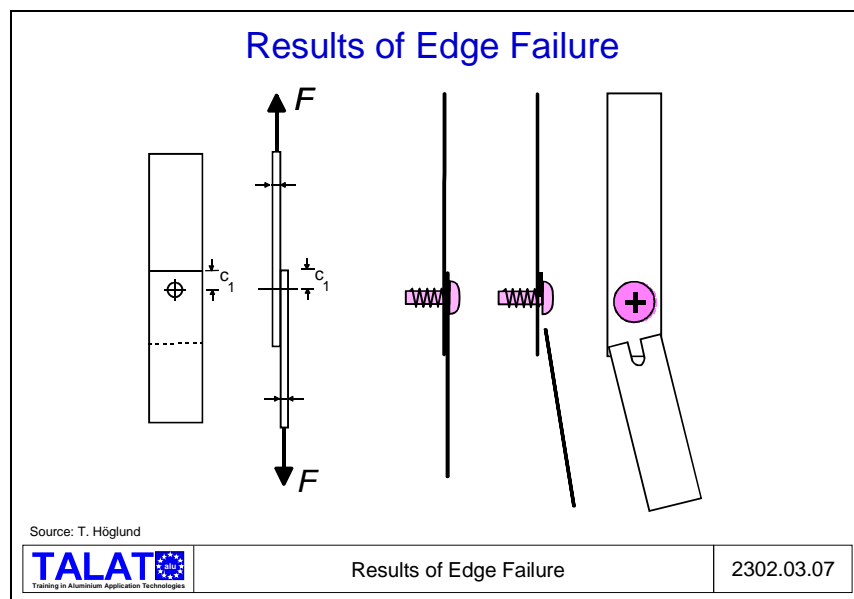


**Inclination Failure, Tilting.** [Figure 2302.03.06](#) illustrates a characteristic load-deflection diagram for inclination failure. The ultimate load is strongly dependent on the thickness of the sheet into which it is screwed, because this sheet forms the nut. For  $t_1 = t$  inclination failure occurs. For  $t_1 > t$  the design strength is related to the bearing strength. As a simplification linear interpolation is recommended between the inclination value at  $t_1 = t$  and the bearing strength at  $t_1 = 2.5 t$ . [Figure 2302.03.06 b](#) gives an impression of the inclination failure mode.

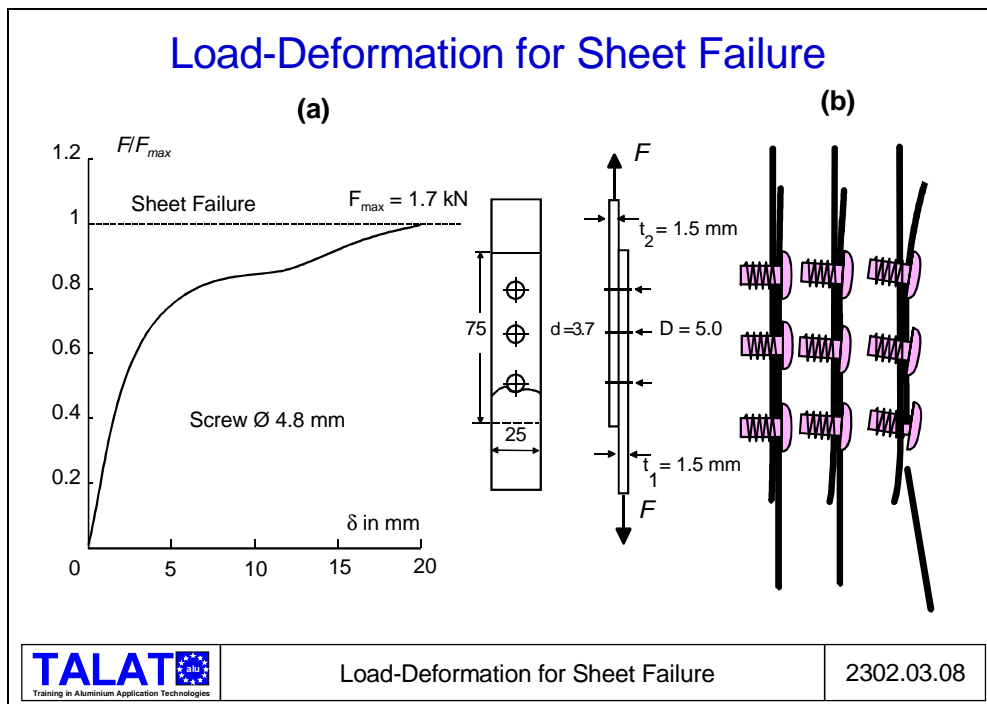


**Edge Failure.** In edge failure, normally the bolts or screws remain perpendicular to the applied load direction. The shear planes are parallel and a distance apart equal to the

fastener diameter. It seems obvious that for this failure mode the ultimate force is depending on the edge distance  $c_1$  (see [Figure 2302.03.07](#)).



**Tension failure in net section** is shown in [Figure 2302.03.08](#) with corresponding load-deformation diagram in. Normally the deformation is sufficient to allow for redistribution of forces.



## 2302.04 Design Strength of Mechanical Fasteners and Spot Welds

- Design strength of fasteners loaded in shear
  - Shear of fastener
  - Hole bearing
  - Tilting and sheet tearing
  - Edge failure
  - Tension failure of net section
- Design strength of fasteners loaded in tension
  - Tensile failure
  - Pull-through failure and pull-over
  - Pull out from underlying member
- Mechanical fasteners in combined shear and tension
- Lap joints and pin connections

### Design Strength of Fasteners Loaded in Shear

A survey of design formulae for various failure modes is given in the following paragraphs. The design strength of a fastening is the smallest value resulting from the formulae for a given type of fastener.

The following symbols are used

$d$	=	diameter of fastener
$F$	=	design strength (subscript depends on failure mode)
$f_y$	=	design value for the yield stress of the member material
$A_{\text{net}}$	=	net cross-sectional area of the member material
$r$	=	force transmitted by the bolt or bolts at the section considered, divided by the tension force in the member at that section
$d_o$	=	diameter of the hole
$g$	=	spacing of bolts perpendicular to the line of stress; in the case of a single bolt, $g$ = width of plate
$n$	=	number of shear planes in a bolt
$A_s$	=	stress cross-sectional area of a bolt
$f_{ub}$	=	design value of the ultimate stress of the bolt material
$t$	=	thickness of member
$t_1$	=	thickness of the thicker member or underlying material

The formulae lead to conservative results because of different producers of fasteners which are all included in the design formulae for each group. In certain cases, it would be advantageous to determine more realistic values by carrying out tests on the particular fastener in question.

The limits for the applications of the formulas are as follows. They are not limits for the use of the fasteners but imposed by the extent of relevant research (**Figure 2302.04.01**).

**Blind rivets** ( $2.6 \leq d \leq 6.4$  mm) and **screws** ( $3 \leq d \leq 8$  mm):

$$c_1 \geq 3d$$

$$c_2 \geq 3d$$

$$e_1 \geq 1.5d$$

$$e_2 \geq 3d$$

**Bolts with nuts**, M6 - M16, 8×8 or 10×9:

$$c_1 \geq 1.5d$$

$$c_2 \geq 4d$$

$$e_1 \geq 4d$$

$$e_2 \geq 1.5d$$

**Cartridge fired pin connections**,  $3.7 \leq d \leq 6$  mm bare material,  $t_1 \geq 6$  mm:

$$c_1 \geq 4.5d$$

$$c_2 \geq 4.5d$$

$$c_3 \geq 4.5d$$

$$c_4 \geq 4.5d$$

**Spot welds:**

$$c_1 \geq 4d$$

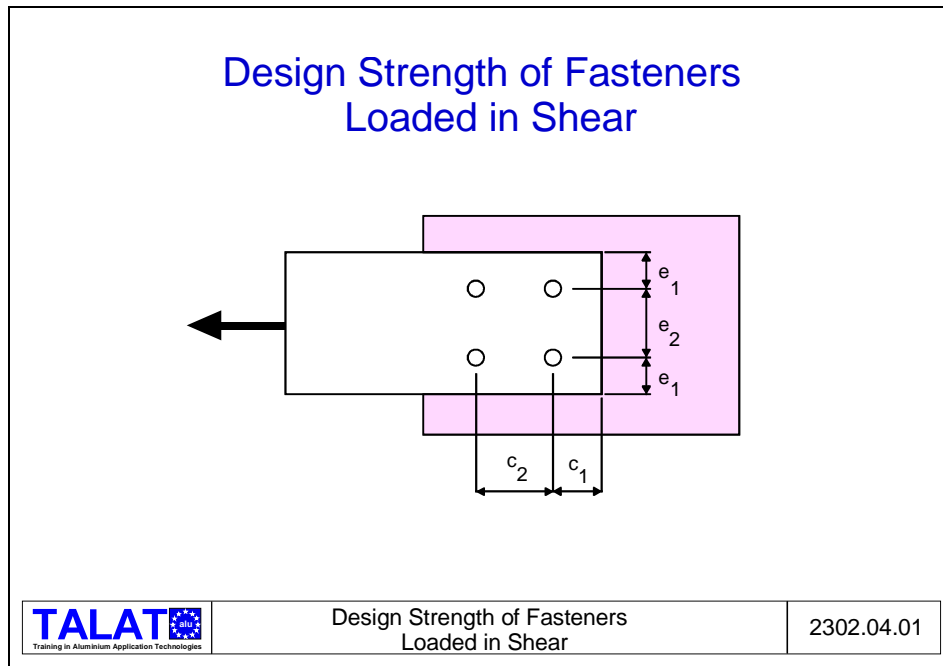
$$c_2 \geq 4d$$

$$e_1 \geq 4d$$

$$e_2 \geq 4d$$

$$t_1/t \leq 3$$

$$0.8 < t < 2.0$$



Design rules for connections made with bolts, rivets and pins are supplied in EC9, too. Indications about the fasteners spacing and end and edge distance are shown in **Figure 2302.04.02** and **Figure 2302.04.03**, for minimum and maximum values, respectively.

### Summary of minimum fasteners spacing and end and edge distance according to EC9

	Normal conditions	Extreme conditions	Max. bearing capacity
$e_1$	$2.0d_0$	$1.2d_0$	$3.0d_0$
$e_2$	$1.5d_0$	$1.2d_0$	=
$p_1$	$2.5d_0$	$2.2d_0$	=
$p_2$	$3.0d_0$	$2.4d_0$	=

### Summary of maximum fasteners spacing and end and edge distance according to EC9

	Compression members	Tension members
$e_1$	12t or 50mm, whichever the larger, or 40mm + 4t (aggressive environment)	12t or 50mm, whichever the larger, or 40mm + 4t (aggressive environment)
$e_2$	12t or 50mm, whichever the larger, or 40mm + 4t (aggressive environment)	12t or 50mm, whichever the larger, or 40mm + 4t (aggressive environment)
$p_1$	14t or 200mm whichever the lesser	28t or 400mm whichever the lesser, but 14t or 200mm whichever the lesser in the outer fasteners row; the above values can multiplied by 1.5 in non aggressive environment
$p_2$	14t or 200mm whichever the lesser	=

#### Legend for **Figure 2302.04.02** and **Figure 2302.04.03**

- $d_0$  hole diameter;
- $e_1$  distance from the centre of a fastener hole to the adjacent end of any part, measured in the direction of the load transfer;
- $e_2$  distance from the centre of a fastener hole to the adjacent edge of any part, measured in the direction perpendicular to the load transfer;
- $p_1$  spacing between centres of fasteners in the direction of the load transfer;
- $p_2$  spacing between centres of fasteners in the direction perpendicular to the load transfer;
- $t$  thickness of the thinnest outer connected part.

### Shear of Fastener

The deformation capacity of a fastener failed by shear is small. Therefore this failure mode is normally not permitted. The characteristic shear strength of fastener shall be 1.25 to 1.5 times larger than other failure modes to allow redistribution of forces in a joints.

**Screws and Rivets.** The ultimate shear strength of screw material is normally not known. Often the design value  $F_{v,Rd}$  is expressed in terms of the ultimate tensile strength  $F_{t,Ru}$  or the torque moment  $M_s$  of the screw. The value of  $M_s$  for a particular screw type is given in national standards.

The following tables give specified values of ultimate strength: for self-tapping screws (**Figure 2302.04.04**), for blind rivets with short break mandrels (**Figure 2302.04.05**) and for rivets with rounded heads (**Figure 2302.04.06**). If these values are used in calculations, it must be demonstrated by test or be guaranteed by the fastener fabricator that actual fasteners meet the strength according to the tables.

Specified Ultimate Forces for Self-Tapping Screws					
$F_{t,Ru}$ = Specified Ultimate Tensile Force (kN/Screw), Characteristic Value *					
Thread	Diameter d in mm	Screw Material			
		Aluminium AA 2014 AlCuSiMn	Carbon Steel, Case Hardened	Stainless Steel, Case Hardened Ferritic	Stainless Steel Austenitic
10	4.8	4	8	8	7
12	5.5	6	11	11	10
14	6.3	8	15	15	13
16	8.0	13	25	25	22

\* The Specified Ultimate Shear Force  $F_{v,Ru}$  is Assumed to be 0.65  $F_{t,Ru}$  (kN/Shear Plane, Characteristic Value)

<b>TALAT</b> Training in Aluminium Application Technologies	Specified Ultimate Forces for Self-Tapping Screws	2302.04.04
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The design strength is

$$F_{v,Rd} = 800 F_{v,Ru} / \gamma_M \text{ [N]} \quad (4.1)$$

where

$F_{v,Ru}$  is the ultimate shear force according to the tables (**Figure 2302.04.04**, **Figure 2302.04.05** and **Figure 2302.04.06**),

$\gamma_M$  is the specified resistance factor.

## Specified Ultimate Forces for Rivets with Short Break Mandrels

$F_{u,s}$  = Specified Ultimate Shear Force (kN/Shear Plane), Characteristic Value \*

Diameter d in mm	Material in Rivet Body				
	Aluminium AA 5052 AlMg2.5	Aluminium AA 5056	Steel	Monel	Stainless Steel Austenitic
4.0	0.8	1.1	1.6	2.4	2.8
4.8	1.1	1.6	2.5	3.5	4.2
5.0	-	1.7	0.6	-	4.6
6.0	-	2.6	-	-	-
6.4	2.0	3.1	-	6.2	-

\* The Specified Ultimate Tensile Force  $F_{u,t}$  is Assumed to be 1.25  $F_{u,s}$  (kN/Rivet, Characteristic Value).



Specified Ultimate Forces for Rivets  
with Short Break Mandrels

2302.04.05

## Specified Ultimate Forces for Rivets with Rounded Heads

$F_{u,s}$  = Specified Ultimate Shear Force (kN/Shear Plane), Characteristic Value \*

Diameter d in mm	Material in Rivet Body			
	Aluminium at Least 99.5% Al	Aluminium Alloy AlMgSi	Steel	Stainless Steel Austenitic
4	0.7	1.6	3.1	5.1
5	1.1	2.6	4.9	8.1
6	1.6	3.8	7.1	11.7

\* The Specified Ultimate Tensile Force  $F_{u,t}$  is Assumed to be 1.25  $F_{u,s}$  (kN/Rivet, Characteristic Strength).



Specified Ultimate Forces for Rivets  
with Rounded Heads

2302.04.06

Shear connections are divided in EC9 into three categories, according to **table 6.3** (see **appendix**). The meaning of each category is summarised in the following:

- Category A: Bearing type

Connections with steel bolts (ordinary or high strength, coated or stainless) or aluminium bolts or rivets. Neither preloading nor special provisions for contact surfaces are required.

- Category B: Slip-resistant at serviceability limit state

Connections with preloaded high strength bolts with controlled tightening. The design serviceability shear load should not exceed the design slip resistance. Both design shear resistance and bearing resistance should not be exceeded at the ultimate limit state.

- Category C: Slip-resistant at ultimate limit state

Connections with preloaded high strength bolts with controlled tightening. The design ultimate shear load should not exceed neither the design slip resistance nor the design shear and bearing resistance.

Tension connections are divided in EC9 into two categories, according to **table 6.3 (see appendix)**. The meaning of each category is summarised in the following:

- Category D: Connections with non-preloaded bolts

Connections with ordinary bolts grade 4.6 and 5.6 or high strength bolts grade 8.8 and 10.9, as well as with aluminium or stainless bolts. No preloading is required. Not recommended for connections frequently subjected to variations of the tensile load.

- Category E: Connections with preloaded high strength bolts

Connections with high strength with controlled tightening. A suitable surface treatment is recommended when subjected to combined tension and shear.

According to EC9, in category C slip-resistant connections as well as in connections where the design shear resistance  $F_{v,Rd}$  of a fastener is less than the design bearing resistance  $F_{b,Rd}$ , the distribution of internal forces between fasteners due to bending moment and to shear must be assumed proportional to the distance from the centre of rotation and uniform, respectively (see **figure 6.9a** of EC9 in the **appendix**).

In other cases the distribution of internal forces between fasteners due to bending at the ultimate limit state may be assumed plastic (see **figure 6.9b** of EC9 in the **appendix**).

EC9 provides rules for the evaluation of the design resistance of bolts and rivets. In **table 6.4 (see appendix)** the expressions of the design shear resistance  $F_{v,Rd}$ , the design bearing resistance  $F_{b,Rd}$  and the design tension resistance  $F_{t,Rd}$  for bolts are supplied.

At the ultimate limit state the design shear force  $F_{v,Ed}$  on a bolt (**Figure 2302.04.07**) shall not exceed the lesser of (see **table 6.4 in the appendix**):

- the design shear resistance  $F_{v,Rd}$ ;
- the design bearing resistance  $F_{b,Rd}$ .

At the ultimate limit state the design tension force  $F_{t,Ed}$ , inclusive of any force due to prying action, shall not exceed the design tension resistance  $B_{t,Rd}$  of the bolt-plate assembly. This should be taken as the smaller of the design resistance  $F_{t,Rd}$  of the bolt and the design punching shear resistance of the bolt head and the nut  $B_{p,Rd}$ , given by:

$$B_{p,Rd} = 0.6 p d_m t_p f_{0.2} / \gamma_{Mb}$$

where:

- p is the centre to centre distance between bolt holes;
- t<sub>p</sub> is the thickness of the plate under the bolt head or the nut;
- d<sub>m</sub> is the mean of the across points and across flats dimensions of the bolt head or the nut, whichever is smaller;
- f<sub>0.2</sub> is the ultimate strength of the member material.

In case of bolts subjected to both shear and tensile force the following requirements must be satisfied:

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4F_{t,Rd}} \leq 1.0$$

The design bearing resistance in **table 6.4** of EC9 (see **appendix**) can be applied only when the edge distance e<sub>2</sub> is not less than 1.5d<sub>0</sub> and the spacing p<sub>2</sub> measured transverse to the load direction is at least 3.0d<sub>0</sub>. If e<sub>2</sub> is reduced to 1.2d<sub>0</sub> and/or p<sub>2</sub> is reduced to 2.4d<sub>0</sub> then the bearing resistance F<sub>b,Rd</sub> shall be reduced to 2/3 of the value given in **table 6.4** (see **appendix**). For intermediate values 1.2d<sub>0</sub> ≤ e<sub>2</sub> ≤ 1.5d<sub>0</sub> and/or 2.4d<sub>0</sub> ≤ p<sub>2</sub> ≤ 3d<sub>0</sub> the value of F<sub>b,Rd</sub> may be determined by linear interpolation.

Similar provisions are supplied in EC9 for rivets. Riveted connections may be designed to transfer forces in shear and bearing. Tension in aluminium rivets is not recommended.

At the ultimate limit state the design shear force F<sub>v,Ed</sub> on a rivet shall not exceed the lesser of (see **table 6.5** of EC9 in the **appendix**):

- the design shear resistance F<sub>v,Rd</sub>;
- the design bearing resistance F<sub>b,Rd</sub>.

In case of rivets subjected to both shear and tensile force the following requirements must be satisfied:

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1.4F_{t,Rd}} \leq 1.0$$

As far as the rules on the design bearing resistance provided in **table 6.5** of EC9 (see **appendix**), the same provisions supplied for bolted connections apply.

## Shear of Fastener

The design value of shear resistance  $F_{V,Rd}$  is proposed to be

$$F_{V,Rd} = 0.8 f_{t,u} / \gamma_m \text{ [kN]}$$

The factor 0.8 is added to take account of the fact that the deformation at shear failure of a fastener is small, about half the diameter.

$\gamma_m$  = specified resistance factor.

The treatment of other types of fasteners are similar.



Shear of Fastener

2302.04.07

### Spot Welds:

$$F_{sd} = 0.4 d^2 f_o / \gamma_M \text{ but not more than } 66 \text{ kN} \quad (4.4)$$

where

$$k = 1.0 \quad (4.5)$$

when weld parameters and strength are closely controlled,

$$k = 0.6 \quad (4.6)$$

for as-rolled material if the welding equipment is set up on the basis of empirical data.

### Hole Bearing

(Figure 2302.04.08)

The shear capacity with regard to hole bearing is the following:

Screws and rivets:

$$F_{b,Rd} = 2.1 t d f_o / \gamma_M \quad (4.7)$$

Bolts with Nuts (see also **tab. 6.4** of EC9 in the appendix):

If  $c_1 / d \geq 6$

$$F_{b,Rd} = 2.1 t d f_o / \gamma_M \text{ [N,mm]} \quad t \leq 1 \quad (4.8)$$

$$= (1.0 + 1.1 t) t d f_o / \gamma_M \quad 1 < t < 2.73 \quad (4.9)$$

$$= 4 t d f_o / \gamma_M \quad 2.73 < t \quad (4.10)$$

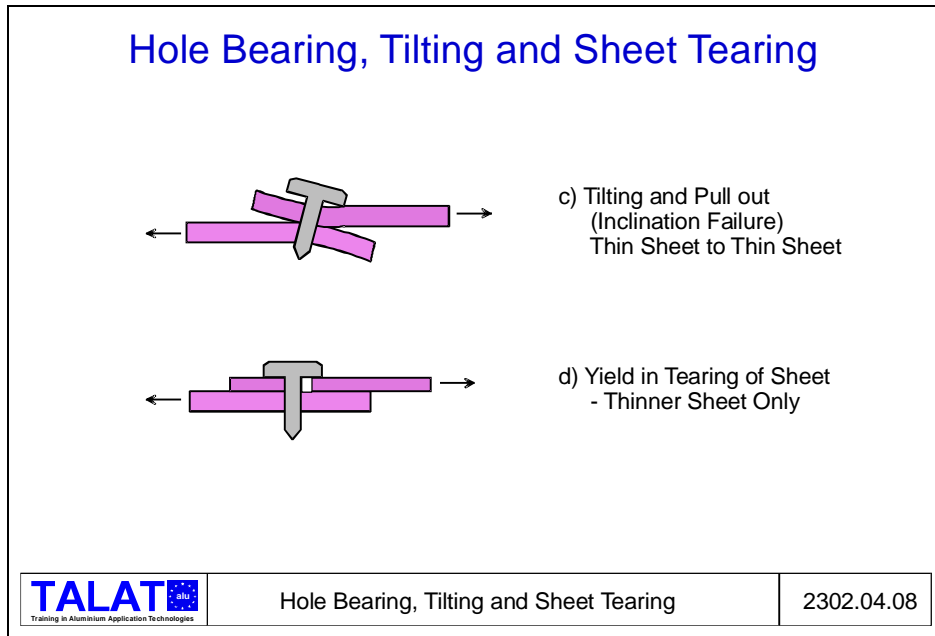
If  $c_1 / d < 6$

$$F_{b,Rd} = 2.1 t d f_o / \gamma_M \text{ [N,mm]} \quad t \leq 1 \quad (4.11)$$

$$= [2.6 - 0.5 t + 0.9 (t - 1) \ln (c_1 / d)] t d f_o / \gamma_M \quad 1 < t < 3 \quad (4.12)$$

$$= [1.1 + 1.8 \ln (c_1 / d)] t d f_o / \gamma_M \quad 3 < t \quad (4.13)$$

According to EC9  $f_o$  can be assumed equal to the conventional yielding stress  $f_{0.2}$ .  
The values for bolts with nuts can also be used for cartridge fired pins.



**Tapping Screws in Screw Grooves:** The shear force capacity is depending on the direction of the force. For a shear force in the direction of the groove opening the design value is

$$F_{b,Rd} = (2 t + 0.16 a) f_o / \gamma_M \quad [\text{N}, \text{mm}] \quad (4.14)$$

where  $t$  [mm] is the wall thickness ([Figure 2302.04.09](#)) and  $a$  [mm] is the thread length in the groove. For a shear force at right angle to the groove opening the capacity is depending on the wall thickness  $t$ . The value according to formula (4.14) is conservative.

### Screw Grooves

a.)

$t > d/3$   
 $d_n < d - 0.55$

Open Direction

b.)

a.) Shear Strength in Open Direction is Less Than in Other Directions.  
b.) Shear Strength in the Extrusion Direction of a Transverse Screw in an Open Groove is Small

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Further groove designs in extrusions and remarks concerning their use can be found in **Figure 2302.04.10**, **Figure 2302.04.11** and **Figure 2302.04.12**.

### Variations in Screw Grooves

Self-tapping screws type ST (B) give good strength in aluminium.  
Use larger than B4

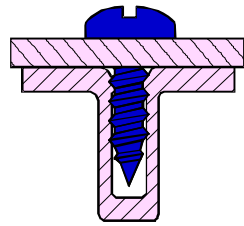
If thread tapping in advance for MM screws, this groove type simplifies tapping.

If screwing perpendicular to the groove, add support at the top

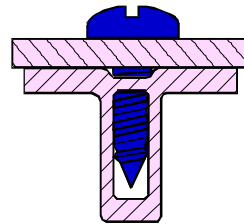
Closed screw channel increases the strength

<b>TALAT</b> <small>Training in Aluminium Application Technologies</small>	Variations in Screw Grooves	2302.04.10
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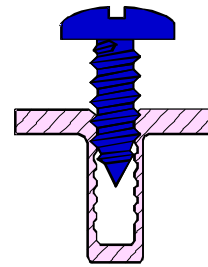
## Longitudinal Screw Grooves



Small shear and tensile strength



Closed groove gives large strength, but drilling of hole is often necessary



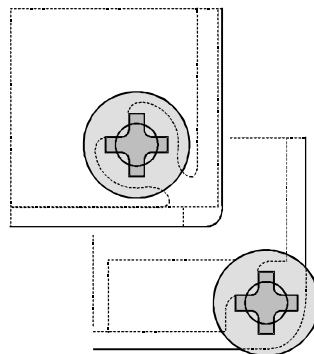
Small ribs increase the tensile strength



Longitudinal Screw Groove

2302.04.11

## Screw Groove at Corner



Avoid screws too close to a corner



Screw Groove at Corner

2302.04.12

### *Tilting and Sheet Tearing*

The shear capacity with regard to tilting (inclination failure) and hole bearing is the following:

Screws and Rivets:

$$F_{v,Rd} = 3.2 \sqrt{t^3} d f_o / \gamma_M \quad \text{for } t = t_1 \quad (4.15)$$

$$= 2.1 t d f_o / \gamma_M \quad \text{for } t = 2.5 \quad (4.16)$$

For wall thicknesses of  $t_1 < t < 2.5t_1$  interpolate between (4.15) and (4.16) (4.17)

Bolts with Nuts and Cartridge Fired Pins: Tilting is not relevant.  
Spot Welds:

$$F_{v,Rd} = 1.6 k d t f_o / \gamma_M \quad \text{but not more than } 250 k d t / \gamma_M \quad (4.18)$$

where k is chosen according to (4.5) and (4.6), respectively.

### *Edge Failure*

(Figure 2302.04.13)

Shear failure of member material is not relevant if

$$\begin{aligned} c_1 &\geq 3d \text{ for screws and rivets,} \\ c_1 &\geq 4.5d \text{ for cartridge fired pins,} \\ c_1 &\geq 4d \text{ for spot welds} \end{aligned}$$

For bolts with nuts the design shear force is

$$F_{v,Rd} = c_1 t f_o / \gamma_M$$

Block shear failure is a combination of shear failure and tension failure and is treated below.

Due to the presence of fasteners holes, a suitable resistance deduction should be kept into account when checking connection plates. As far as shear rupture is concerned, EC9 provides rules for appropriate hole spacing, in order to prevent the connection from “block shear” failure. This mode of failure generally consists of tensile rupture along the horizontal line of fastener holes on the tension face of the hole group, accompanied by gross section yielding in shear at the vertical row of fastener holes along the shear face of the hole group (see **figure 6.7** in the **appendix**).

The design value of the effective resistance to block shear  $V_{eff,Rd}$  or  $N_{eff,Rd}$  is determined via the following formula:

$$V_{eff,Rd} = (f_{0.2} / \sqrt{3}) A_{v,eff} / \gamma_{M0}$$

$A_{v,eff}$  being the effective shear area, evaluated as follows:

$$A_{v,eff} = t L_{v,eff}$$

where:

$$L_{v,eff} = L_v + L_1 + L_2 \quad \text{provided} \quad L_{v,eff} \leq L_3$$

in which

$$\begin{aligned} L_1 &= a_1 \quad \text{but} \quad L_1 \leq 5d \\ L_2 &= (a_2 - k d_{0,t}) (f_u / f_{0.2}) \end{aligned}$$

$L_3 = L_v + a_1 + a_3$  but  $L_3 \leq (L_v + a_1 + a_3 - nd_{0,v}) (f_u/f_{0.2})$   
 $d$  is the nominal diameter of the fasteners;  
 $d_{0,t}$  is the hole size for the tension face;  
 $d_{0,v}$  is the hole size for the shear face;  
 $n$  is the number of fastener holes in the shear face;  
 $t$  is the plate thickness;  
 $k = 0.5$  for a single row of bolts;  
 $= 2.5$  for two rows of bolts

and  $L_v$ ,  $a_1$ ,  $a_2$  and  $a_3$  indicated in **figure 6.7** (see **appendix**)

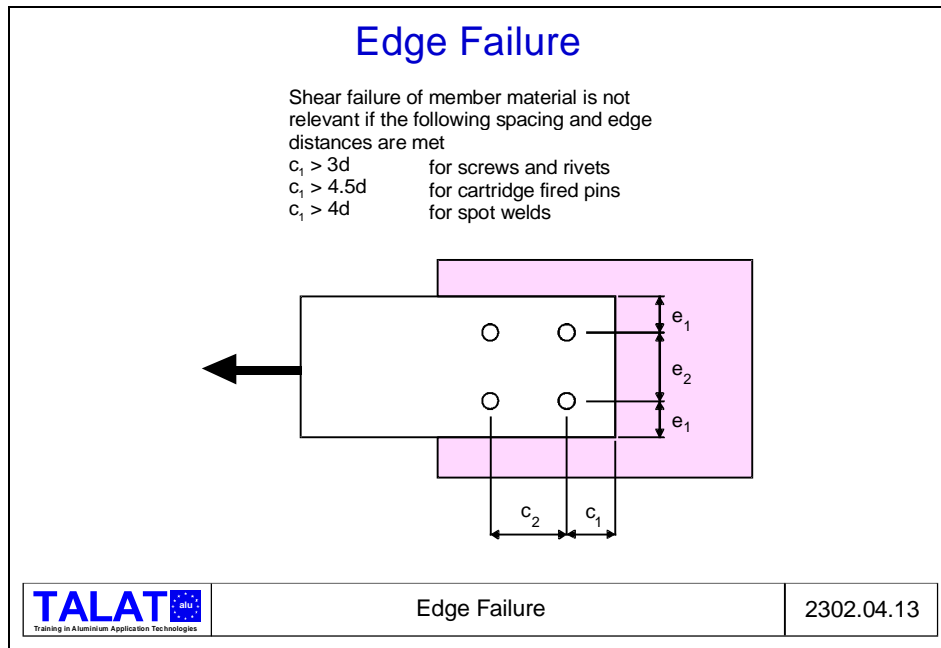
Similar provisions apply in EC9 to unsymmetrical or unsymmetrically connected members, such as for example angles, with or without bulbs, for which the eccentricity of fasteners in end connections and the effects of the spacing and edge distances of the bolts must be taken into account when determining the design resistance. Angle profiles may be treated as concentrically loaded provided a suitable net section is considered in the evaluation of the design ultimate resistance. According to the symbols of **figure 6.8** (see **appendix**), the design ultimate resistance in tension is given by:

with 1 bolt:  $N_{u,Rd} = 2A_1f_u/\gamma_M$

with 2 bolts:  $N_{u,Rd} = \beta_2 A_{Net} f_u / \gamma_M$

with 3 bolts:  $N_{u,Rd} = \beta_3 A_{Net} f_u / \gamma_M$

where  $\beta_2$  and  $\beta_3$  are reduction factors dependent on the bolt pitch  $p_1$  and given in **table 6.2** in the **appendix**.  $A_{Net}$  is the net area of the angle. For an unequal-leg angle connected by its smaller leg,  $A_{Net}$  is evaluated as the net section area of an equivalent equal-leg angle of leg size equal to that of the smaller leg.



### *Tension Failure of Net Section*

The design force with regard to tension failure in the net section is (see also "Edge failure" above):

$$N_{\text{eff,Rd}} = A_{\text{v,eff}} (f_{0.2} / \sqrt{3}) / \gamma_m \quad (4.19)$$

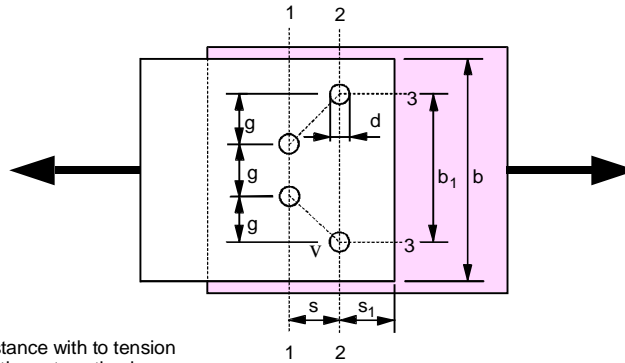
In the case of displaced holes (**Figure 2302.04.14** and **Figure 2302.04.15**), different yield lines are considered to find the smallest net area  $A_n$ . The width is reduced by the diameter of every hole that is passed, and increased by  $s^2/4g$ , but not more than  $0.6s$ , where  $s$  denotes the distance between the center of the holes parallel to the direction of force and  $g$  the distance perpendicular to the same direction.

### **Design Strength of Fasteners Loaded in Tension**

(see also "Design Strength of Fasteners Loaded in Shear")

A survey of design formulae for the various failure modes of fastenings is given in the following paragraphs. The formulae for pull-through failure (4.20 and 4.21) and pull out from underlying member (4.22) till (4.26) are specially derived for sheeting. Therefore, only screws, blind rivets and cartridge fired pins are treated. These are the fasteners normally used for this application. For bolts with nuts tensile failure is determining. For spot welds effects due to deformation of the sheeting shall be taken into consideration.

## Tension Failure in the Net Section

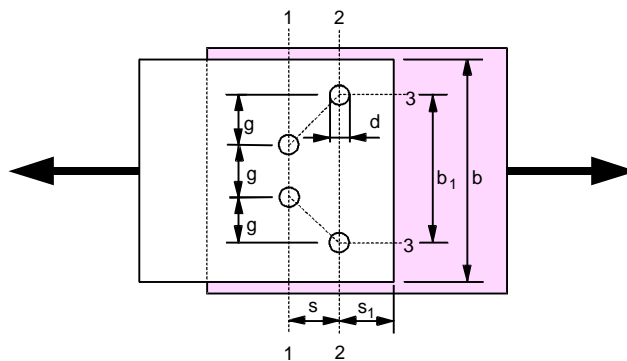


The resistance with to tension failure in the net section is

$$N_{\text{Eff,Rd}} = A_{\text{V,eff}} (f_{\text{t,s}}/1.78)/\gamma_{\text{M2}}$$

Different yield lines are considered to find the smallest net area. The length of the yield line is reduced by the diameter of every hole that is passed and increased by  $s^2/4g$ , but not more than  $0.6s$

## Tension Failure in the Net Section



The net section area  $A_n$  is the smallest of:

$t(b - 2d)$	Section 1
$t(b - 4d + 2s^2/4g)$	Section 2
$t(b - 4d + 2s^2/4g + 2 \cdot 0.6s_1)$	Section 3

The following symbols are used:

- $d$  = diameter of fastener
- $F$  = design strength (subscript depends on failure mode)
- $f_o$  = design value for the yield stress of the connected material
- $f_{o,c}$  = design value for the yield stress of the base material
- $t$  = thickness of connected material
- $t_c$  = thickness of base material

Application limits for the formulae are  $0.5 < t < 1.5 \text{ mm}$   
 $t_c > 1.5 \text{ mm}$  for screws and blind rivets  
 $t_c > 6 \text{ mm}$  for cartridge fired pins

These limits are not limits for the use of the fastener but imposed by the extent of relevant research.

### *Tensile Failure*

Tensile failure in screws and rivets should be avoided. Therefore, the characteristic tensile strength of the fastener shall be larger than other failure modes for screws and rivets.

The ultimate shear strength  $F_{v,Ru}$  [kN] of screws and rivets depends on the fastener material. Specified values for self-tapping screws, blind rivets and rivets with rounded heads are given in tables ([Figure 2302.04.04](#), [Figure 2302.04.05](#) and [Figure 2302.04.06](#)).

The design strength is

$$F_{v,Rd} = 800 F_{v,Ru} / \gamma_M \text{ [N/fastener]}$$

where  $\gamma_m$  is the specified resistance factor.

The design capacity of bolts with nuts ([Figure 2302.04.16](#)) is

$$F_{v,Rd} = \phi_t A_s f_{ub} / \gamma_M$$

where

$A_s$  = stress cross-sectional area of bolt

$\phi_t$  = reduction factor:

= 0.9 for steel bolts

= 0.6 for aluminium bolts

$f_{ub}$  = ultimate strength of bolt material

## Tensile Failure of Bolts with Nuts

The design strength is

$$F_{v,Rd} = \phi_t A_s f_{ub} / \gamma_M$$

where

$A_s$  = stress cross-sectional area of the bolt

$\phi_t$  = reduction factor  
 = 0.9 for steel bolts  
 = 0.6 for aluminium bolts

$f_{ub}$  = ultimate strength of the bolt material

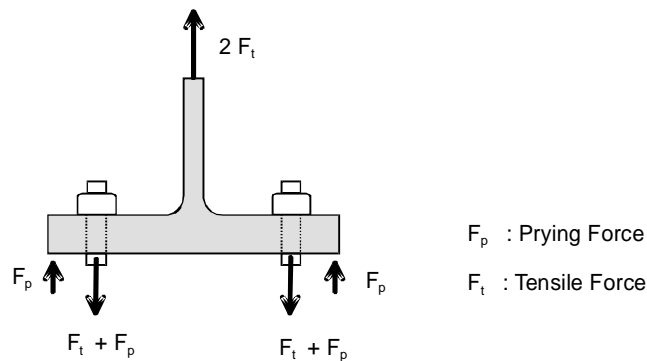


Tensile Failure of Bolts with Nuts

2302.04.16

In designing a connection acted upon by tensile force, it should be borne in mind that prying forces may occur due to deformations (distortions) in the connection. These prying forces must be added to the tensile force due to the external load (**Figure 2302.04.17**). Tensile forces in the bolts due to preloading are to be disregarded. Prying forces due to distortion can be disregarded if the plates which transmit tensile forces to the bolts can transmit the force by bending moment without yielding. If the effect of the prying forces is taken advantage of in the design of the parts, then the prying force should be determined by a suitable analysis.

### Prying Action



Prying Action

2302.04.17

### *Pull-Through Failure and Pull-Over*

#### **(Figure 2302.04.18)**

The resistance design value  $F_{p,Rd}$  with respect to pull-through failure and pull-over can be determined for profiled sheeting according to the following:

For tapping screws and cartridge fired pins axially loaded and provided with heads or washers having a diameter of at least 14 mm and such rigidity that they do not deform appreciably.

$$F_{p,Rd} = 6.5 t f_o / \gamma_M \quad [\text{N, mm}] \quad (4.20)$$

For rivets axially loaded and provided with driving heads of at least 9.5 mm diameter

$$F_{p,Rd} = 2.5 t f_o / \gamma_M \quad [\text{N, mm}] \quad (4.21)$$

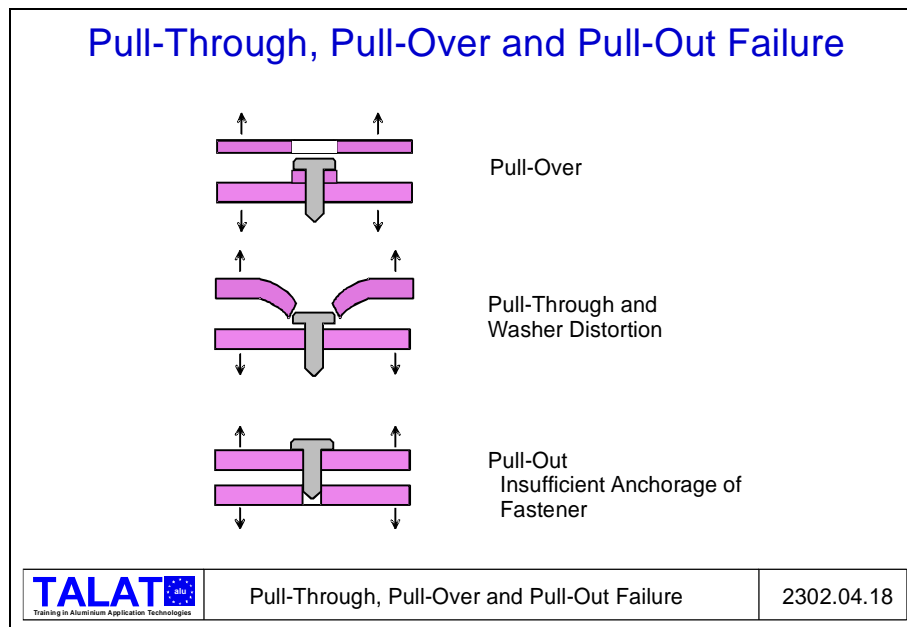
where

$t$  and  $f_o$  refer to the sheet which is placed nearest the head of the fastener.

Pull-through failure or pull over is not relevant for bolts with nuts and spot welds.

The formulae (4.20) and (4.21) are valid for repeated loads with a spectrum similar to wind. For static loads the values can be doubled.

It is assumed that load is applied centrally in a profile flange. When the attachment is at a quarter point, the design value is  $0.9 F_{p,Rd}$  and when it is at both quarter points, it is  $0.7 F_{p,Rd}$  per fastener.



### *Pull Out from Underlying Member*

The resistance design value  $F_{p,Rd}$  with respect to pull-out from the underlying member is determined according to the following:

For tapping screws and underlying member of steel or aluminium with thickness  $t_1 > 0.9$  mm

$$F_{p,Rd} = 0.65 t_1 d f_o / \gamma_M \quad (4.22)$$

for drilling screws and underlying members of steel with  $t_1 \geq 0.5$  mm

$$F_{p,Rd} = 1.5 \sqrt{t_1^3 d} f_o / \gamma_M \quad (4.23)$$

for rivets and underlying member of steel

$$F_{p,Rd} = 0.5 t_1 d f_o / \gamma_{mM} \quad (4.24)$$

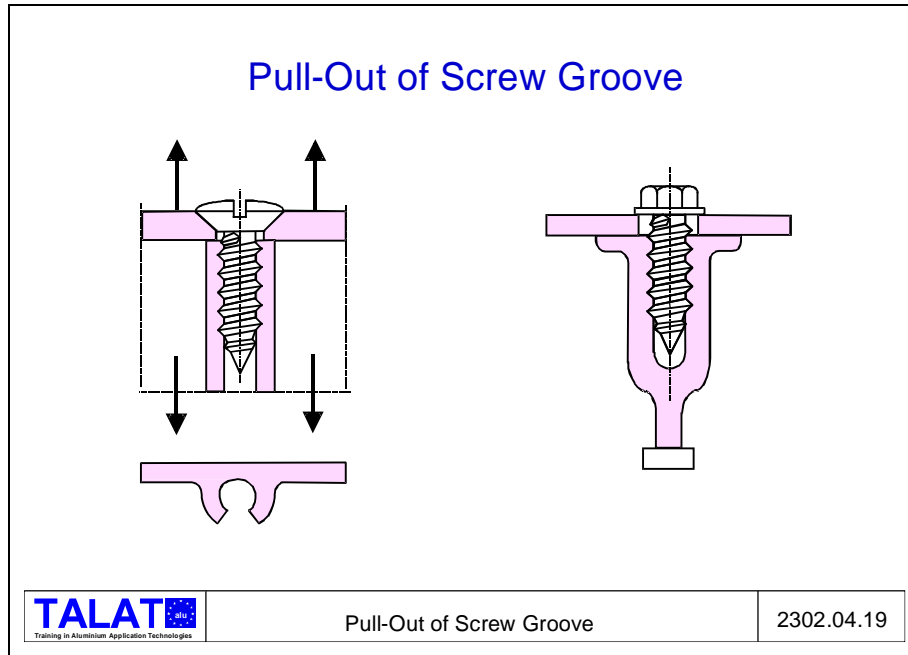
for rivets and underlying member of aluminium

$$F_{p,Rd} = 0.2 t_1 d f_o / \gamma_M \quad (4.25)$$

$t_1$  and  $f_o$  refer to the member placed against the closing head of the rivet,

for tapping screws in screw grooves ([Figure 2302.04.19](#))

$$F_{p,Rd} = 1.6 a f_o / \gamma_M \quad [N, mm] \quad (4.26)$$



where  $a$  [mm] is the thread length in the groove. The thickness round the groove should be at least  $d/3$  and the diameter of the groove should be less than  $d - 0.55$  mm (**Figure 2302.04.09**). The formula is verified by test for  $3 \leq d \leq 7$  mm. Note that the strength is independent of  $d$ .

### Mechanical Fasteners in Combined Shear and Tension

(see also "Fasteners in Shear" and "Fasteners in Tension")

When tensile and shear force act simultaneously, the following conditions shall apply:

Failure in the fastener:

$$\left( \frac{F_{v,Ed}}{F_{v,Rd}} \right)^2 + \left( \frac{F_{t,Ed}}{1.4 F_{t,Rd}} \right)^2 \leq 1.00$$

where

$F_{t,Ed}$ ,  $F_{v,Ed}$  = calculated tensile force and shear force, respectively, due to the design load in the ultimate limit state

$F_{t,Rd}$  = capacity in tension according to the paragraph on tensile failure but for bolts with nuts calculated on the nominal bolt area if the shear plane intersects the unthreaded shank of the bolt

$F_{v,Rd}$  = capacity in shear (according to the paragraph on tensile failure)

Failure in the sheet or profile flange fastened by screws or rivets

$$\left( \frac{F_{v,Ed}}{F_{v,Rd}} \right)^2 + \left( \frac{F_{p,Ed}}{1.4 F_{p,Rd}} \right)^2 \leq 1.00 \quad (4.27)$$

where

$F_{p,Rd}$  = capacity in tension according to the paragraph on pull-through failure or pull over

$F_{v,Rd}$  = capacity in shear as the less of  $F_{b,Rd}$  according to the paragraph on hole bearing and  $F_{v,Rd}$  according to that on tilting.

### Lap joints and pin connections

EC9 also covers one fastener-lap joints and pin connections. The bearing resistance  $F_{b,Rd}$  of single lap joints of flats (see **figure 6.13** in the **appendix**), determined in accordance with point 6.5.5, cannot be greater than:

$$F_{b,Rd} \leq 1.5 f_u d t / \gamma_{Mb}$$

The bolt must be provided with washers under both the head and the nut to avoid pull-out failure. Single rivets should not be used in single lap joints. In case of high strength bolts, grade 8.8 or 10.9, appropriate washers should be used for single lap joints of flats with one bolt only, even where the bolts are not preloaded.

Pin connections are used when free rotation is required. Since pins may be subjected not only to shear but also to bending, at least one of the connected members must be provided with fork ends, or clevis. The pin retaining system, e.g. spring clip, should be designed to withstand a lateral load equal to at least 10% of the total shear load of the pin.

Pin plates provided in order to increase the net area of a member or to increase the bearing resistance of a pin must be of sufficient size to transfer the design force from the pin into the

member and must be arranged in such a way to avoid eccentricity.

The relevant design resistances at the ultimate limit state are given in **table 6.7** in the **appendix**). **Figure 6.14** in the **appendix** shows the criterion to evaluate the bending moments in a pin.

## 2302.05 Design of Welded Connections

- Introduction
- Aluminium alloys and welding technology
- Mechanical properties of weld metal and heat affected zone
- Design of welds
  - Butt welds
  - Fillet welds
  - Design of welded connections
- Design recommendations
  - Design sections
  - Capacity in the ultimate limit state
  - Interaction in connections
  - Influence of welds on overall strength
  - Detailing of welded connections
  - Design of adhesive bonded connections

### Introduction

Although much research on aluminium alloys has been carried out in the past, relatively little attention has been given to their structural behaviour. Therefore, most design rules for aluminium alloy structures are based on design rules for steel structures.

However, applying similar design rules is permissible, since aluminium and steel structures do have very similar structural behaviour. This means, in particular, the application of limit state design methods which allow a better description of the real (non-linear) behaviour of a structure than allowable stress methods. Knowledge is required of the structural behaviour of the members, and apart from strength and stiffness this behaviour is determined by the deformation capacity which enables redistribution of forces to occur in a structure.

### Aluminium Alloys and Welding Technology

Aluminium alloys of the series 5xxx, 6xxx and 7xxx are commonly used for load-bearing structures. The 5xxx series is mainly associated with rolled material, while the 6xxx and 7xxx series are more likely to be concerned with extrusions. Material thicknesses are usually smaller than  $t = 20$  mm, many applications can be found in thin-walled structures with thicknesses below  $t = 6$  mm.

The filler metals most frequently used are: 5356 (= AlMg5), 5183 (= AlMg4-5Mn) and 4043 (= AlSi5). The filler metal 5356 can be combined with nearly all parent metal alloys and is, therefore, the most commonly applied. For some combinations the filler metal 5183 is preferred to 5356, while the filler metal 4043 is mostly combined with parent metal of the 6xxx series.

In the design of welded connections in aluminium alloy structures, the strength of the weld metal is usually lower than the strength of the parent metal. The limiting strength of weld metal strongly depends on the filler metal used. For the above filler metals, EC9 provides the limiting strength of weld metal  $f_w$  (see **table 6.8 in the appendix**) for many types of alloy. The possible combinations of parent and filler metal are shown in **table 3.6 (appendix)**, where the filler metals are grouped into three types (3, 4 and 5), according to the type of alloy.

As far as the welding processes are concerned, the MIG (= Metal Inert Gas welding) and the TIG (= Tungsten Inert Gas welding) processes are generally applied. Within the MIG processes the following can be distinguished: spray-arc, pulsed-arc and sometimes plasma-MIG. Short-circuit MIG is not used because of poor results for the welding of aluminium alloys. With TIG welding, mainly TIG-AC (= Alternating Current) is used.

### **Mechanical Properties of Weld Metal and Heat Affected Zone**


Mechanical properties of weld metal are often given for prescribed combinations of parent and filler metal. For the heat affected zone of non-heat-treatable alloys in the strain-hardened condition the mechanical properties of the parent metal in the annealed condition are applied. For heat-treatable alloys mechanical properties in the heat affected zone are given for a limited number of treatments (often only T6).

In some standards allowable stresses are given both for the weld metal and the heat affected zone. In many standards only the lowest allowable stress or the design strength of the weld metal and heat affected zone is given. In addition, the values for the mechanical properties differ significantly according to different standards.

It can be inferred from the results of investigations carried out in recent years that as far as the weld metal is concerned, the mechanical properties depend on the combination of parent metal and filler metal, the welding process, the plate thickness and the weld type. For the mechanical properties of the heat affected zone the heat-input is of course very important. To give some idea of the variation in values, the main results for the ultimate tensile strength (mean values!) of weld metal and heat affected zone are shown in **Figure 2302.05.01**. It is noted that these results were derived from butt-welded test specimens with a thickness of  $t = 20$  mm. In **Figure 2302.05.08** and **Figure 2302.05.09** recommended values are given.

		Ultimate Strength (Tests <sup>a</sup> ) Heat-Affected Zone ( $\sigma_{uHAZ}$ ) and Weld Metal $\sigma_{uw}$ [N/mm <sup>2</sup> ]					
Parent Metal	Filler Metal		Germany		Italy TIG	N'lands TIG	Poland TIG
			MIG	TIG			
6082-T6	4043	$\sigma_{uw}$	227	194 <sup>b</sup>	142 <sup>b</sup>	168	178
		$\sigma_{uHAZ}$	-	196		175	---
5083-F	5356	$\sigma_{uw}$	309	---	274 <sup>b</sup>	---	272
		$\sigma_{uHAZ}$	306	304	212 <sup>b</sup>	305	---
7020-T6	5356	$\sigma_{uw}$	322	214		---	203
		$\sigma_{uHAZ}$				220 <sup>c</sup>	---

a Tests on butt-welded connections, X-type weld and thickness  $t = 20\text{mm}$ . Mean Values from Test  
 b Weld defects as lack of penetration. Lack of fusion and porosity were observed.  
 c Failure in heat-affected zone at a low stress level, caused by wrong pre-heating

 <small>Training in Aluminium Application Technologies</small>	Main Results for Butt Welds According to an International Institute of Welding Research Programme	2302.05.01
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## Design of Welds

### Introduction

For the design of welded connections has to be verified:

- the design of the welds;
- the design strength of the HAZ adjacent to a weld;
- the design of connections with combined welds.

In the design of welded structures using high strength structural alloys it is necessary to allow for the reduction in strength properties that occurs in the vicinity of welds (heat affected zone, HAZ). The reduction affects the 0.2% proof stress of the material more severely than the ultimate tensile strength. The affected region extends immediately around the weld, beyond which the strength properties rapidly recover to their full unwelded values. For the design purposes, in EC9 it is assumed the throughout the HAZ the strength properties are reduced by a constant factor,  $\rho_{HAZ}$ . A HAZ has to be taken into account for the following classes of alloys:

- Heat-treatable alloys in any heat-treated condition above T4 (6xxx and 7xxx series);
- Non-heat-treatable alloys in any work-hardened condition (3xxx and 5xxx).

It is sometime possible to mitigate the effects of HAZ softening by means of artificial ageing applied after welding.

The deformation capacity of a welded joint can be improved when the design strength of the welds is greater than that of the material in the HAZ.

### *Butt Welds*

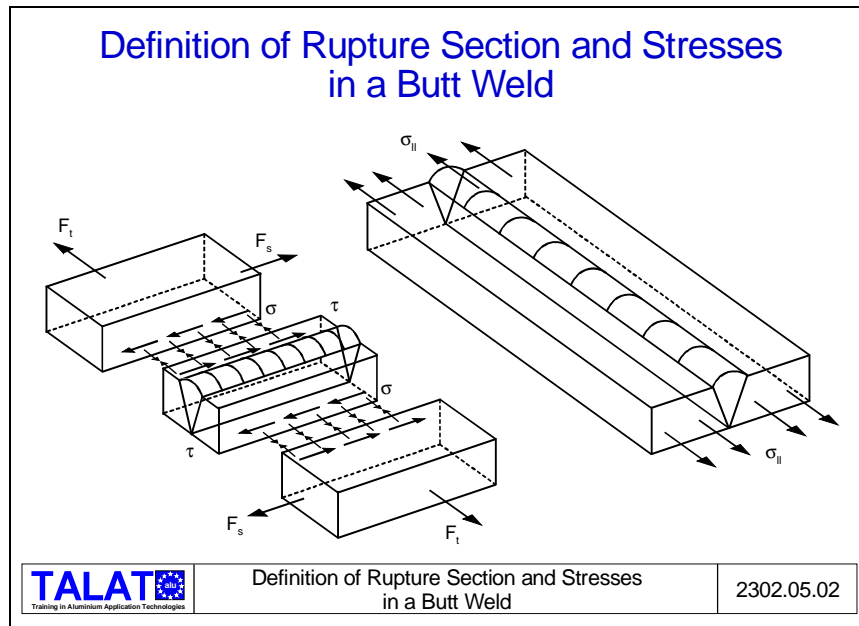
In EC9 butt welds divide into two groups:

- Full penetration butt welds;
- Partial penetration butt weld.

Full penetration butt welds shall be applied for strength members. The effective thickness of such a weld can be taken equal to the thickness of the connected members provided well-exercised weld. With different member thicknesses the smallest member thickness is to be taken into account as weld thickness. The effective length can be assumed equal to the total length when run-on and run-off plates are used. Otherwise, the total length must be reduced by twice the thickness  $t$ .

Partial penetration butt welds can be used for strength members provided the absence of weld defect is verified by testing. In other cases partial penetration but welds can be only used with a higher  $\gamma_{Mw}$  value because of their higher susceptibility for weld defects. For this kind of welding an effective throat section has to be applied (see **figure 6.22** in the **appendix**).

The design of butt welds (**Figure 2302.05.02**) presents few difficulties. The distribution of forces acting in the weld is similar to that in the connected members, and the stressed area is known (for fully-penetrated butt welds; the weld throat  $a \geq$  thickness  $t$ ). This means that the mechanical properties of the weld metal and heat affected zone are the only design parameters.



### *Fillet Welds*

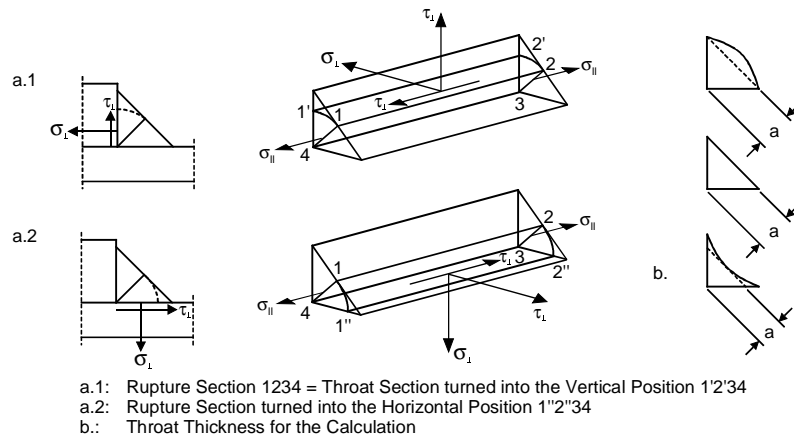
In addition to defining the mechanical properties of the weld metal and heat affected zone, in the case of fillet welds the definition of the rupture section of the weld, and the definition of the stresses in that section, is difficult.

Often for **transverse fillet welds**, in which the direction of the force is perpendicular to the axis of the weld (**Figure 2302.05.03**), the rupture section (= throat section of the weld) is turned to the horizontal or the vertical position, parallel to the direction of the force. This gives a shear stress  $\tau_{\perp}$  perpendicular to the axis of the weld.

For **longitudinal fillet welds**, in which the direction of the force is parallel to the axis of the weld, the shear stress  $\tau_{||}$  (= force divided by the area of the throat section) governs the design.

Another approach which is frequently given in design rules is to divide the force or the resultants of all forces by the total weld throat area ( $F/\sum al$ ) independently of the orientation of the force and the weld. This means that, for reasons of simplicity, no distinction is made between the strength of transverse and longitudinal fillet welds. Sometimes a similar approach is used, but the strengths of transverse and longitudinal fillet welds are distinguished. For transverse fillet welds allowable **tensile** stresses similar to those for butt-welded joints are given, while with longitudinal fillet welds the allowable **shear** stresses coincide. This means that the transverse fillet weld is presumed to be 60% stronger than the longitudinal fillet weld which is not supported by tests. A figure between 45% and 20% is more realistic.

### Definition of Rupture Section and Stresses According to ECCS and DIN 4113 in a Fillet Weld



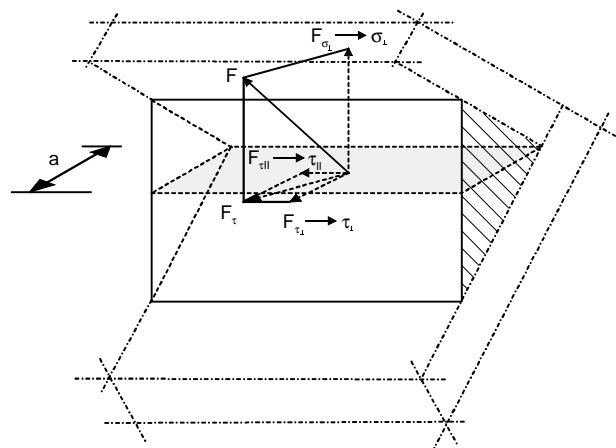
Definition of Rupture Section and Stresses  
According to ECCS and DIN 4113 in a Fillet Weld

2302.05.03

A third approach for determining the strength of fillet welds is to apply the  $\beta$ -formula which is commonly used for steel structures (EC9, IIW, ISO and ECCS Recommendations for steel). With the  $\beta$ -formula it is assumed that:

- failure occurs in the minimum throat section of the weld
- the stress distribution in the throat section satisfies equilibrium
- the stresses are defined in **Figure 2302.05.04**

### Definition of Stresses in Minimum Throat Section of Fillet Welds



Definition of Stresses in Minimum Throat Section  
of Fillet Welds

2302.05.04

According to the  $\beta$ -formula the stresses in the throat section have to satisfy:

$$\beta \sqrt{\sigma_{\perp}^2 + 3(\tau_{\perp}^2 + \tau_{\parallel}^2)} \leq \sigma_d = f_w / \gamma_M \quad (5.1)$$

where

- $\sigma_d$  = design strength of weld metal
- $\beta$  = factor to compensate for the difference in strength and ductility of fillet weld metal and butt weld metal, and to correct the value 3 which in reality is 2.6 for failure

Applying the  $\beta$ -formula, a difference in design strength between transverse and longitudinal fillet welds of  $\sqrt{3} / \sqrt{2} = 1.22$  is assumed.

In ref. [8] results from tests on transverse and longitudinal fillet welds are reported. It appears that:

- The influence of the combination alloy/filler metal/type of specimen (load direction) is very significant. Each combination yields different values for the ultimate strength of the fillet welds.
- The rupture section is very close to the minimum throat section of the welds, except in the case of low strength parent metals and high-strength filler metal. In this case failure occurred at the legs of the weld, as was expected.
- Transverse fillet welds are at least 20% stronger than longitudinal fillet welds. An „exact“ figure cannot be derived from these tests.
- Except for parameters similar to those mentioned above and influencing the mechanical properties of fillet welds, it was observed that the shear strength of longitudinal fillet welds was below the shear strength of the weld metal (butt weld test).
- The deviation in results was considerable, which meant a considerable difference between mean value and characteristic strength (95% confidence level).
- Many weld defects were found, such as lack of fusion, lack of penetration and porosity. MIG welding yielded better results than TIG, while longitudinal fillet welds showed fewer defects than transverse fillet welds.
- Comparison of test results is difficult e.g. because of different definitions of the rupture section.
- The thickness of the rupture section of a fillet weld can be significantly higher than the throat thickness, this being due to positive root penetration. This penetration has to be ensured in the qualification procedure.
- The location and the orientation of the rupture section justify the assumption that the rupture and the throat section of the fillet weld coincide.

For the design of fillet welds it was further found that:

- The  $\beta$ -formula, which can be similarly applied to steel structures, gives the best approximation of the strength of a fillet weld compared with other methods.
- If, applying the  $\beta$ -formula, the design is based on the characteristic strength of the weld metal and the dimensions of the throat section, and a value  $\beta = 1.0$  is adopted, a design strength is obtained which is a reliable lower limit of the actual ultimate strength.
- For simple connections simple design formulas derived from the  $\beta$ -formula can be applied.

According to EC9, the following design formulas, derived from the  $\beta$ -formula, have to be applied for two frequently occurring cases:

- double fillet welded joint loaded perpendicular to the weld axis (see **figure 6.20** in the **appendix**). For the throat thickness  $a$  it must be:

$$\alpha > 0.7 \frac{\sigma t}{f_w / \gamma_{Mw}}$$

where:

$\sigma = F/tb$	is the normal stress in the connected member;
$F$	is the design load in the connected member;
$b$	is the width of the connected member;
$t$	is the thickness of the connected member;
$f_w$	is the limiting strength of the weld metal according to <b>table 6.8</b> in the <b>appendix</b> .

- double fillet welded joint, loaded parallel to the weld axis (see **figure 6.21** in the **appendix**). For the throat thickness  $a$  it must be:

$$\alpha > 0.85 \frac{\tau t}{f_w / \gamma_{Mw}}$$

where:

$\tau = F/th$	is the shear stress in the connected member;
$F$	is the design load in the connected member;
$h$	is the height of the connected member;
$t$	is the thickness of the connected member;
$f_w$	is the limiting strength of the weld metal according to <b>table 6.8</b> in the <b>appendix</b> .

### *Design of Welded Connections*

For the design of welded connections it is often required that a prescribed design stress is nowhere exceeded in the connection. Even with simple connections elaborate calculations have to be carried out, so simplifications are applied which lead to over-dimensioning of the connections. Besides, in reality the allowable stress will always be exceeded locally because of stress and strain concentrations.

A second approach is to distribute the forces acting on the connection over the respective welds in a convenient way and take care to satisfy equilibrium. Then a check should be made to see if the welds are capable of carrying the loads distributed to them.

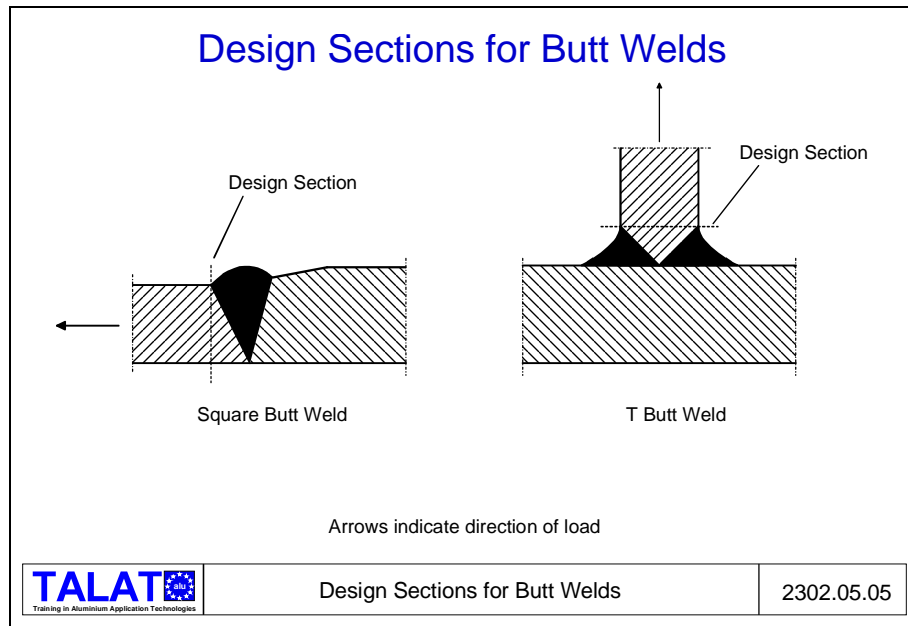
A third approach is very similar to the second, but gives additional rules for the design, i.e. it should be checked whether the forces distributed over the welds can occur in reality. In other words, do the welds possess sufficient deformation capacity to allow the assumed force distribution over them?

Alternatively, it is permissible to calculate the welds for the stresses occurring in the connected parts of a member. For example, in a beam-column connection loaded by moment and shear forces, the flange welds balance the tensile stresses in the flange due to the moment force, and the web welds balance the tensile and shear stresses due to both moment and shear forces.

## **Design Recommendations**

### *Design Sections*

**Butt welded connections:** For a butt welded connection comprising a square butt weld or a T butt weld, the forces shall be calculated at the weakest section adjacent to the weld [Figure 2302.05.05](#)). If the strength of the filler metal (weld bead) is lower than that of the heat affected zone in the parent material, forces shall also be calculated at the weakest section through the weld.



According to EC9 the check of butt welds is done in the following way:

- for normal stress perpendicular to the weld axis (see **figure 6.15** in the **appendix**):

$$\sigma_{\perp} \leq f_w / \gamma_{Mw}$$

- for shear stress (**figure 6.16**):

$$\tau \leq 0.6 f_w / \gamma_{Mw}$$

- for combined normal and shear stress:

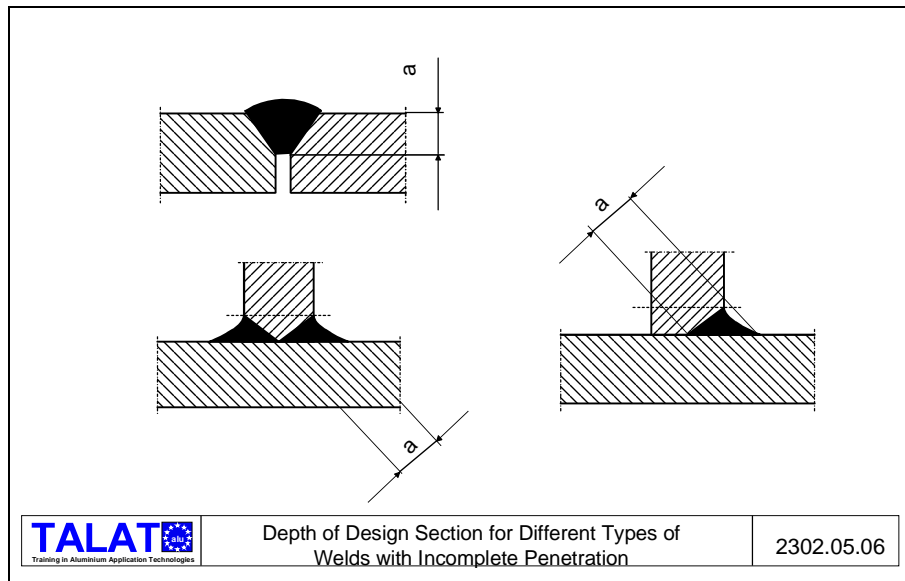
$$\sqrt{\sigma_{\perp}^2 + 3\tau^2} \leq f_w / \gamma_{Mw}$$

where:

- $f_w$  is the limiting strength weld metal according to **table 6.8**;
- $\sigma_{\perp}$  is the normal stress, perpendicular to the weld axis;
- $\tau$  is the shear stress, parallel to the weld axis;
- $\gamma_{Mw}$  is the partial safety factor for welded joints.

Normal stresses parallel to the weld axis do not have to be considered.

Forces in a welded connection with incomplete penetration shall be calculated as for a fillet weld (**Figure 2302.05.06**).



**Fillet welded connections:** In a fillet welded connection, forces shall be calculated both at the section through the weld which has the least nominal sectional area, and at the section immediately adjacent to the weld (**Figure 2302.05.07**).

For the design section through the weld, the height of the section is equal to the nominal throat thickness of the weld, which is the height of the largest triangle that can be inscribed between the fusion faces and the top surface of the weld. The length of the section, the effective weld length, is the length without crater pipes etc.

A weld length greater than 60 times the throat thickness shall not be taken into consideration for a fillet weld if the weld in its longitudinal direction transmits a force which, for the sake of simplicity, is assumed to be uniformly distributed over the length of the weld. For a structure not subjected to fatigue loading or where the risk of brittle fracture is small, the weld length which may be taken into consideration can, however, be increased to 100 times the throat thickness.

The throat thickness of a weld shall not be less than 3 mm. When the throat thickness exceeds 15 mm, the reduction in strength in large fillet welds should be borne in mind.

According to EC9, the effective length is taken as the total length of a fillet weld when:

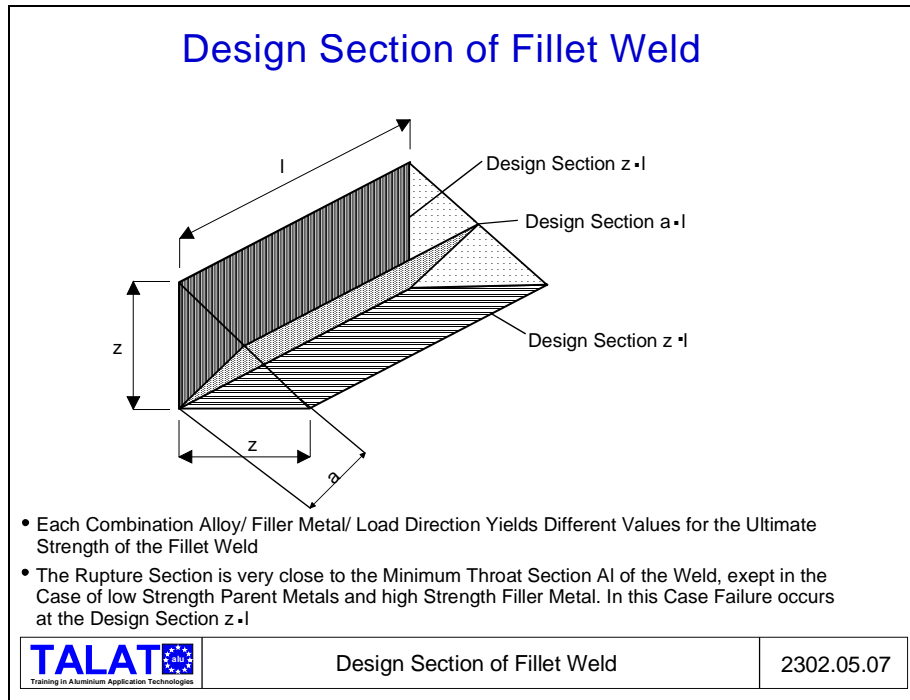
- the length of the fillet is at least 8 times the throat thickness and
- the length of the fillet weld does not exceed 100 times the throat thickness with non-uniform stress;
- the stress distribution along the length of the weld is constant (see **figure 6.17** in the **appendix**).

If the above requirements are not fulfilled, or if the stiffnesses of the connected members differ considerably from each other, the effective weld length of longitudinal fillet welds has to be reduced according to the following formula:

$$L_{w,eff} = (1.2 - 0.2 L_w/100a)L_w \quad \text{with } L_w \leq 100a$$

where:

- $L_{w,eff}$  effective length of longitudinal fillet welds;  
 $L_w$  total length of the longitudinal fillets welds;  
 $a$  effective throat thickness (see **figure 6.18** in the **appendix**).



### *Capacity in the Ultimate Limit State*

The capacity shall be checked for design sections through the weld and through the heat affected zone adjacent to the weld.

The capacity of a design section is determined by the design value of the strength of the weld metal,  $f_{wd}$ , and the strength  $f_{haz,d}$  in the heat affected zone calculated from

$$f_{wd} = \frac{f_w}{\gamma_{Mw}} \quad (5.2)$$

$$f_{haz,d} = \frac{f_{a,haz}}{\gamma_{Mw}} \quad (5.3)$$

where  $f_u$  is the characteristic strength of the electrode material and  $f_{a,haz}$  is the characteristic ultimate strength in the heat affected zone after welding.

In EC9 the limiting stresses  $f_0$ ,  $f_a$  and  $f_v$  in the HAZ are defined in the following way:

$$\begin{aligned}f_0 &= \rho_{\text{haz}} f_{0.2} \\f_a &= f_u \\f_v &= f_0/\sqrt{3}\end{aligned}$$

where  $\rho_{\text{haz}}$  is reduction factor accounting for the material softening due to HAZ, whose values are provided in **tab. 5.2** in the **appendix**. In 7xxx material, values of  $\rho_{\text{haz}}$  are influenced by the nature of the stresses on the HAZ in the following way:

- values a) (**tab. 5.2**) apply when a tensile stress acts transversely to the axis on a butt or a fillet weld;
- values b) apply for all other conditions, i.e. longitudinal stress, transverse compressive stress or shear stress.

The values in **tab. 5.2** are valid from the following times after welding, providing the material has been held at a temperature not less than 10°C:

6xxx series alloys     3 days,  
7xxx series alloys     30 days,

otherwise the recovery time will be prolonged.

The severity of softening can also be taken into account by maintaining the same limiting stresses in the HAZ as for parent metal, but reducing the area over which the stresses act. Thus the limiting load for a simple rectangular section affected by HAZ softening can be expressed as  $(f_0 \rho_{\text{haz}})A$  or  $f_0(A \rho_{\text{haz}})$ .

The HAZ is assumed to extend to a distance  $b_{\text{haz}}$  in any direction from a weld, measured as follows (see **figure 5.6** in the **appendix**):

- a) transversely from the centre line of an in-line butt weld;
- b) transversely from the point of intersection of the welded surfaces at fillet welds;
- c) transversely from the point of intersection of the welded surfaces at butt welds used in corner, tee or cruciform joints;
- d) in any radial direction from the end of a weld.

The HAZ boundaries are generally assumed as straight lines normal to the metal surfaces. In case of thick material it is allowed to assume a curved boundary of radius  $b_{\text{haz}}$  (see **figure 5.6j** in the **appendix**). The values for  $b_{\text{haz}}$  depend on both thickness and welding procedure, according to the table of **Figure 2302.05.08**.

## Values of $b_{haz}$

Thickness t	MIG (interpass cooling to 60°C or less)	TIG
$0 < t \leq 6 \text{ mm}$	$b_{haz} = 20 \text{ mm}$	$b_{haz} = 30 \text{ mm}$
$6 < t \leq 12 \text{ mm}$	$b_{haz} = 30 \text{ mm}$	=
$12 < t \leq 25 \text{ mm}$	$b_{haz} = 35 \text{ mm}$	=
$t > 25 \text{ mm}$	$b_{haz} = 40 \text{ mm}$	=



Values of  $b_{haz}$  according to EC9

2302.05.08

For MIG welding on thickness  $> 12 \text{ mm}$  there may be a temperature effect, because cooling may exceed 60°C unless there is a strict quality control. This will increase the width of the HAZ. For TIG welding the extent of HAZ is greater because of the greater heat input. When two or more welds are close to each other, their HAZ boundary overlap, so to give place to a single HAZ for the entire group of welds.

When a weld is too close to the free edge of an outstand ( $< 3 b_{haz}$ ), the factor  $\rho_{haz}$  applies to the entire width of the outstand.

If the temperature  $T_1$  between weld passes is higher than 60°C (but lower than 120°C), there can result an increase of the HAZ extent. In this case the  $b_{haz}$  is multiplied by a coefficient given by:

6xxx alloys:  $\alpha = 1 + (T_1 - 60)/120$ ;

7xxx alloys:  $\alpha = 1 + 1.5(T_1 - 60)/120$ .

The values of design strength of HAZ according to EC9 are shown in the table of **Figure 2302.05.09**.

	Tensile force perpendicular to the failure plane	Shear force in failure plane	Combined shear and tension
HAZ Butt welds	$\sigma_{haz} \leq \frac{f_{a,haz}}{\gamma_{Mw}}$ at the toe of the weld (full cross section)	$\tau_{haz} \leq \frac{f_{v,haz}}{\gamma_{Mw}}$ at the toe of the weld	$\sqrt{\sigma^2 + 3\tau^2} \leq \frac{f_{a,haz}}{\gamma_{Mw}}$ at the toe of the weld
HAZ Partial penetration butt welds	$\sigma_{haz} \leq \frac{t_e f_{a,haz}}{r \gamma_{Mw}}$ at the fusion boundary (partial penetration)	$\tau_{haz} \leq \frac{t_e f_{v,haz}}{r \gamma_{Mw}}$ at the fusion boundary	$\sqrt{\sigma^2 + 3\tau^2} \leq \frac{t_e f_{a,haz}}{r \gamma_{Mw}}$ at the fusion boundary
HAZ Fillet welds	$\sigma_{haz} \leq \frac{f_{a,haz}}{\gamma_{Mw}}$ at the toe of the weld (full cross section)	$\tau_{haz} \leq \frac{f_{v,haz}}{\gamma_{Mw}}$ at the toe of the weld	$\sqrt{\sigma^2 + 3\tau^2} \leq \frac{f_{a,haz}}{\gamma_{Mw}}$ at the toe of the weld
	$\sigma_{haz} \leq \frac{g_1 f_{a,haz}}{r \gamma_{Mw}}$ at the fusion boundary (figs 6.16 and 6.22)	$\tau_{haz} \leq \frac{g_1 f_{v,haz}}{r \gamma_{Mw}}$ at the fusion boundary	$\sqrt{\sigma^2 + 3\tau^2} \leq \frac{g_1 f_{a,haz}}{r \gamma_{Mw}}$ at the fusion boundary



Design strength for HAZ according to EC9

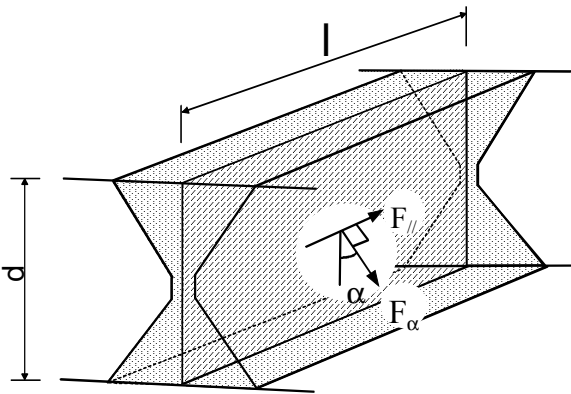
2302.05.09

Legend for the table of **Figure 2302.05.09**:

$\sigma_{\text{haz}}$	design normal stress perpendicular to the weld axis;
$\tau_{\text{haz}}$	design shear stress parallel to the weld axis;
$t$	thickness connected member;
$t_e$	effective throat thickness partial penetration butt weld;
$g_l$	leg length fillet weld (see <b>figure 6.18</b> in the <b>appendix</b> )
$f_{a,\text{haz}}$	limiting strength of HAZ;
$f_{v,\text{haz}}$	limiting shear strength of HAZ;
$\gamma_{Mw}$	material factor for welded joints

The capacity in the ultimate limit state for a design section through the weld shall be calculated in accordance with the following expressions (symbols in accordance with **Figure 2302.05.10** and **Figure 2302.05.11**).

### Resistance of Butt Welds




$$F_{R//} = 0.6 d l f_d$$

$$F_{R\alpha} = \frac{d l f_d}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}}$$

$$f_d = \min \left\{ \begin{matrix} f_{wd} \\ f_{hd} \end{matrix} \right\}$$

$$f_{wd} = \frac{\phi f_{wuk}}{1.2 \gamma_m}$$

$$f_{hd} = \frac{\phi f_{huk}}{1.2 \gamma_m}$$



Training in Aluminium Application Technologies

Resistance of Butt Welds

2302.05.10

$$F_{R//} = 0.6 d l f_{wd} \quad (5.4)$$

and

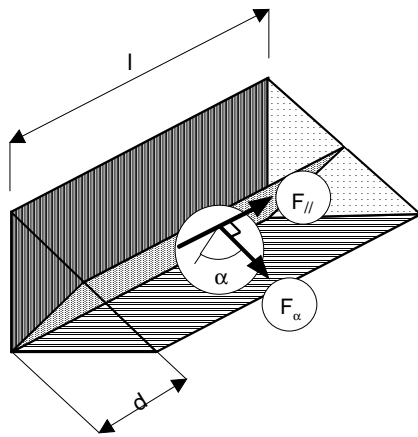
$$F_{R\alpha} = \frac{d l f_{wd}}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}} \quad (5.5)$$

where

$d$  = height of design section

$l$  = effective weld length

## Resistance of Fillet Welds



$F_{//}$  is the component of the resultant force in the longitudinal direction of the design section

$F_{\alpha}$  is the component in a plane perpendicular to the longitudinal direction

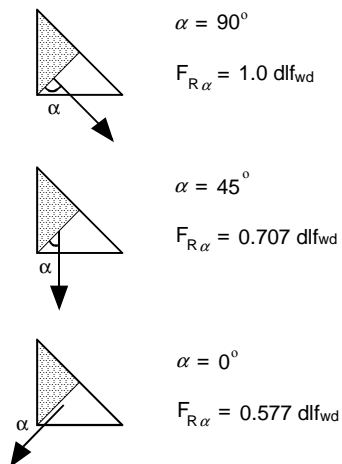
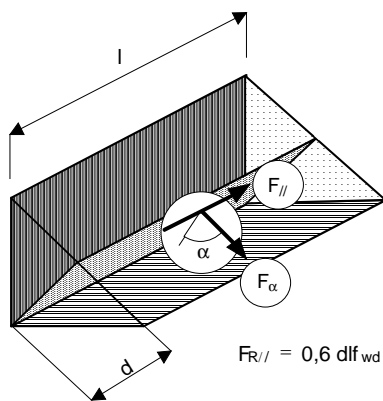
$\alpha$  is the angle between  $F_{\alpha}$  and the design section

$$F_{R\alpha} = \frac{dlf_{wd}}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}}$$

$$F_{R//} = 0.6 dlf_{wd}$$

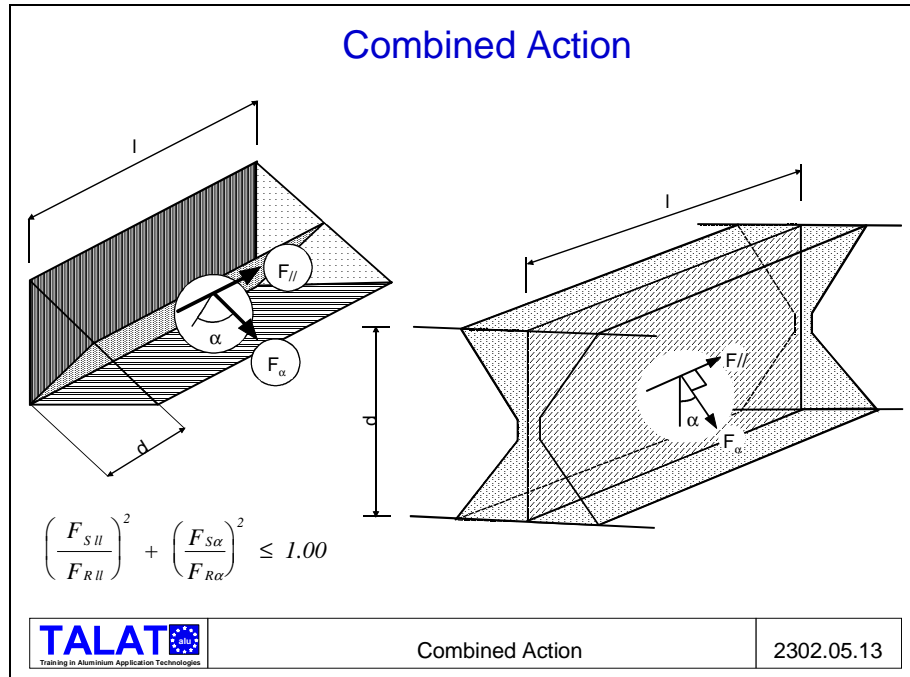
Equation (5.5) is derived from the  $\beta$ -formula 5.1 with  $\beta = 1$  and  $\sigma_d = f_{wd}$ . In the special case  $\alpha = 90^\circ$  then  $F_{R90} = dlf_{Nd}$ . If  $\alpha = 45^\circ$  then  $F_{R45} = 0.707 dlf_{wd}$  and if  $\alpha = 0$  then  $F_{R0} = 0.577 dlf_{wd}$  (**Figure 2302.05.12**).

## Examples of Resistance of Fillet Welds



When the weld is acted upon by forces in both the transverse ( $F_{s\alpha}$ ) and longitudinal ( $F_{\parallel}$ ) directions, see **Figure 2302.05.13**, it shall be shown that the following condition is satisfied:

$$\left( \frac{F_{s\parallel}}{F_{R\parallel}} \right)^2 + \left( \frac{F_{s\alpha}}{F_{R\alpha}} \right)^2 \leq 1.00 \quad (5.6)$$



For a design section in the heat affected zone adjacent to the weld, the capacity shall be calculated in accordance with formulae 5.4 till 5.6,  $f_{wd}$  in formulae 5.4 and 5.5 being replaced by  $f_{hd}$  for the heat affected zone of the parent material and  $d$  replaced by the leg length  $z$  of a fillet weld according to **Figure 2302.05.07**.

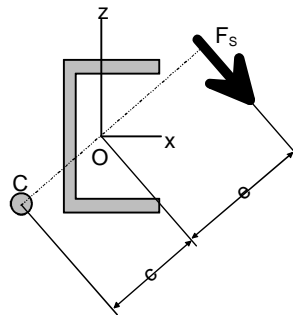
### Interaction in Connections

Longitudinal and transverse fillet welds in e.g. a connection comprising splice plates, or at the attachment of a profiled member, may be designed for a distribution of forces calculated in accordance with the elastic theory or for some other distribution of forces which can be demonstrated to be applicable (see below).

Where a welded connection is combined with a bolted connection, the welded connection is normally designed for the entire force unless it is demonstrated that acceptable interaction occurs. In the case of a welded connection combined with a high strength friction grip bolt connection, interaction may be assumed.

**Eccentrically Loaded Group of Welds in Shear:** For welds subjected to an eccentric load,  $N$ , in the  $x$ - $z$  plane (**Figure 2302.05.14**), the procedure to determine the resistance could be as follows:

## Welds Eccentrically Loaded in Shear

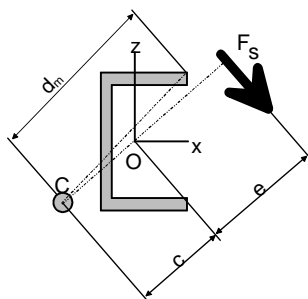


- a. Determine the position of the centroid, O, of the weld pattern, and the Eccentricity of the Applied Force, e.
- b. Compute the total length,  $l_{tot}$ , of the median line of the weld. Compute the polar moment of inertia,  $I_p$ , of the weld pattern about the centroid, using a constant throat,  $a = 1$ .  
(  $I_p = I_x + I_y$  )

- a) Determine the position of the centroid, O, of the weld pattern, and the eccentricity, e, of the applied force.
- b) Compute the total length,  $l_{tot}$ , of the median line of the weld. Compute the polar moment of inertia,  $I_p$ , of the weld pattern about the centroid, using a constant throat,  $a = 1$ . ( $I_p = I_x + I_y$ ).
- c) Determine the distance, c, from the centroid to the centre of rotation of the weld, C, using:

$$c = \frac{I_p}{a l_{tot} e}$$

## Resistance to Fatigue



Procedure (continued):

- c. determine the distance, c, from the centroid to the centre of rotation of the weld, C, using:

$$c = I_p / (l_{tot} e)$$

- d. for **design against fatigue**, the maximum force per unit length of weld is given by:

$$v_m = F_s d_m / (l_{tot} e)$$

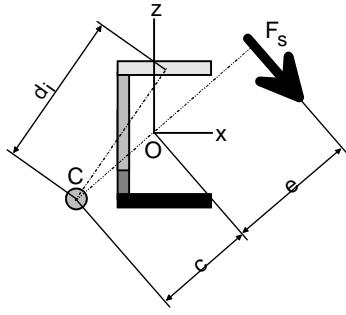
where  $d_m$  is the distance from the centre of rotation, C, to the extreme point of the weld.

d) For design against fatigue, the maximum force per unit length of weld is given by: (Figure 2302.05.15)

$$v_m = \frac{F_s d_m}{l_{tot} \cdot c}$$

where  $d_m$  is the distance from the centre of rotation, C, to the extreme point of the weld.

### Calculation of Static Resistance




e. to calculate the **Static Resistance**, the weld shall be divided into convenient straight elements on each side of the line.

Joining the points C and O, and the distances,  $d_i$ , from the point C to the mid-points of the elements are determined.

The resistance shall be given by:

$$F_{Rsd} = \frac{\sum l_i d_i v_{ri}}{e + c}$$



Training in Aluminium Application Technologies

Calculation of Static Resistance I

2302.05.16

To calculate the design resistance, the weld shall be divided into convenient straight elements on each side of the line joining the points C and O, and the distances,  $d_i$ , from the point C to the mid-points of the elements determined (Figure 2302.05.16).

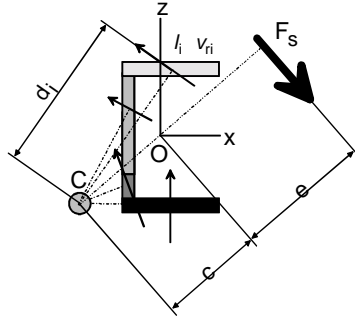
The design resistance shall be given by (Figure 2302.05.17):

$$F_{R,d} = \sum \frac{l_i d_i v_{ri}}{e + c}$$

where

- $l_i$  = length of the i-th element
- $d_i$  = distance from centre of rotation, C, to the mid-point of the i-th element
- $v_{ri}$  = the design value of resistance per unit length of the weld, given by  $0.6af_w$ . Less conservatively, the value of  $v_{ri}$  may be that appropriate to the direction of the force on each length of weld.

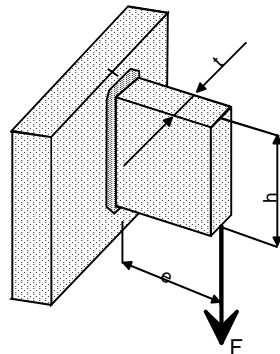
## Calculation of Static Resistance II



$$F_{Rsd} = \frac{\sum l_i d_i v_{ri}}{e + c}$$

$l_i$  = length of  $i_{th}$  element  
 $d_i$  = distance from centre of rotation, C, to the mid-point of the  $i_{th}$  element  
 $v_{ri}$  = the design value of the resistance per unit length of the weld, given by  $0.6 f_{wu}$ .  
 Less conservative, the value of  $v_{ri}$  may be that appropriate to the direction of the force on each length of weld

## Eccentrically Loaded Group of Weld in Bending



$$F_d = \frac{v_c v_t h^2}{2 e (v_c + v_t)}$$

$v_c$  = Design Value of Resistance in Compression per Unit Length

$v_t$  = Design Value of Resistance in Tension of the Weld

The Weld Shall be Continued Around the Edges of the Plate.

**Eccentrically Loaded Group of Welds in Bending:** For double fillet welds subjected to eccentric loading,  $F_{R,d}$ , in the x-y plane (**Figure 2302.05.18**), the weld shall be continued around the edges of the plate. The design resistance shall be given by:

$$F_{R,d} = \frac{v_c v_t h^2}{2e(v_c + v_t)}$$

where

$e$  = eccentricity

$h$  = length of fillet welded joint

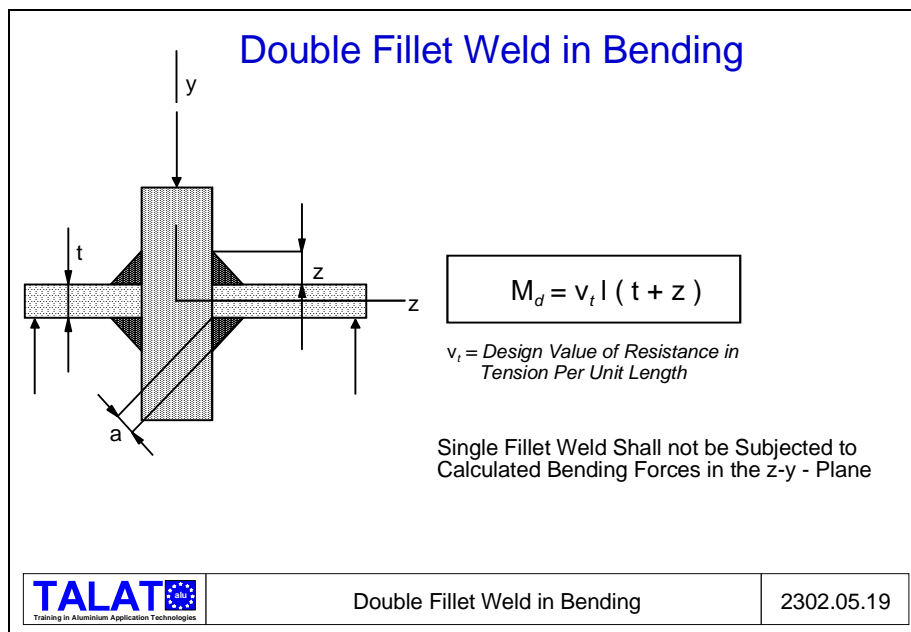
$v_c$  = design value of resistance in compression per unit length

$v_t$  = design value of resistance in tension of the weld

**Fillet Welds in Bending:** For double fillet welds in bending in the z-y plane (**Figure 2302.05.19**), the moment resistance shall be given by:

$$M_{R,d} = v_t l(t + z)$$

Single fillet welds shall not be subjected to calculated bending forces in the z-y plane.



**Flare Groove Welds:** Where welds are to be made between rounded surfaces, as between round bars and at the corners of formed shapes, procedures shall have been demonstrated to give the required penetration and throat thickness.

The requirements may be shown to be satisfied by measurement of the weld throat or by load tests. If measurement is made, the throat shall exceed that required for the design strength by 3 mm. If tests are made, there shall be at least three specimens made consecutively using the same procedure. The lowest value obtained shall be used as the characteristic strength.

**Slot and Plug Welds:** A connection made by a fillet weld along the inside edge of a hole or slot is acceptable if the radii of the corners are not less than the thickness of the plate plus 5 mm.

The weld shall extend around the full length of the inside edge of the hole. The length of the weld shall be taken as the length of the centroidal axis of the fillet. Holes or slots which are completely filled with weld metal shall not be permitted to carry calculated forces.

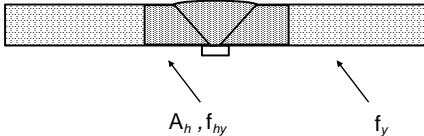
#### *Influence of Welds on Overall Strength*

**Tension and Compression in Constrained Members (Figure 2302.05.20):** In concentrically-loaded tension members, and compression members which do not buckle, longitudinal heat affected zones shall be considered to reduce the resistance by an amount given by:

$$A_h (f_y - f_{hy}) l$$

for each longitudinal weld.

### Influence of Transverse Welds on Overall Strength



In centrally loaded tension members and compression members which do not buckle, longitudinal heat affected zones shall be considered to reduce the resistance by an amount given by:

$$A_h (f_y - f_{hy})$$

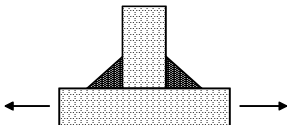
Longitudinal welds may be disregarded where resistance is controlled by local buckling

<b>TALAT</b> <small>Training in Aluminium Application Technologies</small>	Influence of Transverse Welds on Overall Strength I	2302.05.20
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**Influence of Transverse Welds on Overall Strength:** Where a fillet weld is applied to a plate, and the plate is continuous past the weld (**Figure 2302.05.21**), the resistance of the plate shall be the lower of the yield strength of the base metal and the ultimate strength in the heat affected zone, for both tension and compression.


For beams and columns, with a transverse weld within  $L/5$  of the ends of the member, where  $L$  is the member length, the resistance shall be limited to that given in **TALAT Lecture 2301** (Design of Members).

### Influence of Transverse Welds on Overall Strength



Where a fillet weld is applied to a plate, and the plate is continuous past the weld, the resistance of the plate shall be the lower of the yield strength of the base metal and the ultimate strength of the heat affected zone, for both tension and compression.

$$f_d = \min \begin{cases} f_{yd} \\ f_{hd} \end{cases} \quad \begin{matrix} \text{(Yield Stress)} \\ \text{(Ultimate Strength)} \end{matrix}$$

	Influence of Transverse Welds on Overall Strength II	2302.05.21
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**Influence of Welds on Local Buckling:** Longitudinal welds may be disregarded where resistance is controlled by local buckling. Unrestrained transverse welds limit the compressive stress to the ultimate strength of the heat affected zone.

#### *Detailing of Welded Connections*

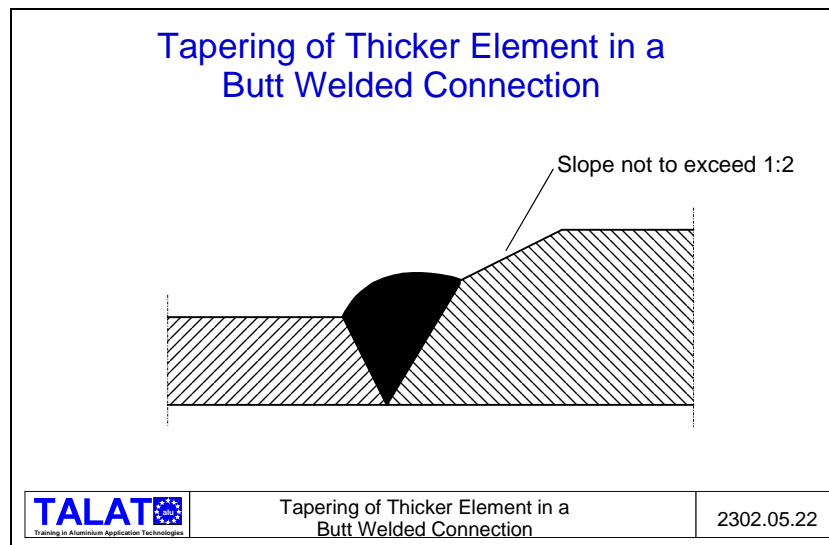
To eliminate unnecessary distortions and reduction of strength in heat affected zones there should be as little welding as possible in a structure, and especially where thin gauge metal is involved. The use of castings, extrusions, forgings and bent or roll-formed shapes can often help to eliminate welds. However, when welds must be used they should always be as small as possible for the strength required. Groove welds should be narrow and as symmetrical as possible through the thickness of the joint. Welds in beams or similar structures should be located on, or near, the neutral axes. If welds must be placed away from the neutral axis and more than one weld is required, it helps to position them so that their contraction stresses can balance each other.

Joint design should be chosen which lend themselves to automatic welding, to high speed welding and to the minimum number of weld passes to complete a joint.

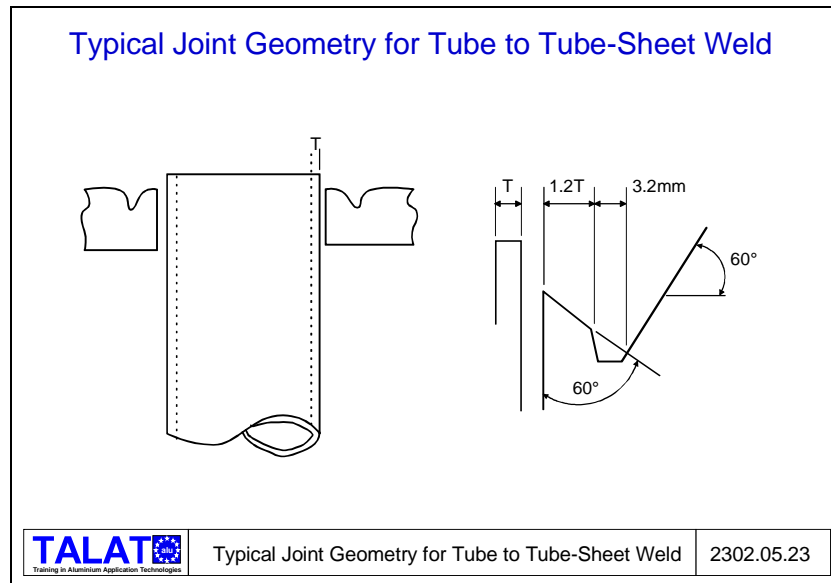
Intermittent welds tend to cause less distortion than continuous ones, but may be inappropriate for other reasons ( see below).

**Direct Bearing:** Transmission of pressure between two parts of a welded structure may be assumed to take place in direct bearing between the faying surfaces provided that the fit between the faying surfaces is satisfactory. Such faying surfaces shall be marked on drawings.

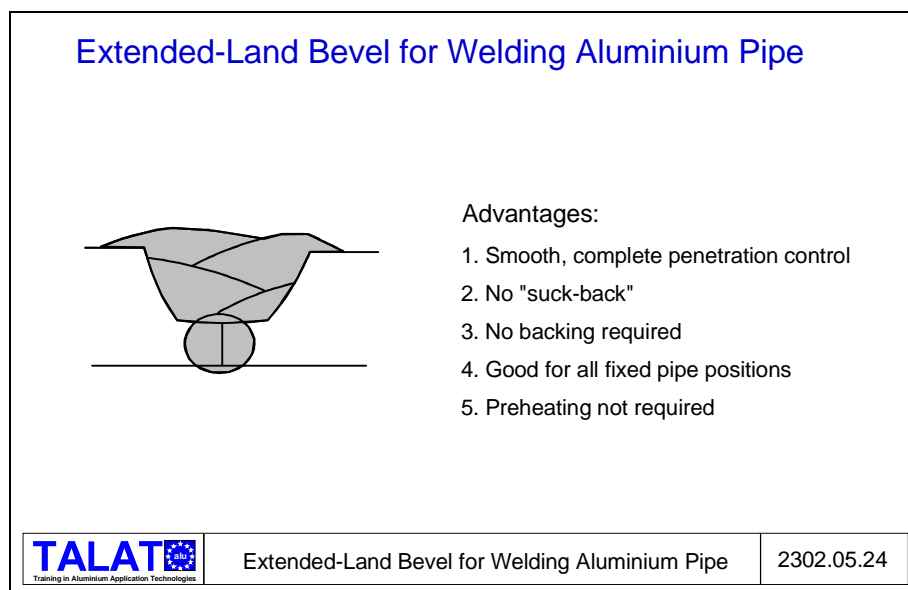
**Elements of different Thickness:** Where a butt weld is made between elements of different thicknesses, the thicker element shall be tapered at a slope of 1:2 or flatter (**Figure 2302.05.22**).



A special groove weld design in the tube to tube-sheet welds in heat exchangers has been developed to permit successful welding of an otherwise unweldable joint between elements with very different thicknesses **Figure 2302.05.23**. The groove reduces the tube-sheet thickness locally at the joint, so that a weld can be made at current levels and welding speeds at which the arc does not melt through the tube.



Another special groove weld design, the extended-land beveled joint (**Figure 2302.05.24**) is used to make circumferential arc welds in pipe. In joining pipes welding must be done from one side only, in all welding positions and yield a smooth uniform penetration bead.



The effectiveness of this joint design is dependent on surface tension supporting the molten metal in the weld pool. To make this possible, the U-groove formed by the extended-land bevel is applied to all thicknesses over 3 mm. The bottom of the groove must be wide enough that it will accept the full root bead, which penetrates the 1.6 to 3.2 mm thick root and produces good root bead formation. The groove is then filled by making additional weld passes. This technique has been used very successfully for pipe welding, even in the horizontal fixed position.

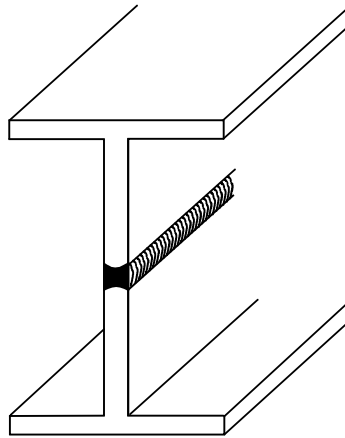
Groove welds may be required to be fully penetrated or only to be partially penetrated. The latter are not common because they are not effective under loading which puts the weld root in tension, and also because it is difficult to determine penetration depth by common inspection methods. However, national standards do allow for the use of partially penetrated groove welds under carefully controlled conditions.

**Intermittent Welds:** The cost of fillet welds is mainly a function of the square of their size. Thus large intermittent fillet welds are not as efficient for carrying loads as small continuous fillets. This is the case, even without taking into account that some design standards specify that the ends of each weld are to be considered non-load carrying, which means that intermittent welds must be longer than theoretically necessary. If we also take into account that weld starts and stops are locations of potential defects, it becomes evident that a sounder and more economical structure results from continuous fillet welds than from intermittent ones. The only factor which may sometimes favor intermittent welds is control of distortion because intermittent welds tend to produce less distortion.

**Compensation for Strength Loss at Welds:** If the welds in a structural member have much lower strength than the base metal, as for example welds in 6061-T6 alloy, and if postweld heat-treatment is not practical, efficient design often requires that an attempt must be made to minimize the loss of load carrying capacity. Three common ways of achieving this are as follows:

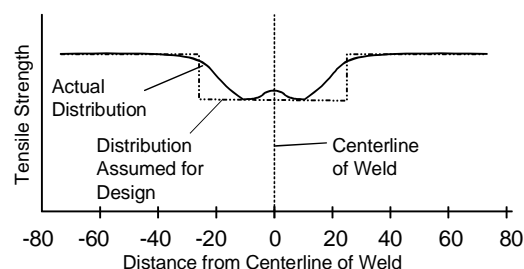
- Locate welds in low stress areas. Beams loaded in bending can be fabricated by welding together two or more longitudinal extrusions with the joints located in the web or webs, at or near the neutral axis (as illustrated in [Figure 2302.05.25](#)). This has the secondary benefit that the metal thickness in the web is often much thinner than the flanges, which reduces the amount and cost of welding.

### Example of a Weld at Neutral Axis of Beam



- Locate welds parallel to the principal stress direction. There are occasions when welds must be in highly stressed locations but their orientation is optional, i.e. they can be either parallel or transverse to the principal stress. If the weld can be parallel, its effect will be limited to a narrow zone, leaving the balance of the member at full strength. **Figure 2302.05.26** shows the normal design allowance for the reduced strength zone on either side of a butt or fillet weld.
- Add reinforcement to butt joints to increase their strength. If transverse groove welds must be used, their static strength can almost be fully restored by the application of doubler plates. The fatigue performance of the joint will be dependent largely on the care taken in designing the doubler and in welding it.

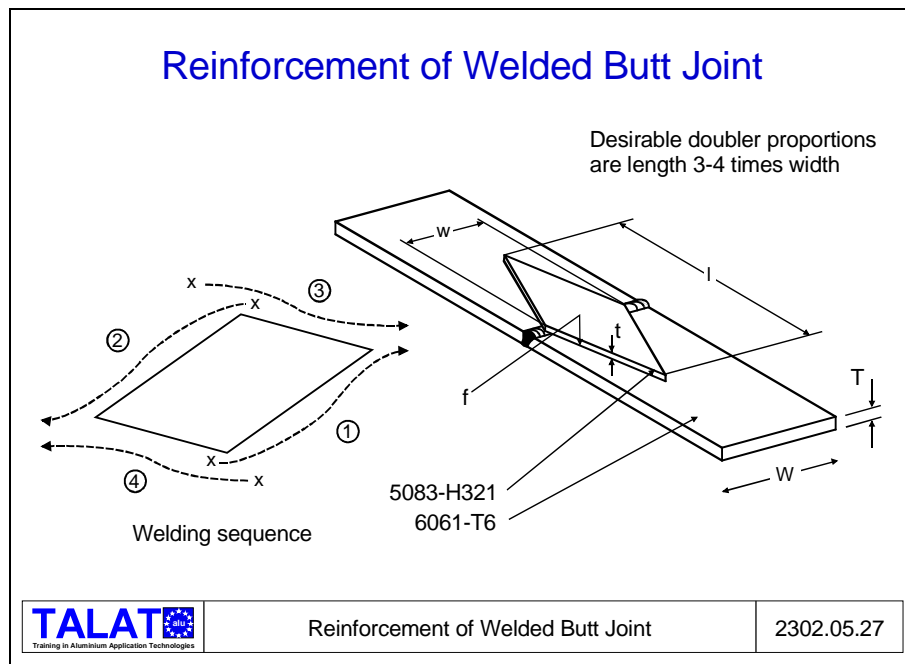
### Design Strength of Welds



In principle the design section through the weld and sections through the heat affected zones shall be checked.

The resistance of a design section is determined by the design value of the strength of the weld metal,  $f_{wd}$ , and the strength,  $f_{hd}$ , in the heat affected zone, respectively.

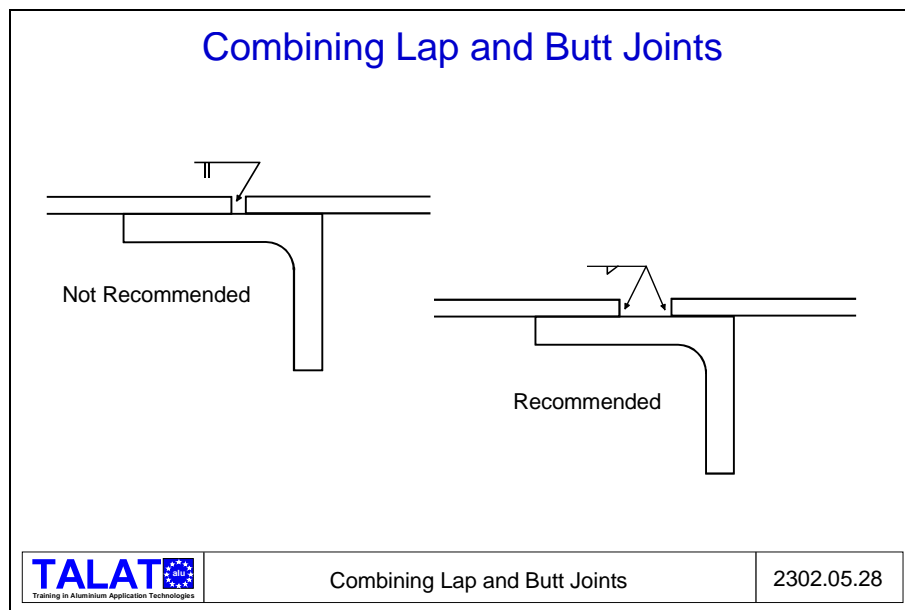
**Doubler Plates:** Doubler designs for steel are not necessarily suitable for aluminium. The commonly used rectangular plates welded on four sides introduce transverse welds which reduce the main member strength. Or if welding is limited to the sides of the doubler, which are parallel to the stress direction, the longitudinal fillet welds are so highly stressed at their ends that they fail progressively at unsatisfactory load levels. Even welding around the corners for a short distance is not effective because it represents some transverse welding, and also does not totally eliminate the stress concentrations at the ends of the fillet welds. Instead, a diamondshaped doubler with pointed ends has been found to be the best shape (Figure 2302.05.27).



The doubler thickness is chosen to have enough tensile strength at its midpoint to replace the strength loss in the main member.

The fillet welds should be made in the sequence shown in [Figure 2302.05.27](#) and should begin from the midpoint of the doubler and progress to each tip. The arc should be extinguished on the base metal and a crater avoided by increasing the welding speed before the arc is broken. This doubler design has the additional advantage that it leaves no crevices for possible corrosion attack.

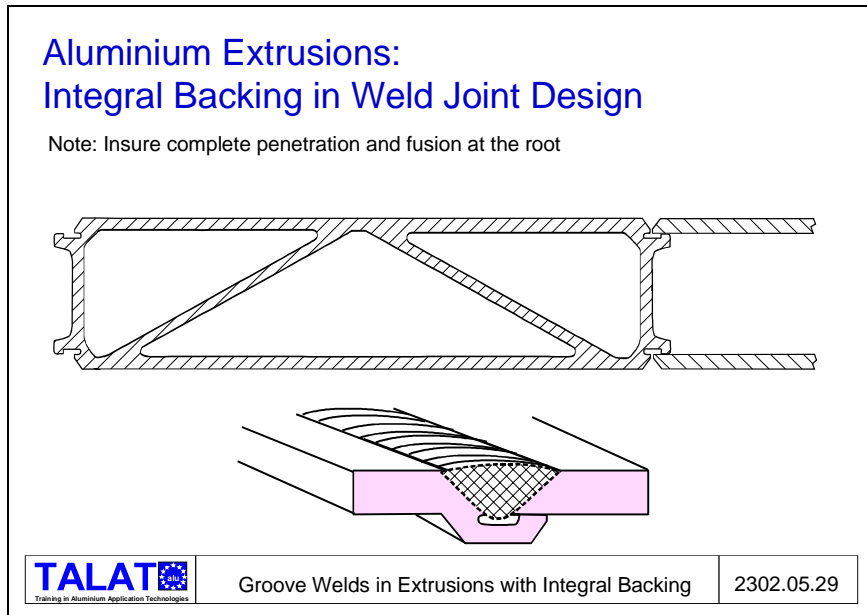
**Combined Lap and Butt Joints:** When sheet metal panels are to be welded to extruded members, as for the roofs on railcars, an attempt has sometimes been made to use a joint opening between panels and set the welding procedure to make both a groove weld and also give adequate attachment to the extrusion ([Figure 2302.05.28](#)). In effect, what is desired, resembles a slot weld, but it seldom proves to be practical. The joint fit and the welding procedure are both critical, if the sheet edges are not to melt back from the joint when the welding current is high enough to penetrate the extrusion. Further complicating the situation is the fact that 5xxx series sheet alloys have lower thermal conductivity than 6xxx series extrusion alloys, which means that the arc melts the sheet more readily than the extrusion, even if their thicknesses are comparable, and even if the joint fit is ideal. Consequently, it has been found to be preferable to specify conventional lap joints for this application.



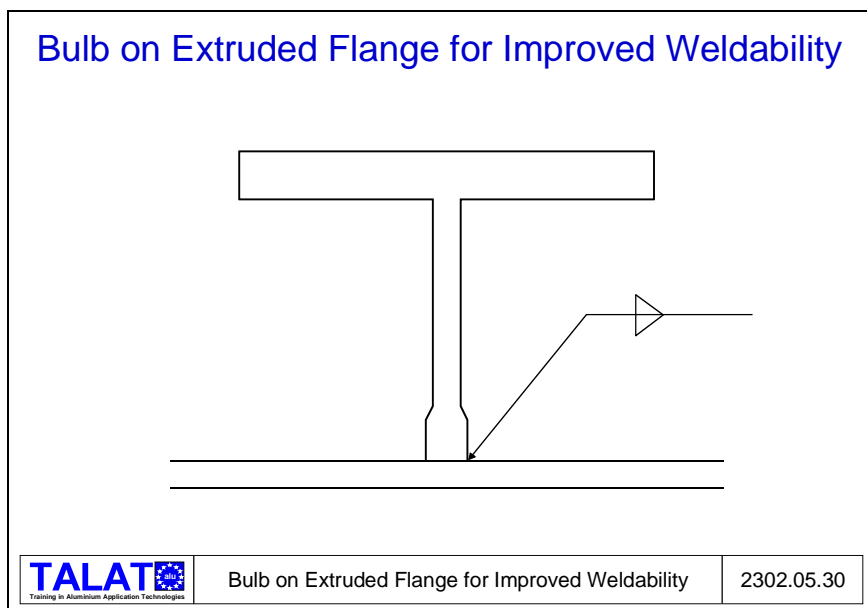
**Extruded Shapes:** The design freedom afforded by using special extrusions can be of greatest benefit to a designer seeking to improve the ease and accuracy of assembling and welding aluminium structures. Several of the more common special extrusions with features especially designed to improve their weldability will be described.

Integral backing can be designed into an extrusion (see [Figure 2302.05.29](#)). An example can be a double-wall extrusion for a side-sill of a rail car. In this case, there is no access

for double-sided welding of the butt joints, and it would be impractical to use removable backing strips for single-sided welding. Instead, a backing flange added to each extrusion, provides weld backing for the butt joints, as well as alignment for the components. A joint with integral backing requires care to ensure complete penetration and fusion at the root.

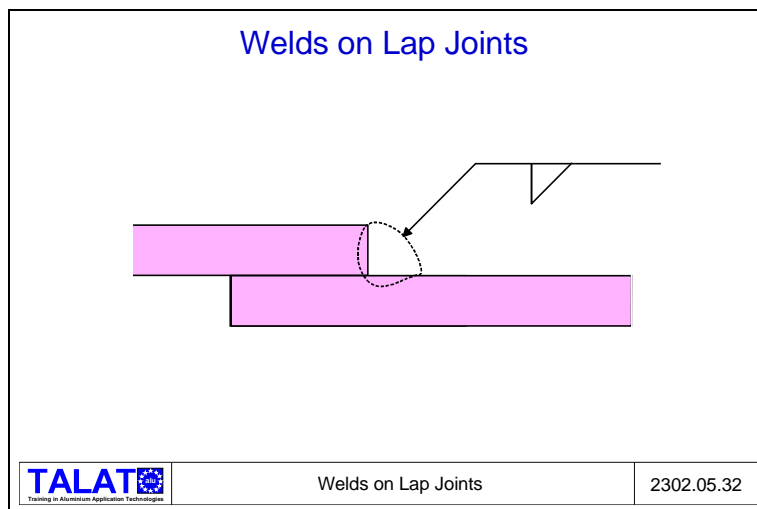
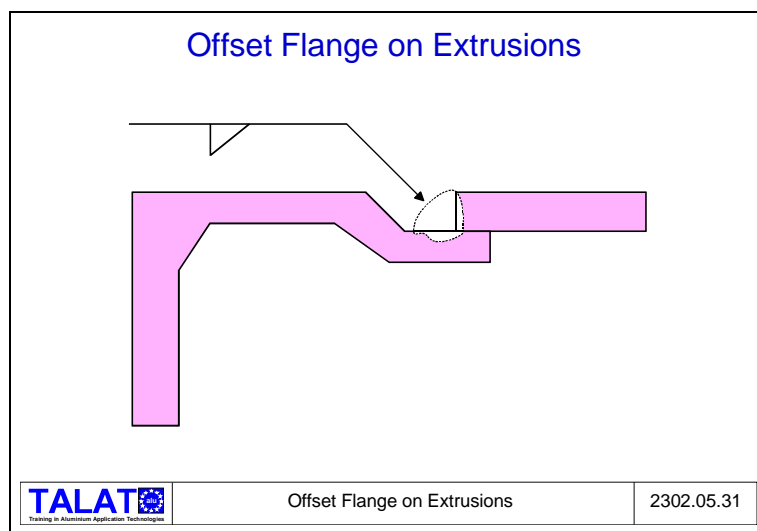


Efficient panel stiffening members commonly have thick flanges and thin webs; they are not necessarily chosen for easiest welding. A thin web to be welded to a thicker panel member is often difficult to weld without overheating the toe of the extrusion. Also the webs have a tendency to deflect easily as welding progresses. In such cases adding a bulb to the toe of the web (**Figure 2302.05.30**) can be beneficial or, if the upper flange width makes access to the joint for welding difficult, replacing the bulb by a narrow flange can be helpful.



Lap joints have an advantage over butt joints, in that they allow some variation in overlap without affecting joint weldability, but they do not provide flush surfaces. Also the offset at the joint creates a bending moment when the joint is loaded in transverse tension or compression. The stress raisers at the toes of the fillet welds combined with the bending moment cause lap joints to have lower fatigue strength than butt joints. An offset extrusion (**Figure 2302.05.31**) can help to reduce this effect.

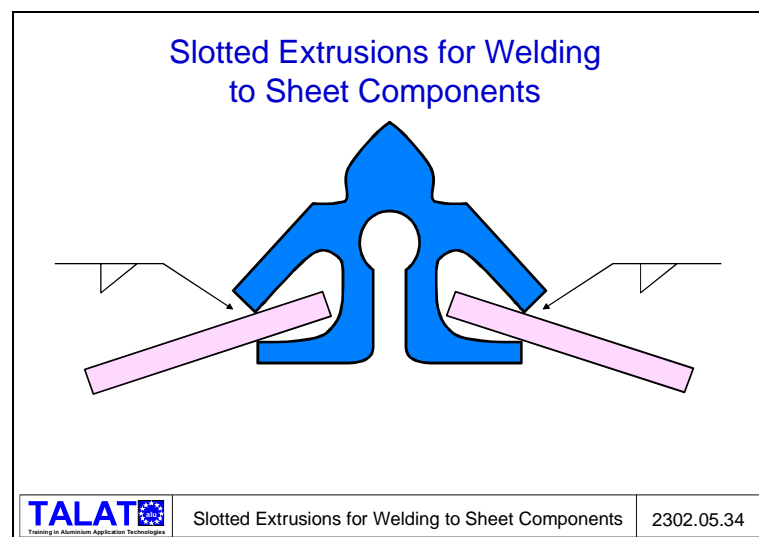
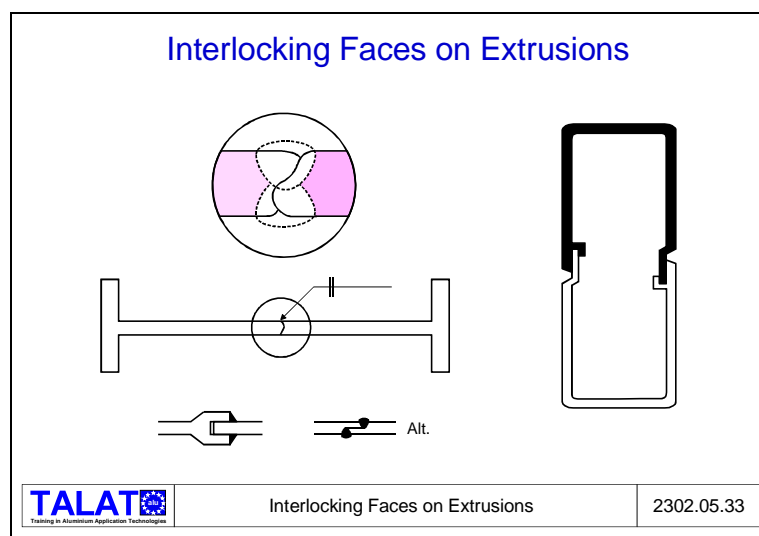
Lap joints that require fillet welds of a size approaching the metal thickness, can be difficult to arc weld. The arc heat tends to melt the exposed corner and to flow molten metal into the root of the joint before it is adequately penetrated. It also tends to produce the unsatisfactory weld shape shown in **Figure 2302.05.32**. TIG welding is more prone to cause this problem, but, even with MIG welding, care is necessary to avoid it.



If a butt joint is to be made between extruded members, as is often the case in fabricating a beam from two T-extrusions, joint alignment is more easily maintained if

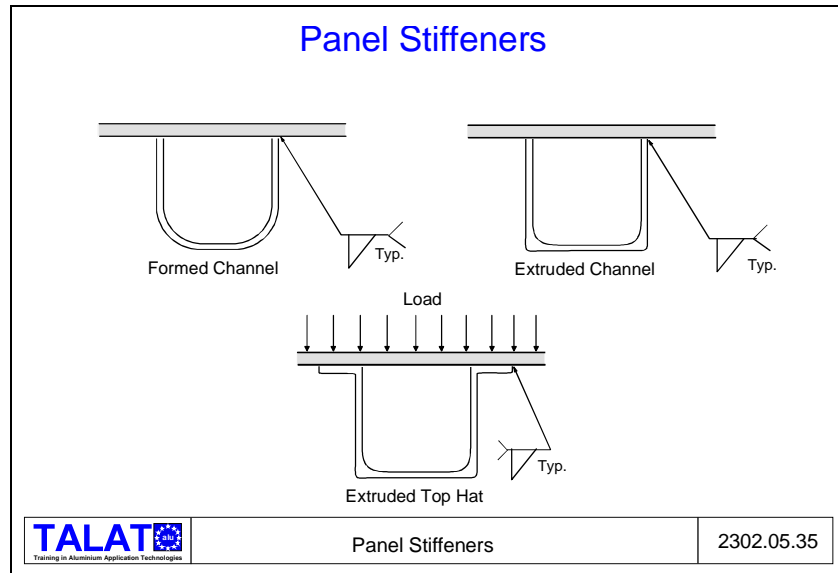
the mating edges can be keyed or locked together. **Figure 2302.05.33** shows a keying arrangement which was chosen to permit the use of identical extrusions. The only fixturing needed was clamping force to hold the mating edges together. **Figure 2302.05.33** also shows a box beam made by two equal channel sections.

Butt joints between light gauge sheets always pose problems of fixturing and alignment; this is especially true in the building of small marine craft, where it is seldom practical to provide conventional fixturing. To overcome these problems a slotted extrusion similar to the one in **Figure 2302.05.34** has sometimes been used. It permits some variation in sheet size and also in the angle between sheet members, without affecting the joint weldability.

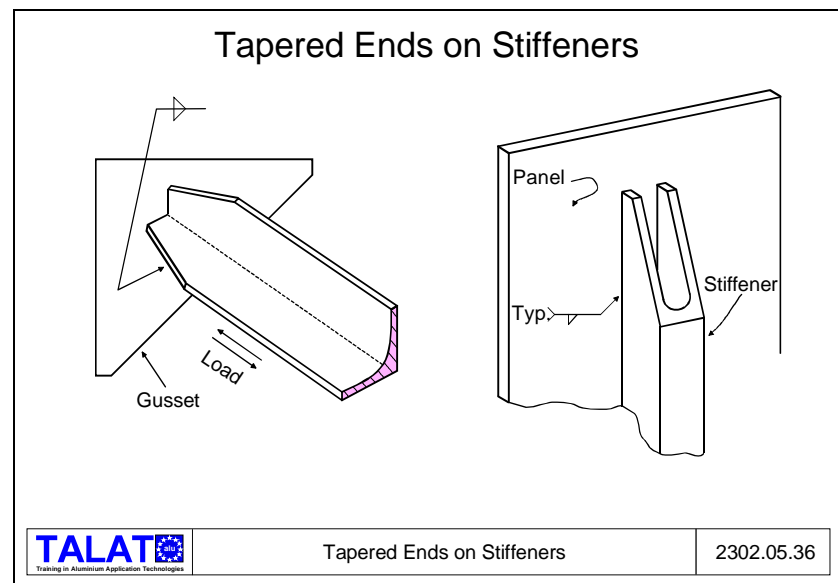


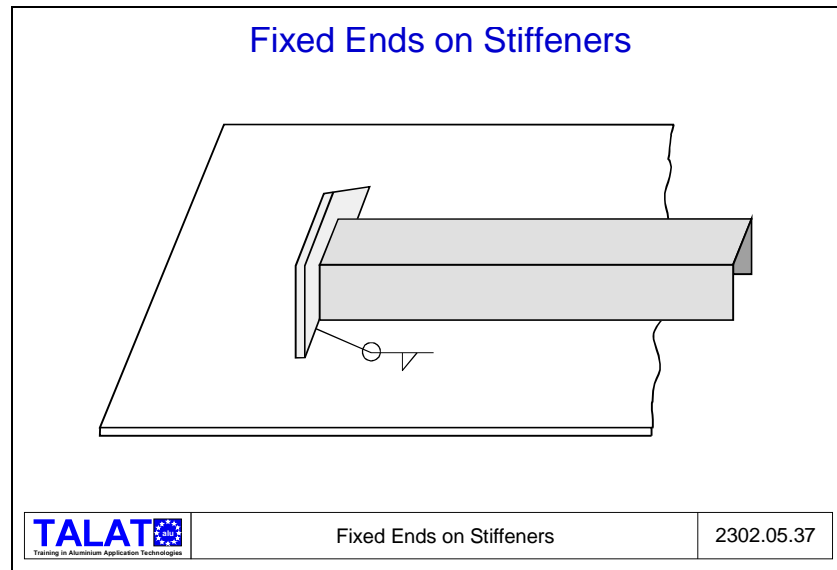
**Panel Stiffeners:** In general, channel-shaped stiffeners, of one form or another, are most suitable for aluminium fabrication. With their toes welded to the panel they form closed-

box stiffeners, which make them more effective stiffeners than angles or tees. They can be more easily fitted to a curved surface and their fixturing for welding is also simpler. Hat-shaped sections often give improved accessibility for welding. Where a panel is supported by stiffeners, such as in the floor of a truck body, and impact loadings can flex the panel, it is preferable to use a flanged shape for the stiffener, so that the welds are displaced from the zones of highest bending moment. **Figure 2302.05.35** shows typical examples of stiffeners for aluminium welded structures.

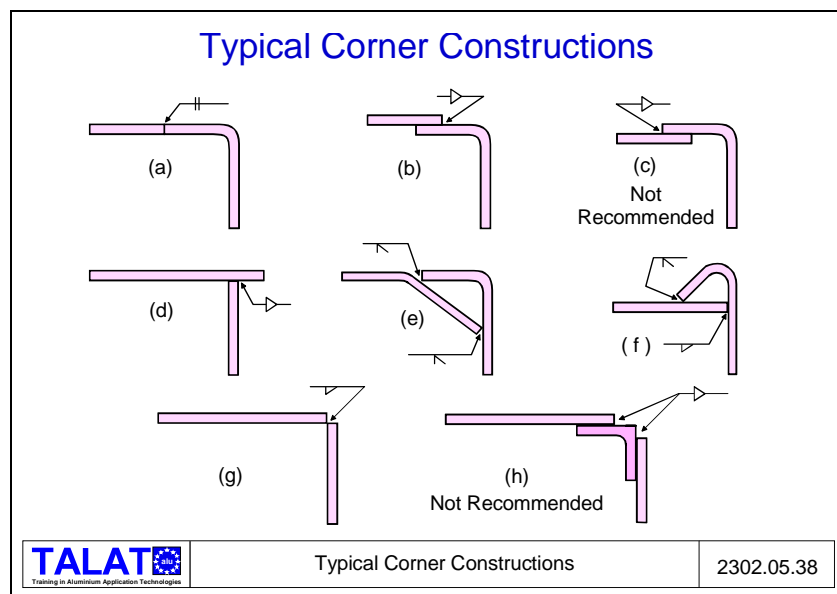


Stiffeners which terminate within a panel, and are not attached to other structural members, are often tapered at their ends (**Figure 2302.05.36**) to help reduce the stress concentrations at these locations. A further reduction can sometimes be effected by fixing the stiffener ends (**Figure 2302.05.37**).

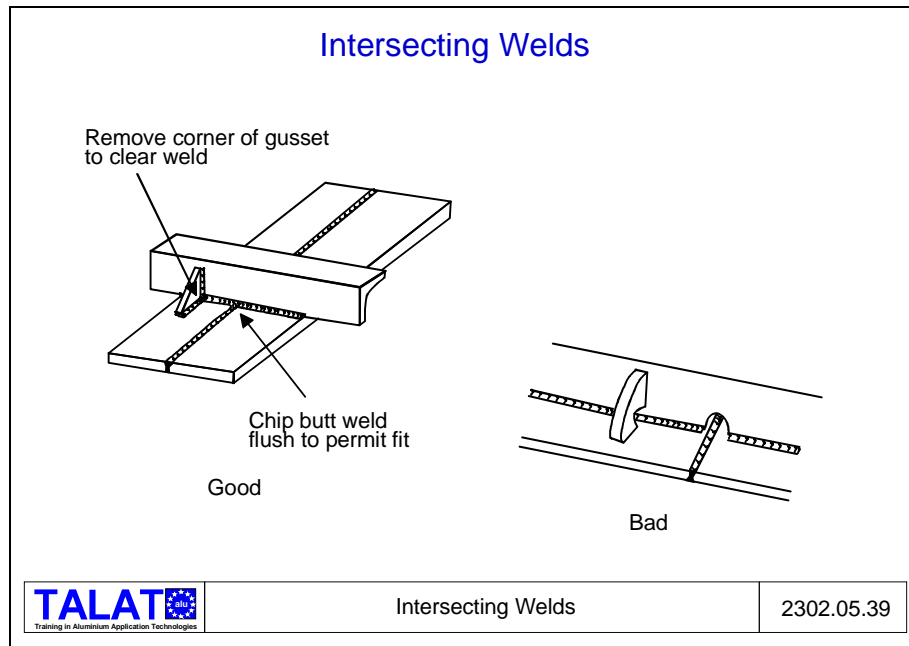




**Corner Constructions:** A very common design problem is how to join members at corners to give an economical, structurally-sound, connection, also having good appearance. **Figure 2302.05.38** shows a number of corner designs, with comments on their relative suitability for aluminium.



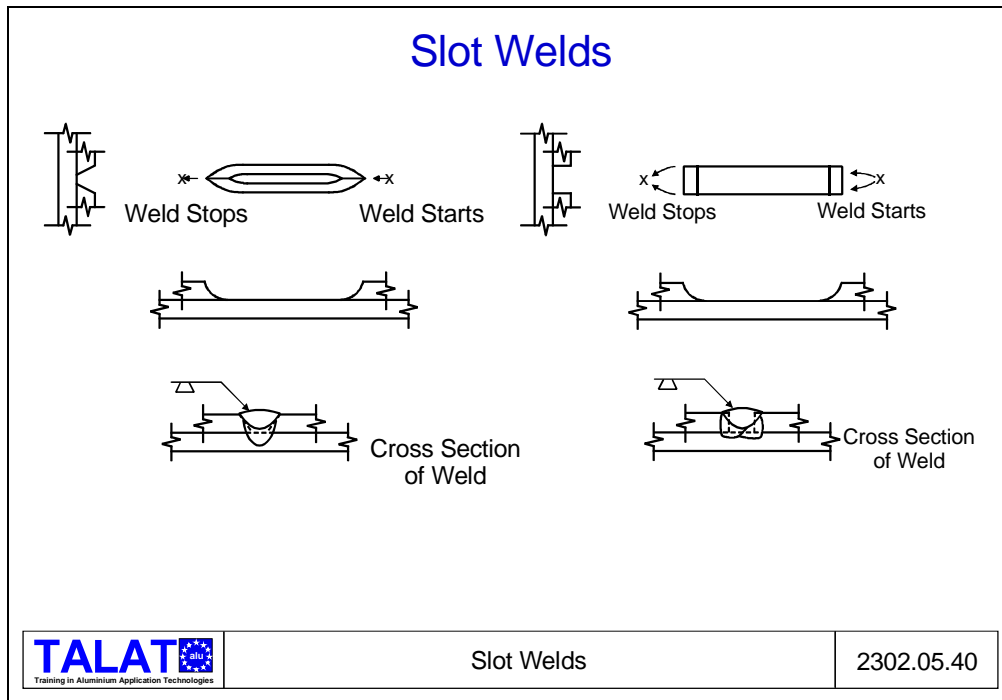
**Intersecting Welds:** The metallurgical soundness of an aluminium weld is not affected by a second weld that intersects it. Thus no special care has to be taken to avoid intersecting welds, as is the common practice with other metals. With aluminium, it is much better to have intersecting welds than gaps in welds. Welds starting and stopping at gaps or openings are exceedingly difficult to make free from defects, with either TIG or MIG welding. Also they represent potential sites for stress concentrations, leading to reduced fatigue strength. **Figure 2302.05.39** illustrates the preferred and nonpreferred intersectings of aluminium welds.



**MIG Spot Welds:** It is important to be aware of the serious limitations of this process for structural applications. MIG spot welds are very prone to variable quality and strength. They frequently have serious peripheral cracking, leading to unsatisfactory fatigue performance. Because they are not cylindrical in form, i.e. the weld face is much larger than the root, they tend to distort an assembly, and especially if multiple MIG spot welds are fairly closely spaced. Their appearance is generally much less attractive than resistance spot welds. For these reasons the use of MIG spot welding on aluminium is limited mainly to nonstructural and noncritical applications.

**Plug and Slot Welds:** A plug weld is made into a circular hole in one member to join it to a second member. It is sometimes called a circular fillet weld. In aluminium neither the plug weld nor the circular fillet weld proves to be practical, mainly because of the limitations of the gas shielded arc welding processes.

A TIG arc cannot be directed to penetrate adequately into the second member without overheating the first. Also a TIG gun and filler rod combination cannot be manipulated quickly enough to make a satisfactory fillet weld around a small hole. MIG welding provides a sufficiently concentrated arc but it adds filler metal as soon as the arc is struck, and thus begins to fill the hole before the arc can adequately fuse the second member. This results in welds which are much smaller than the hole and thus have insufficient strength. To overcome this limitation, some have attempted to make circular fillet welds with MIG but, unless the hole is very large, impossible skill is needed to manipulate the gun around it. For these reasons, plug welds and circular fillet welds are not practical for structural applications in aluminium.

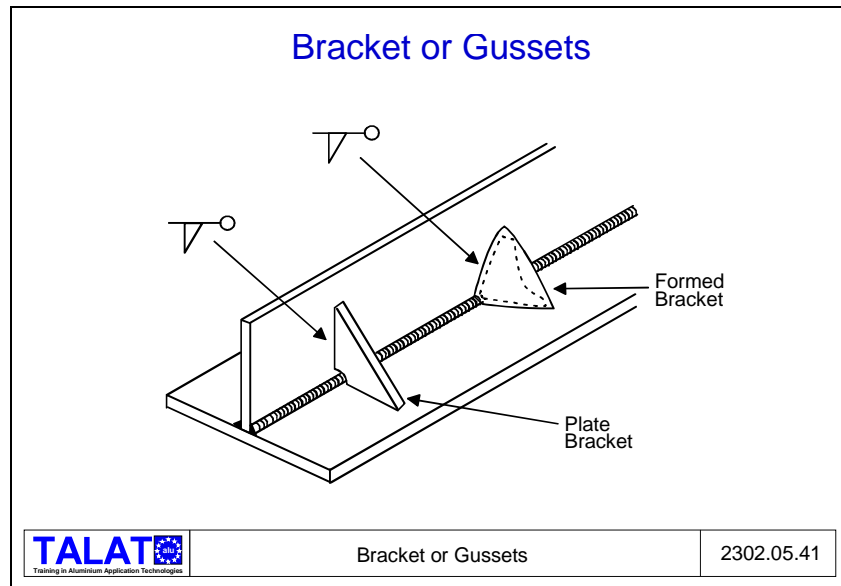


Slot welds avoid most of the disadvantages of plug welds. A slot weld is made into an elongated hole. It requires a single weld along the centerline of the slot; if each side is fillet welded, the joint is termed a fillet welded slot. Both are suitable for aluminium. Slot welds are for the lighter gauges and fillet welded slots for gauges above about 4.8 mm. Both types are best welded by the MIG process. Typical shapes and dimensions for the slots are shown in [Figure 2302.05.40](#). Note that it is a preferred practice to begin and end the welds beyond the ends of the slots in order to minimize the possibility of defects in the stressed portion of the weld.

The static shear strength of slot welds and fillet welded slots may be calculated by multiplying the area that is loaded in shear by the shear strength of fillet welds.

**Brackets and Gussets:** The welding of brackets or gussets requires several weld starts and stops. Limited access makes maintaining correct torch or gun angles very difficult. However, by careful bracket design it is possible to improve their weldability and to reduce the incidence of weld defects. [Figure 2302.05.41](#) shows two bracket types, the first is the most common type. It is made of a plate thick enough to allow fillet welding both sides without overheating it. Note that it has had just enough of the inside corner removed to clear the tee-joint fillet weld. Note also that ends of the toes have been cut back slightly to reduce their tendency to melt away when being welded.

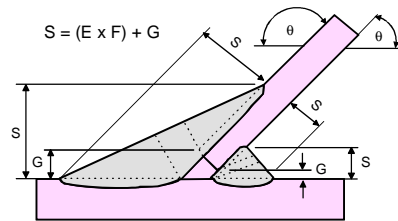
The second bracket or gusset type has been made from lighter gauge metal bent to form an angle. The inside corners have been trimmed to clear the tee-joint fillet weld. This shape is more costly to make than the simple triangular bracket, but it is easier to weld because the correct gun angles are more easily maintained. Also this bracket is easier to hold in place for welding.



**Butt Joints Between Unequal Thicknesses:** A butt joint between different thicknesses of metal is usually required to have the thicker one beveled to match the thinner one. This is designed to balance the heat sink for uniform melting and good fusion, and to reduce the stress raiser caused by a change in thickness. Most welding standards specify a 1 in 4 bevel on the thicker component. However, welds tested both with and without such bevelling, indicate that this practice has no beneficial effect on fatigue strength. Under cyclic loading, failure has been found to occur at the weld toe in the thinner member at the same loading whether the thicker member has been bevelled or not. Nevertheless a slope of 1 to 2 or flatter is recommended (see [Figure 2302.05.22](#)).

**Joints Other than at Right Angles:** When two members meet in a tee joint at an angle other than 90 degrees, the welding of this joint becomes more difficult. The acute or closed side of the joint has less access for the gun. The obtuse or open side poses no problem of access, but it is more difficult to make a weld having a sufficiently large throat. [Figure 2302.05.42](#) shows a typical joint of this type together with a method of calculating the equivalent 90 degree fillet weld size. Note that welding symbols must reflect the fact that these are not standard fillet welds.

## Tee Joints at Other Than Right Angles



S = measured size

E = effective size<sup>1</sup>

G = gap<sup>2</sup>

θ = angle between fusion faces

$$F = \frac{\cos 45^\circ \sin \theta}{\cos (\theta/2)} \text{ (see table below)}$$

<sup>1</sup> Size of an equivalent fillet weld between fusion at 90° having the same throat thickness as measured fillet size under the skewed condition.

<sup>2</sup> The gap on either side including fabrication tolerance shall not exceed 5 mm.

θ°	60	65	70	75	80	85	90	95	100	105	110	115	120
F	0.707	0.760	0.811	0.861	0.909	0.955	1.00	1.04	1.08	1.12	1.16	1.19	1.22

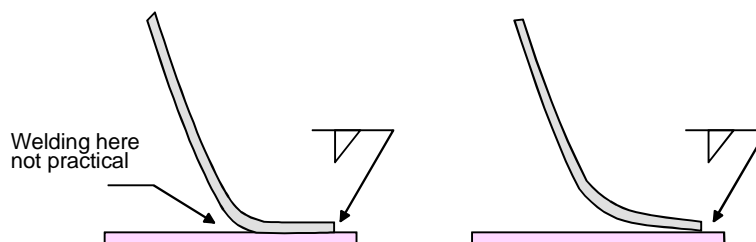


Tee Joints at Other Than Right Angles

2302.05.42

**Bulkhead to the Shell Joints:** Figure 2302.05.43 shows a typical joint used in road tanker construction. This is included to illustrate single-welded lap joints designed to be loaded only in shear but any flexing of the joint introduces a bending moment in the weld, which can result in fatigue failure. Thus the bulkhead flange must be formed to fit tightly into the tanker shell so that vertical forces are reacted by metal to metal contact, and the weld is protected against stresses other than shear.

## Bulkhead to Shell Joints



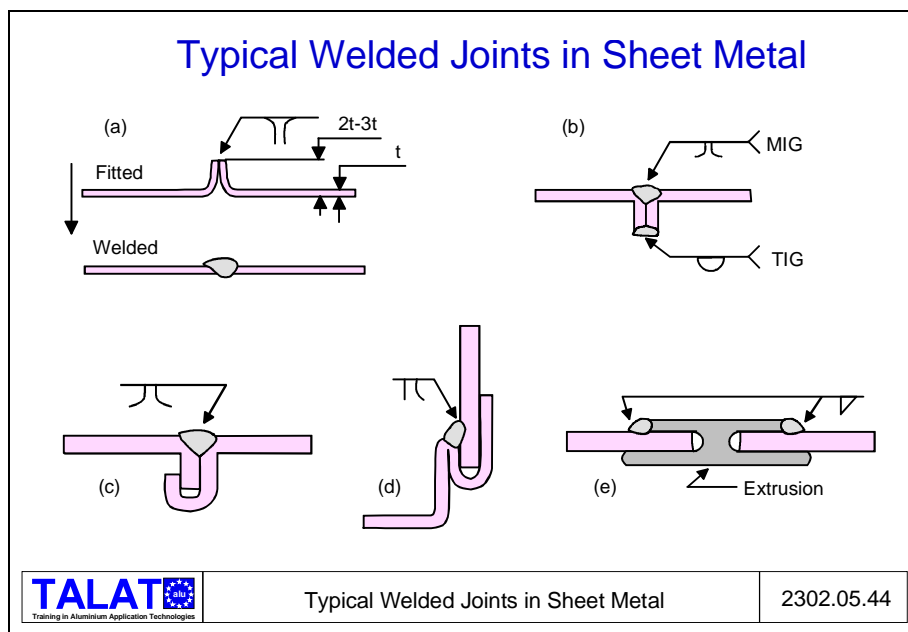
Bulkhead to Shell Joints

2302.05.43

**Partial Penetration Groove Welds:** Partial penetration groove welds are not common in aluminium, because in most structures the joint strength is required to match, as

nearly as possible, the base metal strength. Even if a partially-penetrated joint is considered adequate for the service, the user should be aware that the weld penetration, for design purpose, does not exceed the depth of the edge preparation. Also, butt joints only partially penetrated from one side can have severe eccentricity under most loadings, and thus be relatively weak. For these reasons single-welded, partial penetration groove welds are not common in aluminium fabrication.

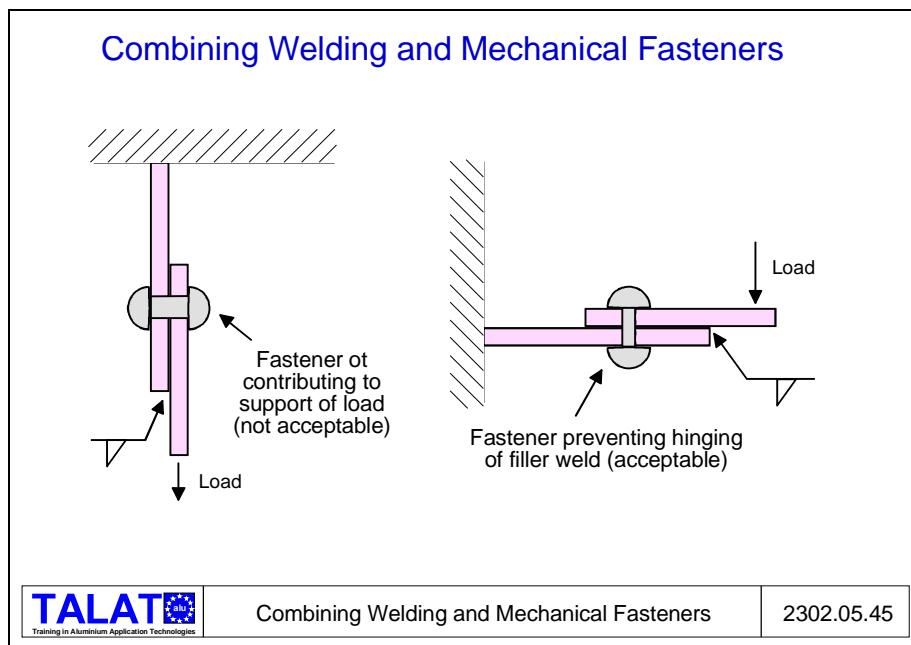
**Sheet Metal Joints:** The welding of aluminium in gauges suitable for sheet metal work (3 mm and thinner) requires special care in joint design, jiggling and welding. Distortion is present to some degree in all light gauge weldments and if not adequately controlled during the welding operation, it will affect joint alignment even to the extent that welding may become impossible. With adequate jiggling and high arc travel speeds, the simple butt, lap and tee joints may be applied successfully but for broader fabrication needs, a number of special joints have been evolved which, to some extent, are self jiggling, provide backing, and increase the resistance of the joint to distortion. Typical for such joints are those shown in [Figure 2302.05.44](#).



Joint (a) is suitable for butt welds in alloys which permit autogenous TIG welds, i.e. without filler. Note that it is good practice to bend the flanges slightly past the right angle so that when fitted together they butt tightly at the bends. Joints (b) and (c) are similar except that one additional forming operation (c) provides a jigging flange so that only one weld is required. In both these joints, the groove weld is possible only if small-radius bends are made to minimize the depth of the groove. Joint (b) is also self-jiggling and provides backing in case the weld over-penetrates. Joint (e) illustrates the use of an extrusion to provide the same jigging and backing for a butt connection. Many other joints can be devised for special applications.

**Welds Combined with Mechanical Fasteners:** It is often not appreciated that mechanical fasteners such as rivets and conventional bolts do not give rigid connections. On the other hand, a weld is a rigid connection. Thus in a joint which has been both welded and mechanically fastened to share the same load, the weld will carry the entire load while the mechanical fastenings will remain unstressed. If the weld is sufficiently strong, the mechanical fastenings are redundant, but if the weld should fail, the fastenings would then assume the load. Obviously, this is seldom an efficient use of the two joining methods. The left arrangement in [Figure 2302.05.45](#) shows such a combination.

Nevertheless, there is sometimes a justification to combine welds and mechanical fasteners. Mechanical fasteners may be used merely to prevent the hinging of a weld, and thus protect it from stresses it is not well suited to resist. The right joint in [Figure 2302.05.45](#) is typical of this use of combined welds and fasteners.



**Designing for Cyclic Loading:** The fatigue strength of welds is discussed in [TALAT Lecture 2400](#) (Fatigue Design) and a general reference was made to the role that joint geometry plays in determining fatigue strength. The designer needs to know which welded constructions are better for cyclic loading and which should be avoided. In [TALAT Lecture 2400](#) possible joint arrangements are classified into groups and their fatigue performances are compared. With this resource, the designer can more readily choose the most suitable joint for each application.

**Welding Costs:** While there are no simple formulas for calculating welding costs, it is possible to estimate direct costs if consumption quantities can be determined for the specific welding procedure to be used. The principal consumptions in arc welding of aluminium, are shielding gas, filler metal and labor. Although some gun components,

such as the tungsten electrodes, contact tips, gas nozzles and flexible liners can be damaged from time to time and require replacing, their consumption is variable and unpredictable and thus we shall consider only the principal factors, i.e. shielding gas, filler metal and labor.

A very important factor when estimating welding costs is the expected arc duty-cycle. This is the ratio of productive arc time to the total time allocated to a specific welding operation, expressed as a percentage. For example, if in an 8-hour shift the total time a welder is actually running his arc to produce sound welds is 2 hours, his duty-cycle is 25%. The duty-cycle is a critical factor in welding costs. Shielding gas and filler metal costs are not much affected by the duty-cycle but labor costs are very sensitive to it.

The following welding cost breakdown is given as an example and is considered to be typical for costs for semiautomatic MIG welding of aluminium using argon shielding gas:

5-15% for shielding gas  
10-25% for filler metal  
60-85% for labor (welder and helper)

It is evident from these figures that the best opportunity for cost reduction is in the labor cost. Often this leads to the assumption that increasing welding speed is the best way of lowering welding costs. But increasing speed to the point where quality suffers and weld repairs become necessary, can be counterproductive. Much more significant savings are possible, usually without any sacrifice of weld quality, by increasing the welding duty-cycle. This is usually considered a responsibility of the fabricating shop but the designer of welded structures is also able to influence the duty-cycle and he should be aware of the factors which affect it.

### *Design of adhesive bonded connections*

According to EC9, the values for the limiting shear strength of adhesives  $f_{v,adh}$  for structural applications are shown in **tab. 6.9** in the **appendix**.

The design shear stress must fulfil the condition:

$$\tau \leq \frac{f_{v,adh}}{\gamma_{M,adh}}$$

where:

$\tau$  is the shear stress in the adhesive layer;  
 $f_{v,adh}$  is the limiting shear strength value of adhesive;  
 $\gamma_{M,adh} = 3.0$  is the material factor for adhesive bonded joints,

Such a high value for  $\gamma_{M,adh}$  is necessary because;

- the design of the joint is based on ultimate shear strength of the adhesive;
- the scatter in adhesive strength can be considerable;
- the experience with adhesive bonded joints is small.

Limiting shear strength values of adhesive higher than those given in **tab. 6.9** may be used when thick adherent shear tests are carried out (**fig. 6.24**).

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