Aluminium Structural Design, resistance of connections

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Aluminium Structural Design
Resistance of Connections

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Contents

1 Introduction

Although a lot of research on aluminium alloys has been carried out in the past, relatively little attention has been given to their structural behaviour. Therefore, in the past most design rules for aluminium alloys were based on design rules for steel.
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 are capable of.
However, the use of limit state design methods requires knowledge of the structural behaviour of members and connections. In the past decades quite a number of studies have been carried out to further enlarge the above mentioned knowledge. In particular the joint industry research initiated by Technical Committee 2 “Aluminium Alloy Structures” of the European Convention for Constructional Steelwork should be mentioned here.
Main subjects of research have been: stability (global and local stability); connections (bolted, welded, adhesive bonded connections); and last but not least fatigue (in particular fatigue of welded connections).
The above research effort has resulted in an adequate knowledge of the structural behaviour of aluminium members and connections today. Moreover design rules in national codes have been up-dated, but most important a (draft) European code “Eurocode 9: Design of aluminium structures” has been edited in 1998, which contains up-to-date design rules for aluminium structures.

In the following chapters attention is given to the state of the art concerning connections. In chapter 2 joining technology is described while in chapter 3 the design of joints is dealt with, in particular the design of welded, bolted, and adhesive bonded joints. In chapter 4 a number of structural aluminium applications is dealt with an emphasis on connections. At last in chapter 5 final remarks are given.

2 Joining Technology

2.1 General

Well designed joints are essential to answer the satisfactory performances of a 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 much larger. A significant weight advantage results from the use of welding which reduces the above 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 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.

When designing connections it is distinguished between:
- joints in primary structures, and
- joints in thin-walled structures.

In primary structures typical element thicknesses are larger than 3 mm. Joining techniques applied are:

- welding;
- mechanical fastening i.e. bolts and rivets;
- adhesive bonding;
- hybrid connections.

Sometimes special connections are used such as profile to profile joints, snap joints etc.
In addition to the above joining techniques in primary structures for thin-walled structures specific joining techniques are used such a screws, (blind) rivets, and spot welding.

2.2 Joints in primary structures

2.2.1 Welding

Welding is defined as the joining of materials by the use of heat – sometimes force or combining heat and force – with or without a filler metal. The welding of aluminium is widely established and has been developed into an important method of joining.
Inert gas shielded are welding processes (TIG and MIG) have considerably extended the possibilities for welding aluminium, and are even used in ordinary workshops.
Advantages of welded connections is saving of work and material, absence of drilling and overlap, tight joints, and no crevice corrosion in case of butt welds, see also fig. 1.
By the extrusion technique groove preparation and backing can be integrated in the profile, strength reduction in heat affected zones can be compensated by locally increasing the thickness, and difference in thickness can be levelled out. Butt-welded joints are preferable in most cases.
It gives a favourable state of stress in members in bending and tension. More details of welded connections are given in chapter 3.

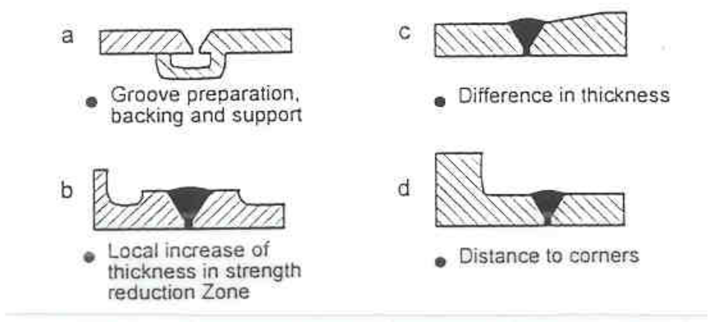

Fig. 1: Welded connections

The aluminium welding processes commonly used in workshop practice are:

- Gas welding (autogenous welding);
- Metallic arc welding (flux-coated electrodes);
- Inert gas shielded arc welding with a non-consumable tungsten electrode (TIG), or with a consumable metal electrode (MIG);
- Laser welding;
- Friction welding.

Gas welding as well as metallic arc welding commonly used in steel structures, are not widely used in aluminium structures because of low efficiency and bad quality in particular susceptibility for defects.

Inert gas shielded arc welding (TIC and MIG) are the most wide-spread welding techniques that are used for structural applications. In fig. 2 the principle of TIG welding is shown.

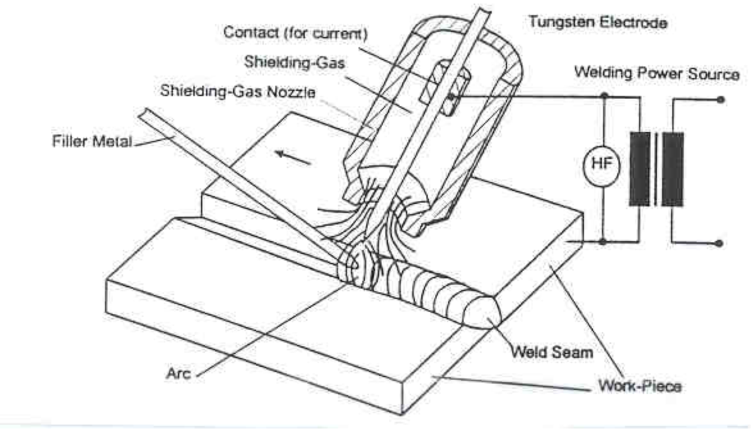

Fig. 2: Principle of TIG Welding

During TIG Welding an arc is maintained between a tungsten electrode and the work-piece. The molten metal and the electrode are shielded by an inert gas flow (argon, helium, or a mixture). The filler metal is usually introduced manually.

A major difference between the welding of steel and the TIG (or MIG) welding of aluminium is the adhering oxide film on the aluminium surface which has to be removed and the shielding of the molten metal against oxygen from the atmosphere.

In fig. 3 the principle of MIG welding is shown. Analogous to TIG welding, MIG welding is conducted using inert gases. The arc is drawn between a melting wire electrode and the work piece.

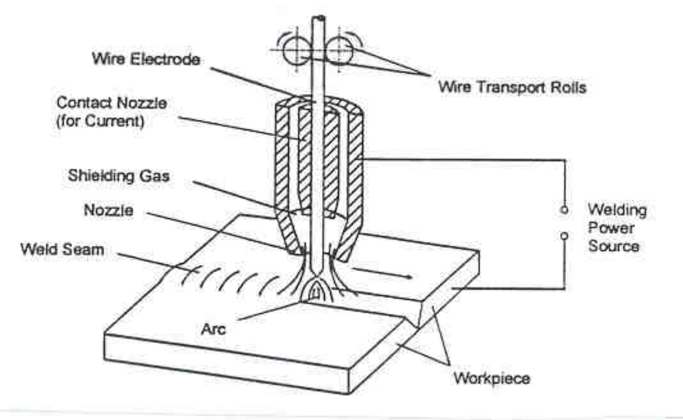

Fig. 3: Principle of MIG Welding

The current used with MIG welding is much higher than with TIG welding which results in a better penetration (thicker material can be welded) and a higher welding speed. MIG welding is the more efficient process compared to TIG welding and it is also easier to mechanize.

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 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 of shrinkage, modulus of elasticity, and its melting point.

Although the following processes are much less used compared to TIG and MIG welding some of them have specific applications.

With laser welding of aluminium two types of lasers are used i.e. solid-state laters (Nd-YAG) and gas-discharge lasers (CO2). The first ones operate at lower energy and are most suited for thinner material while the gas-discharge lasers operate at higher energy and are used for thicker material.

With friction welding usually rotational symmetrical parts are rotated while being pressed together, thereby generating heat of friction which causes the parts to weld. This process also enables to weld aluminium to steel.
A more recently developed process is friction stir welding (FSW). In fig. 4 the principle of friction stir welding is shown. A specially shaped rotation pin moves between the abutting faces of the joint which generates frictional heat that creates a plasticised region around the tool. The contact of the shouldered region of the tool with the workpieces also generates significant frictional heat as well as preventing plasticised material from being expelled. The tool is moved along the joint line, forcing the plasticised material to coalesce behind the tool to form a solid-phase joint.

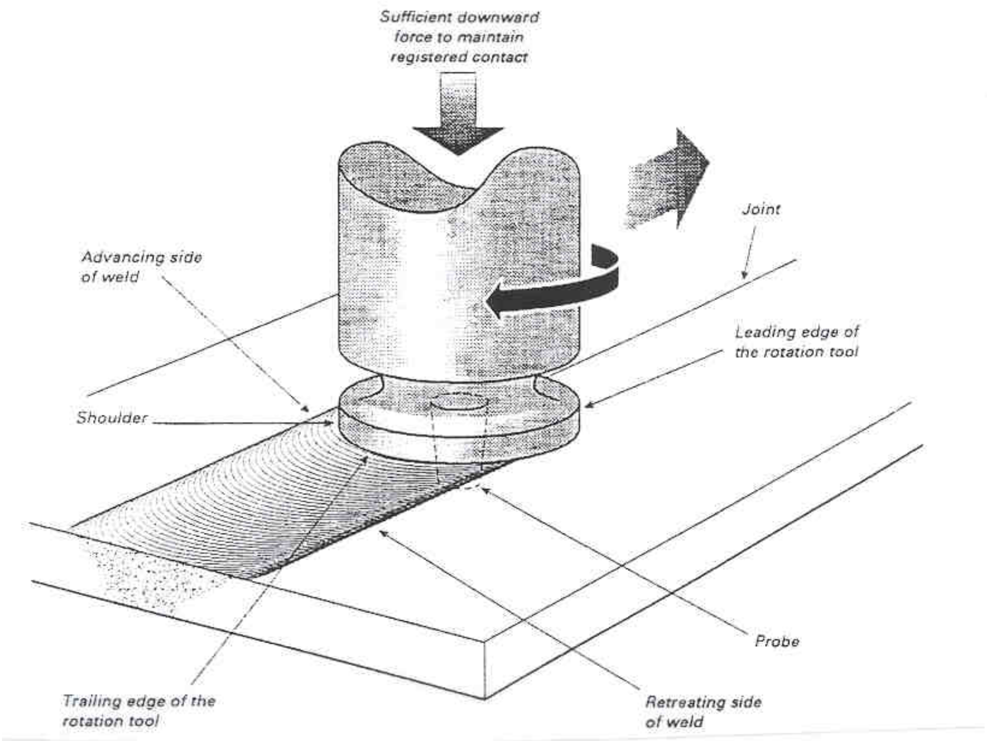

Fig. 4: Friction stir welding with a rotating tool

Friction stir welding can be regarded as an autogenous keyhole joining technique, where consolidated welds are solid-phase in nature and do not show fusion welding defects. No consumable filler material or edge preparation is normally necessary. The distortion is significantly less than that caused by arc fusion welding techniques.

In addition to laser welding and friction welding solid state welding processes to be mentioned, are:

- explosion welding;
- ultrasonic welding;
- diffusion welding;
- cold or hot pressure welding.

Except for welding aluminium these processed enable aluminium to be welded to a wide range of other metals.

2.2.2 *Mechanical fastening*

In primary structures most commonly used mechanical fasteners are <u>bolts</u>, either aluminium or steel bolts. In some cases also rivets are used but they are considered to be rather outdated and uneconomical. At the contrary for thin-walled structures special rivets have been developed with a wide field of application, see chapter 2.3.

Compared to welded joints mechanical fasteners have the advantage that there is no softening of the materials due to the influence of heat. Furthermore, mechanical fasteners can be used on site contrarily to welding which is an in-shop method. So for the assembly on site preferably bolting is the joining method.

<u>Aluminium bolts</u> offer the advantage that changes in the tightness of the joints due to thermal expansion, which can occur when using steel bolts, are avoided.
The aluminium bolt material is chosen to match the material forming the compoments to be joined. Further information is given in chapter 3.

The following general points should be born in mind with bolts:
- Excessively high pressure on the surface of the aluminium when the fastener is tightened, can be avoided by fitting hard aluminium washers under de head of the bolt and the nut.
- 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 inserts, see also fig. 5.
- For joints exposed to moisture the aluminium bolts should be sealed.

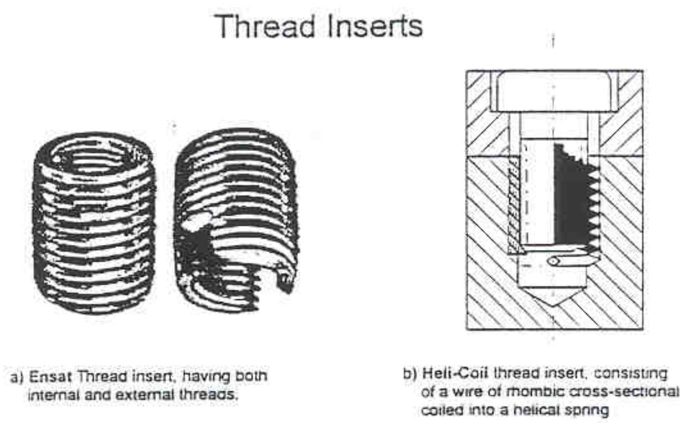

Fig. 5: Thread inserts in aluminium components

<u>Steel bolts</u> used in aluminium structures exposed to weathering or other corrosive environments must be protected against corrosion; for example the steel bolts may be galvanised. However, it is becoming increasingly common to use bolts made of stainless steel. To avoid excessive surface pressure steel bolts are also fitted under the bolt head and nut with galvanised washers to arrive at a more evenly distributed load.
Combined steel bolts and female threads in materials of low shear stress is avoided by using threat inserts. The latter enable a higher load bearing capacity of the joint; in case

of frequently loosening and tightening up of the bolt the thread of the aluminium component is not worn.

When used in primary structures solid aluminium rivets (see fig. 6) are driven while cold. Contrarily to hot-driven rivets, cold-driven rivets do not shrink and therefore do not press the sheets together. That means that cold-driven rivets are loaded in a similar way as bolts (see also chapter 3).

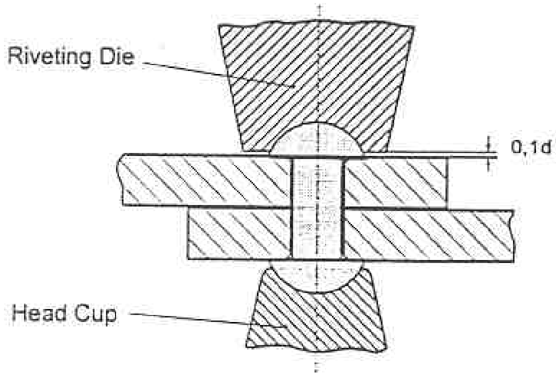

Fig. 6: Aluminium solid rivets

Sometimes special mechanical joints are used such as profile to profile joints, snap joints, and corner joints. In all these cases use is made of extruded connections like the tongue and groove connection shown in fig. 7. Many times these types of connections are combined with other types of fasteners.
In the example of fig. 7 locking of the profiles in longitudinal direction is possible by the use of screws.

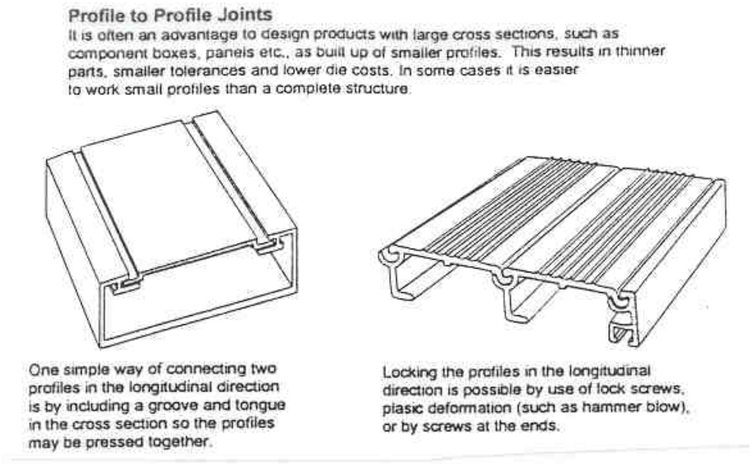

Fig. 7: Special mechanical joint

2.2.3 *Adhesive bonding*

Although not yet widely used in structural applications, adhesive bonding of aluminium will become more and more important in particular because of the geometrical possibilities enabled by extrusion.
Since adhesive bonding is not very familiar outside the aerospace industry in the following the most important aspects with respect to bonding technology will be reviewed.

Adhesive bonding is defined as the process of joining parts using a non-metallic substance (adhesive) which undergoes a physical or chemical hardening reaction causing the parts to join together through surface adherence (adhesion) and internal strength of the adhesive (cohesion).

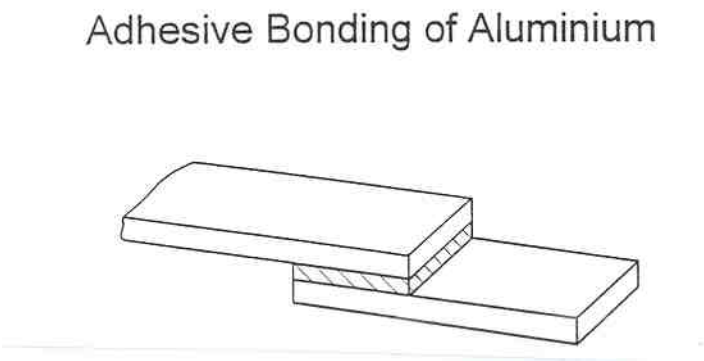

Fig. 8: Adhesive bonding of aluminium

Adhesive bonding has a number of advantages compared to mechanical fastening and welding. But at the same time a number of disadvantages as well .
The advantages are:
- continuous joints, no holes (fasteners), no heat input (welding) which affects parent metal strength and also results in deformations;
- more uniform stress and strain distributions; stress concentrations at a lower level than with mechanical fasteners; in particular for cyclic loaded structures (fatigue conditions) this results in a longer life time of the structure.
- joining of aluminium with other materials;
- more flexibility in designing;
- very thin materials and small components can be adhesively bonded;
- tight joints; liquid as well as gas tight joints;
- isolating or conductive (electricity, heat);
- decreasing vibrations.

The disadvantages are:
- specific joint design; lower stress levels, shear forces, large surface areas needed;
- surface treatment;
- curing time adhesives;
- adhesion difficult to control; NDT methods hardly available;
- demounting/repair difficult;
- restricted structural behaviour at high temperature.

Fig. 9: Adhesive joint design. Left figure not suitable. Right figure typical adhesive joint design.

Adhesive joint are composite systems whose strength depends on both the geometrical design and loading type as well as on the individual strengths of the different members of the joint as illustrated in fig. 10.

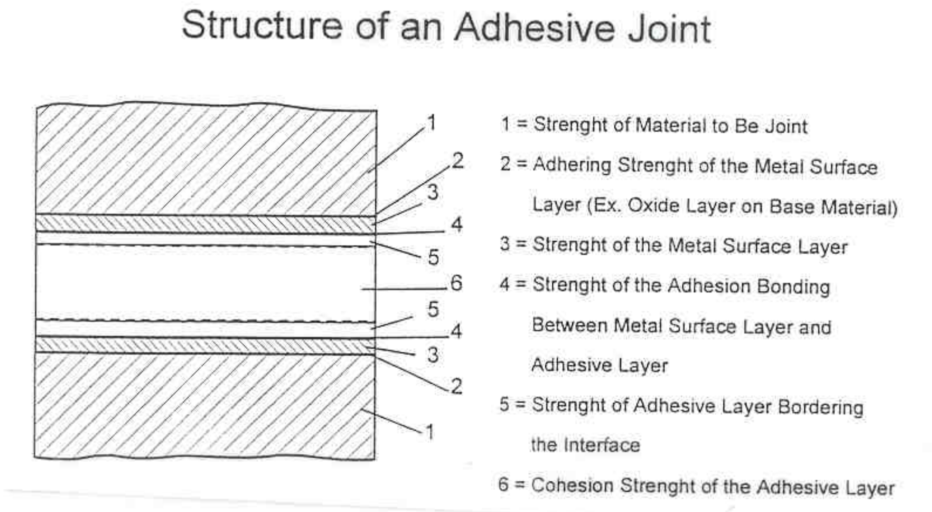

Fig. 10: Different members of an adhesive bonded joint

<u>Adhesion</u> is defined as the force acting between the adhesive and the surface of the material. This force is the result of the <u>mechanical interlocking</u> between the adhesive and the material surface roughness as well as the <u>physical and/or chemical interaction</u> between the adhesive and the material.

<u>Cohesion</u> is the <u>strength of the adhesive</u> itself. This is a result of the mechanical entangling and interlocking of the adhesive molecules and their physical and/or chemical affinity for each other.

The separation of adhesive bonded joints occurs due to the failure of adhesion or cohesion or a mixed adhesion and cohesion failure, see figure 11.

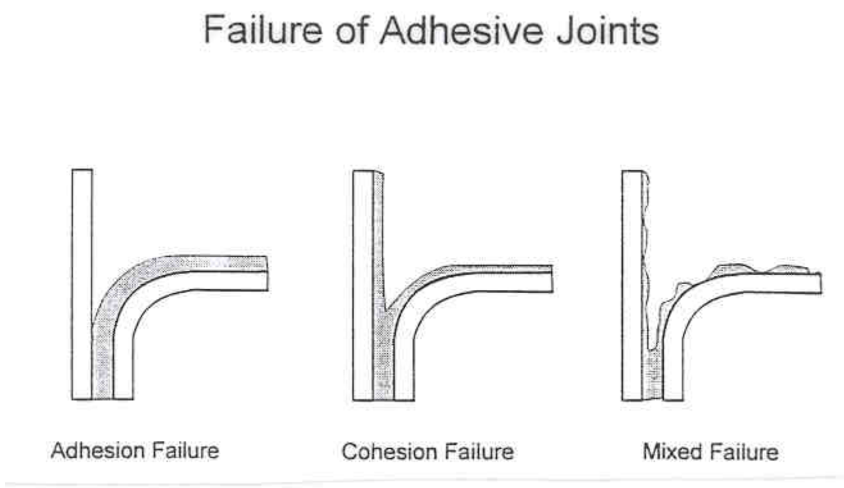

Fig. 11: Failure of adhesive joints

When designing bonded aluminium structures, one of the primary decisions to be made in selection of the right adhesive. Many factors have to be evaluated such as:
- function of the adhesive: structural or non structural;
- curing temperature: cold-curing, heat-curing;
- specific curing conditions: humidity needed, absence of oxygen;
- number of components: one component, two components;
- application form: liquid, paste, solid, tape;
- chemical composition: epoxy, acrylic, polyurethane;
- physical behaviour: thermosetting, thermoplastic;

The above described factors have to do with the variety of adhesives available. On the other side one has to bare in mind the application.

Factors involved with the application are:
- structural aspects: strength, durability, flexibility;
- materials to be connected: aluminium- aluminium or aluminium – other material;
- surface treatment: higher strength but more particular higher durability requires more rigorous surface treatments;
- curing: time needed, temperature, pressure, in-shop or on-site;
- application: apparatus, “open” time adhesive;
- quality assurance: testing, destructive, non-destructive.

Although far from complete in the following some guidance will be given how to arrive at selecting the right adhesive.
As far as structural applications are concerned three types of adhesives are used: phenolic adhesive systems; epoxides; and acrylics.

For semi structural applications: polyurethanes; hot melt systems; and silicones.
For non-structural applications: cyanoacrylates; contact adhesives.
The adhesives mentioned above are suited to bond aluminium to aluminium but also aluminium to steel, or stainless steel, or zinc. Adhesion depends to a large extent on the surface treatment applied.

<u>Surface treatment</u> prior to bonding results in:
- higher initial adhesion of the adhesive and the aluminium surface;
- higher durability of the joint.

The better the interaction between adhesive and the aluminium surface the higher the strength of the interface between them and also the less susceptible the interface is for ageing i.e. decrease of adhesion due to environmental attack.
Preparing the surface prior to bonding the first step should be cleaning and degreasing. Further steps can be: <u>mechanical pretreatment</u> such as grit blasting, brushing, or <u>chemical pretreatment</u> like etching, anodising, chromate conversion of the surface. For aluminium anodising is a well-known surface treatment which results in a very stable oxide layer on the bare metal with a high resistance against environmental attack.
A final step can be the application of a <u>primer</u> which can further enhance the adhesion to the surface as well as decrease the ageing susceptibility of the interface. A primer is sometimes used to bridge the time span between preparing the surface and the actual bonding of the parts.
Whether or not one has to carry out a more sophisticated surface treatment depends on the application. However, almost all applications need at least the first step mentioned i.e. cleaning and degreasing.

To illustrate the effects of ageing in fig. 12 the results are given of accelerated tests (high temperature, high humidity) for phenolic resp. epoxy adhesives without mechanical stressing (fig. 12a) and with mechanical stressing (fig. 12b).

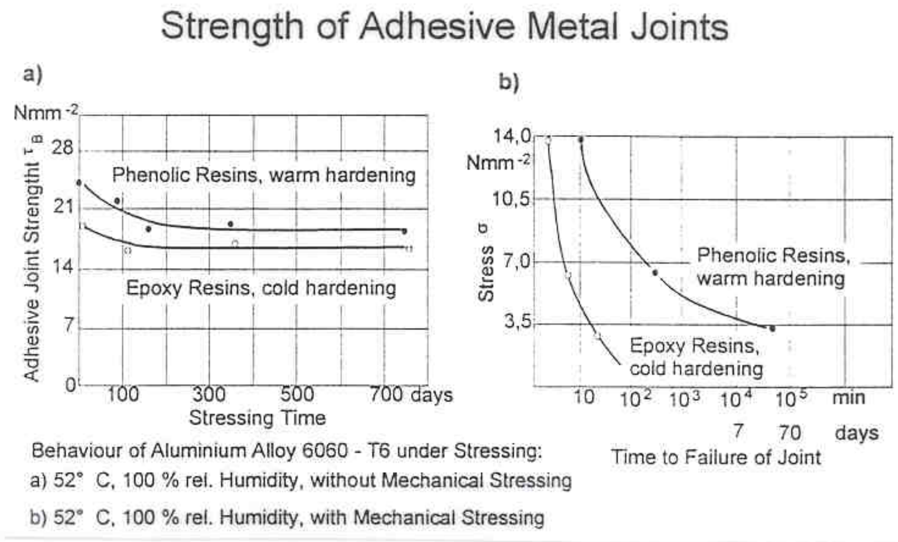

Fig. 12: Accelerated tests on adhesive bonded joints.

Applying adhesive bonded joints it is essential to design the joints for bonding and not simply substitute it for other means of joining. Care should therefore be taken that stress concentrations be avoided and the loads be carried over as large an area as possible.
Wherever possible, the adhesive should be loaded in shear so that peel and cleavage stresses are avoided.
Most widely used are lap joints as shown in fig. 13.

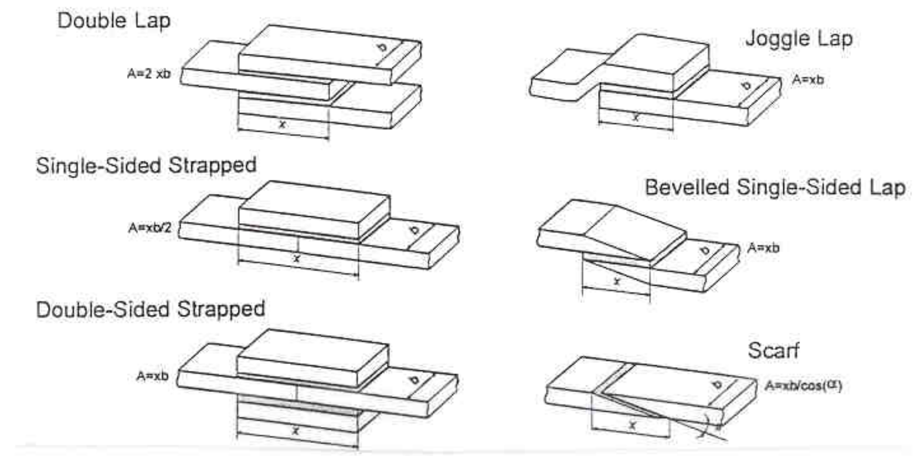

Fig. 13: Adhesive bonded lap joints

Other examples for joint design which have proven to be successful are given in figs. 14 and 15.

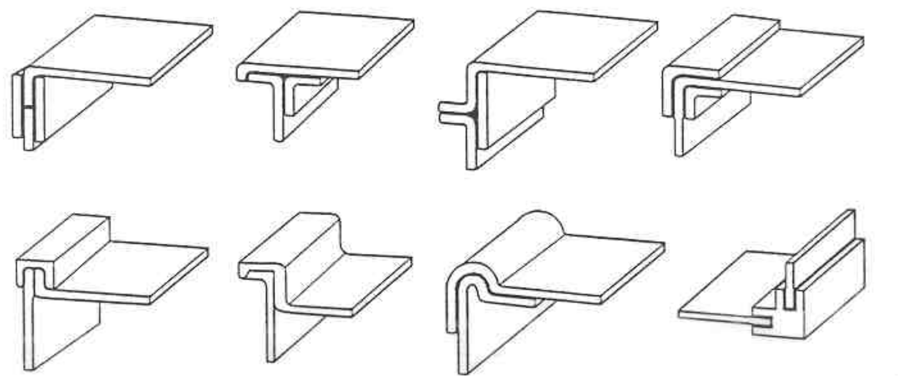

Fig. 14: Examples of adhesive bonded corner joints

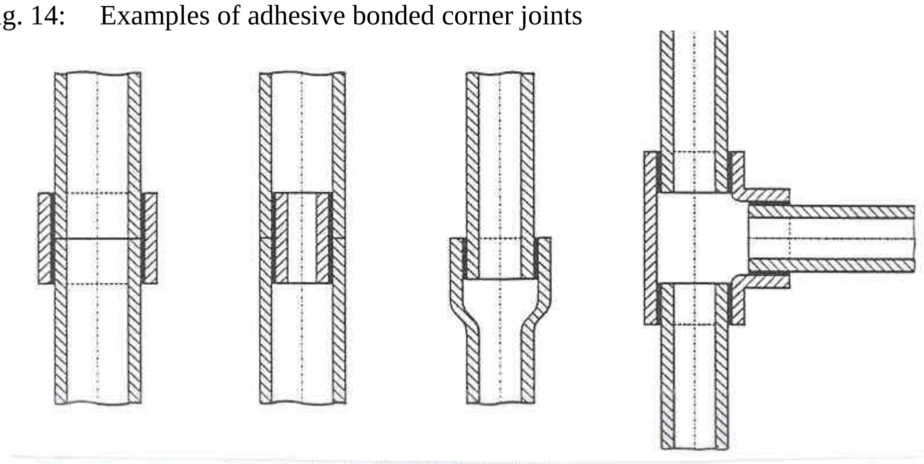

Fig. 15: Examples of adhesive bonded tube joints.

Other successful examples of adhesive bonded structural applications to be mentioned are:

- strengthening / stiffening of structural components;
- bonded sandwich structures;
- bonded, built-up profiles.

2.2.4 *Hybrid joints*

In some applications different joining methods are combined. Well-known combinations in primary structures are welding and bolting as shown in fig. 16.

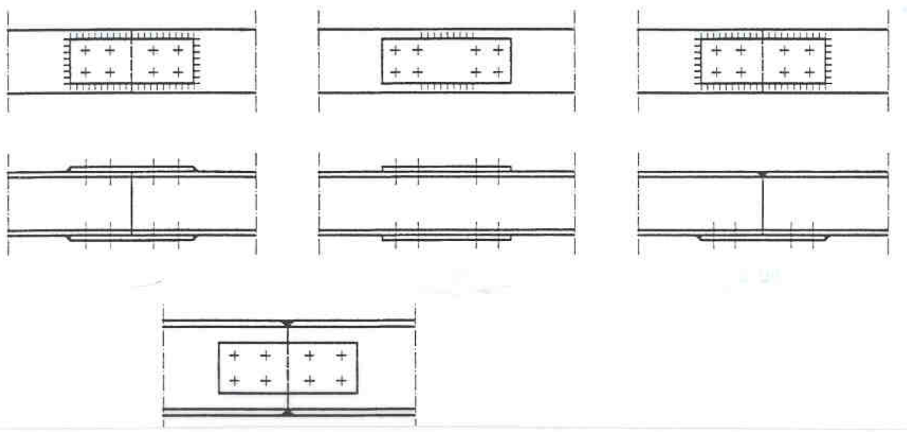

Fig. 16: Hybrid joints

2.3 Joints in thin-walled structures

The joining methods as described for primary structures, can also be used in thin-walled structures. In addition to that specific joining methods for thin-walled structures have been developed. The latter methods will be shortly reviewed in the following.

2.3.1 *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, a much lower equipment cost, and the portability of the gun, all compared to resistance welding. For those reasons in particular MIG spot welding has been quite widely applied but nowadays resistance spot welding is by far the most widely used method.
Resistance spot welding 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. 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, special care is needed to achieve the desired results.
Resistance spot welding produces a local weld “spot” by clamping two (or sometimes more) sheets of metal between two electrodes for a brief interval with the metal under pressure, see fig. 17. The heat required for coalescence is generated by the bulk electrical resistance of the metal and also by the interface resistance between the metal sheets. It is a fusion welding process because melting must occur at the interface between the joint members to cause coalescence, form a cost nugget and joint the member together.

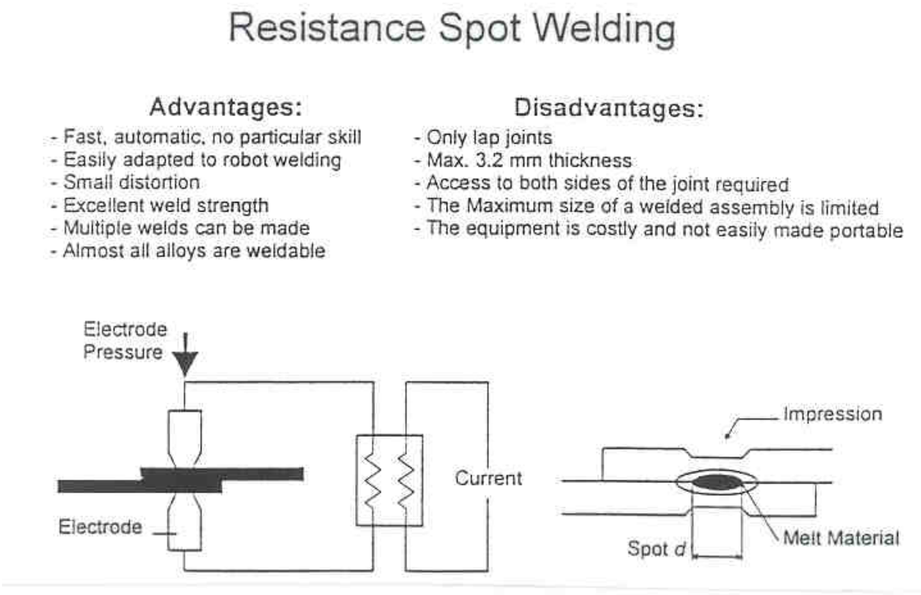

Fig. 17: Resistance spot welding

Resistance spot welding is a high production joining method for fabricating sheet structures ranging from aircraft to cooking intensils. 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.

It has also some disadvantages such as:

- Only lap joints can be welded;
- The thickness is limited to about 3 mm;
- Both sides of the joint must be accessible.

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. When the welds are spaced, it is termed intermittent seam welding. When the welds overlap each other, it is termed seam welding. The latter is often used to make gas or liquid tight joints.

2.3.2 *Mechanical fastening*

With thin-walled structures special mechanical fasteners such as screws and (blind) rivets are used.
The most usual application of screws is the fastening of thin to thin or thin to thick material.
Thread forming or thread cutting screws are installed in predrilled or punched holes or screw grooves, which can be easily extruded.

Self drilling screws are provided with a drilling cutter or a sharp bore bit to drill the hole, see fig. 18.

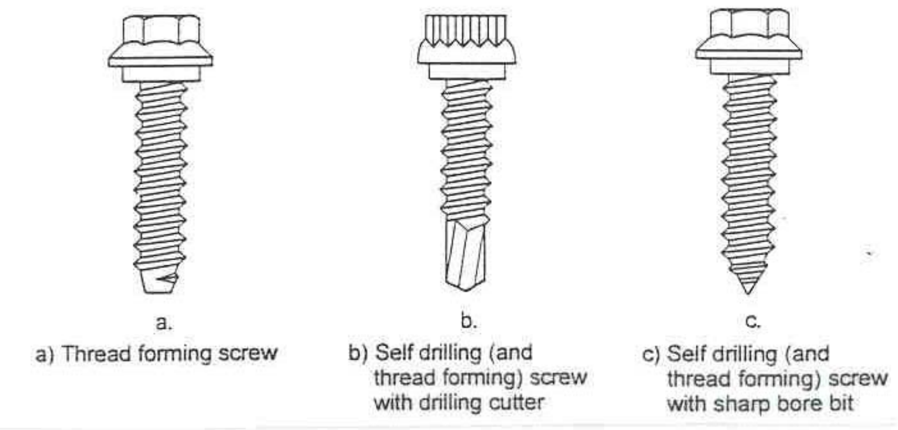

Fig. 18: Thread forming and selfdrilling screws

When components have to be riveted together in situations where the rivet is not accessible from both sides, 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 period of time and are nowadays often used in stead of solid rivets.
Probably most well-known is the so called pop rivet, see fig. 19.

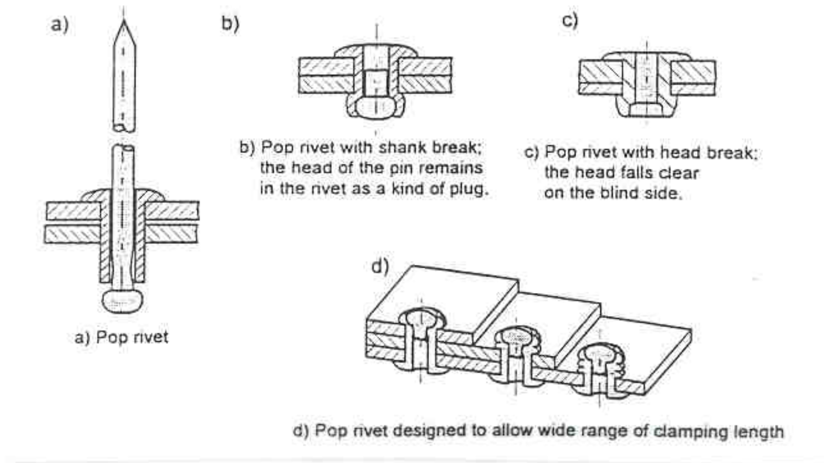

Fig. 19: Pop-rivets

Pop rivets consist of a riveting pin and a rivet sleeve with a flat or countersunk head. In the riveting process the tool first pulls the sheets tightly together and then forms the closing head. Finally, the pin breaks 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.

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 (AIMg5, 5056A). The joint can withstand very high shear and tensile stresses. Huckbolts are fasteners consisting of two parts, the rivet bolt itself, with a mushroom or countersunk head, and a closing collet, see figure 20. The bolt has a smooth, cylindrical shank to withstand shear stresses.

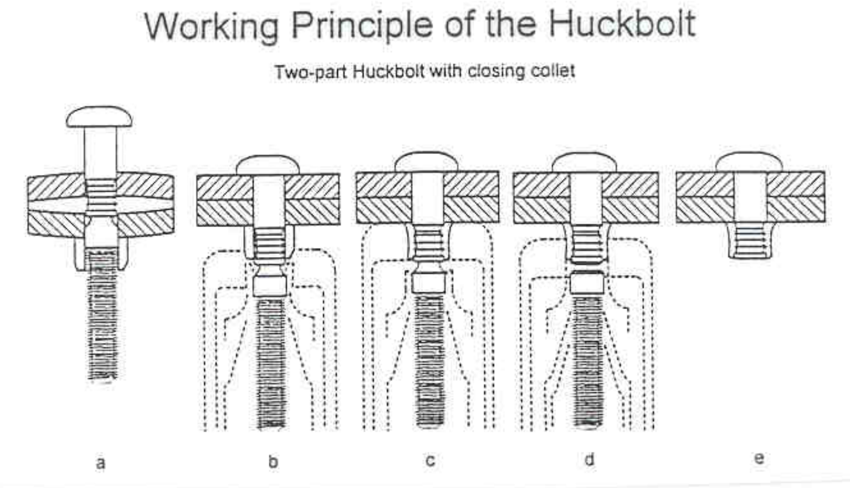

Fig. 20: Huckbolts

2.3.3 *Adhesive bonding*

Adhesive bonding is used both in primary structures as well as in thin-walled structures. Similar aspects as described in 2.2.3, have to be dealt with when applying bonding technology in thin-walled structures. Very nice examples of thin-walled adhesive bonded structures are sandwich panels, consisting of thin outer skins of aluminium sheet adhesive bonded to a (isolating) core material, forming an element with excellent mechanical properties.

2.3.4 *Hybrid joints*

With thin-walled structures different joining methods can be combined. Widely used combinations are: spot-welding and adhesive bonding; riveting and adhesive bonding; screws and adhesive bonding.
In some applications the two joining methods are complementary for example spot-welding and adhesive bonding; in others the fasteners are meant to hold the parts in position while the adhesives are curing and finally joint strength is arrived at.

3 Design of Joints

3.1 Principles of design

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 2 a variety of joining methods is available for aluminium structures. Correct selection is governed by a large number of factors, structural and non-structural.
This chapter focuses on structural requirements.
For the design of a connection two quantities have to be considered:

F_{sd} = the force in the connection caused by the design load;

F_{rd} = the design strength (resistance) of a connection (see also fig. 21).

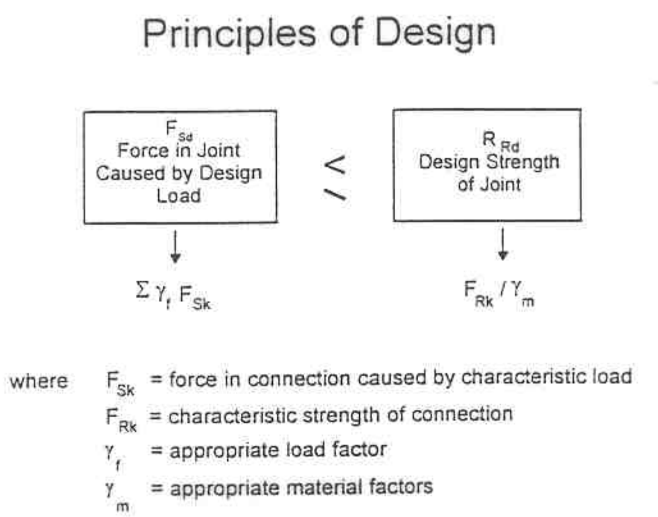

Fig. 21 Principles of design

The forces in connections are dependent on the:

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

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.

Strength, Stiffness and Deformation Capacity

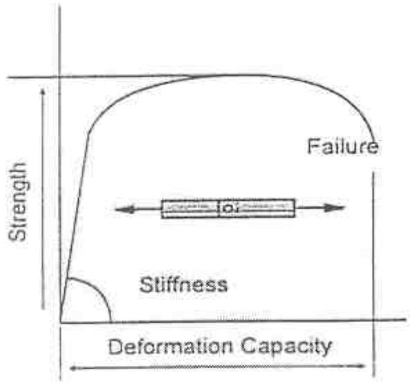

Fig. 22 Strength, stiffness and deformation capacity

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 settlings 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.

3.2 Design of welded connections

3.2.1 General

In the design of welded joints consideration should be given both to the strength of the welds and to the strength of the heat-affected zone. The design guidance given here which complies with Eurocode 9, applies to:

- Strength members under predominantly static loads.
- The welding process MIG for all material thicknesses and TIG only for thicknesses up to 6 mm and for repair.
- The welder and welding procedure are approved in accordance with qualification requirements as specified resulting in a normal quality level.
- Combinations of parent and filler metal as given in fig. 23.

If - in case of strength members – the above conditions are not fulfilled representative test pieces have to be welded and tested. For partial strength or non-strength members a lower quality can be specified by the designer resulting in lower design strength values. The latter can be obtained by using a partial safety factor $\gamma_M = 1{,}6$ instead of $\gamma_M = 1{,}25$ as usual for strength members.

In order to ensure the welding quality qualification specimens have to be welded according to a written welding procedure specification. This enables to approve the welder and the welding method as well as to determine the welding parameters and other relevant data, which can be added to the welding procedure specification. And, if necessary, these qualifications specimens can be subjected to mechanical testing to prove the design and the procedures.

Parent metal combinations *)						
Parent metal	7020	6082	6061	6060	5454	5083
7020	5356 5183 4043					
6082	5356 5183 4043	5356 5183 4043				
6061	5356 5183 4043	5356 5183 4043	5356 5183 4043			
6060	5356 4043	5356 4043	5356 4043	5356 4043		
5454	5356 5183	5356 5183	5356 5183	5356	5356 5183	
5083	5356 5183	5356 5183	5356 5183	5356	5356 5183	5356 5183
*) Filler metals for parent metal combinations are shown in one box, which is located at the intersection of the relevant parent metal row and column.						

Fig 23 Selection of filler metal

3.2.2 *Welded connections*

Contrarily to structural steels with aluminium due to the heat-input by welding a heat-affected zone (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 series).

The severity of the HAZ is given in fig. 24 by means of a softening factor ρ_{HAZ} . Applying this factor to the ultimate strength (f_u) of the alloy results in the limiting strength of the HAZ.

Alloy series	Condition	ρ_{HAZ} (MIG)	ρ_{HAZ} (TIG)
6xxxx	T5 T6	0,65 0,65	0,60 0,50
7xxx	T6	0,80	0,60
5xxx	H22 H24	0,86 0,80	0,86 0,80
3xxx	H14, 16, 18	0,60	0,60

Fig. 24 HAZ softening factor ρ_{HAZ}

The HAZ is assumed to extend a distance b_{HAZ} in any direction from a weld as shown in fig. 25. The values of b_{HAZ} depend on the welding process and the material thickness, see fig. 26.

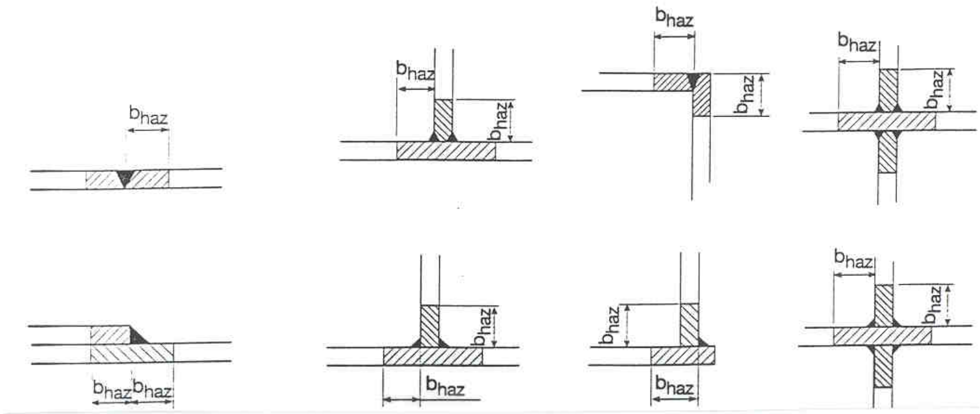

Fig. 25 Extent of heat-affected zones (HAZ)

	b_{HAZ} in mm	
thickness *t* in mm	MIG	TIG
0 < t ≤ 6	20	30
6 < t ≤ 12	30	-
12 < t ≤ 25	35	-
t > 25	40	-

Fig. 26 Distance b_{HAZ} in mm

In case of temperature build-up higher than 60°C when multi-pass welds are laid down, higher values of b_{HAZ} have to applied.
It is noted that both severity and extent differ for TIG and MIG welding. For TIG welding a higher extent (larger HAZ area) and more severe softening occurs due to the higher heat-input.

For the limiting strength of weld metal (f_w) the values according to fig. 27 may be used, provided that the combinations of parent metal and filler metal as given in fig. 23, are applied.
For the limiting strength of weld metal it is distinguished according to the filler metal used. The choice of filler metal can have a significant influence on the strength of the weld metal. With the design of welded connections in aluminium structures it is noted that – except for the strength reduction in the HAZ – also the strength of the weld metal usually appears to be lower than the strength of the parent metal. It is recommended to take that into account with the design of members as well.

Limiting strength	Filler metal	Alloy								
		3103	5052	5083	5454	6060	6005A	6061	6082	7020
f_w [N/mm^2]	5356		170	240	220	160	180	190	210	260
	4043A	95	-	-	-	150	160	170	190	210
For alloy 5754 the values of alloy 5454 and for alloy 6063 the values of alloy 6060 can be used. If filler metals 5056A, 5556A or 5183 are used then the values for 5356 have to be applied. If filler metals 4047A or 3103 are used then the values of 4043A have to be applied. For different combinations of alloys the lowest limiting strength of the weld metal has to be used.										

Fig. 27 Limiting strength values of weld metal f_w.

3.2.3 *Design of welds*

Using <u>butt welds</u> in aluminium structures for strength members full penetration butt welds shall be applied. In that case the effective thickness of the butt weld equals the thickness of the connected members. With different member thickness the smallest one shall be taken into account.
Reinforcement or undercut of the weld within the limits as specified should be neglected for the design.
The effective length of the weld shall be taken as equal to the weld length when run-on and run-off procedures are sues. Otherwise the total length shall be reduced by twice the thickness *t*.

Partial penetration butt welds shall only be used for strength members when verified by testing that no serious weld defects are apparent. In other cases partial penetration butt welds shall be only applied with a higher γ_M value (see also 3.2.1) because of the high susceptibility for weld defects of partial penetration butt welds.
For partial penetration butt welds effective lengths is referred to full penetration butt welds. As far as the effective throat section t_e is considered fig. 28 is governing the design.

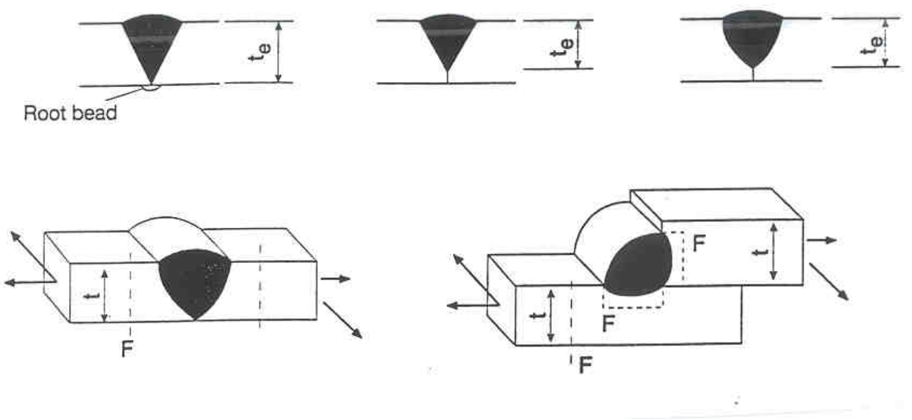

Fig. 28 Effective throat thickness t_e (butt welds)
Failure planes (F) adjacent to a weld

As far as the design of butt-welded joints is concerned, the following holds: the stresses occurring in the weld should be related to the design strength of the weld metal. For example a tensile stress, perpendicular to the weld axis, has to satisfy:

$\sigma_\perp \leq \frac{f_w}{\gamma_M}$ where f_w = limiting strength weld metal (see fig. 27)

γ_M = partial safety factor; usually γ_M = 1,25

For <u>fillet welds</u> the throat section (see fig. 29) shall be taken as the governing section, since the actual strength of a fillet weld is well approximated by considering the throat section and the forces acting on that section. The throat section is determined by the effective length and the effective throat thickness of a fillet weld.

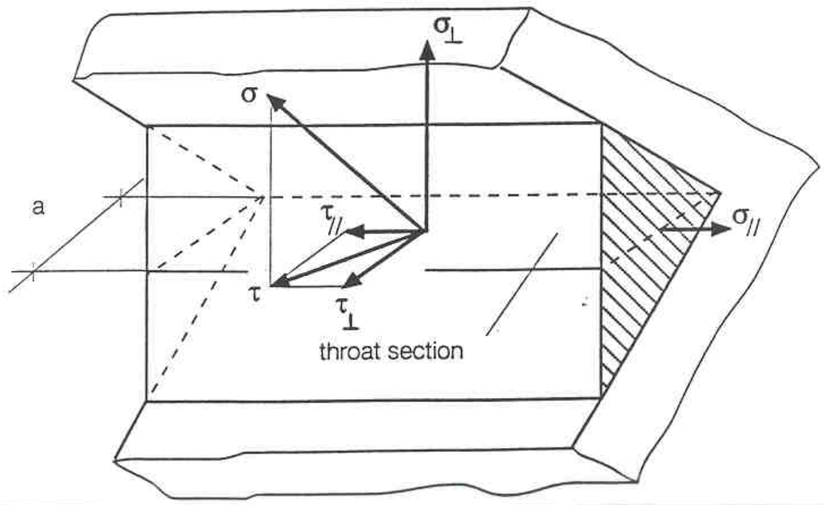

Fig. 29 Stresses $\sigma_\perp, \tau_\perp and \tau_{//}$ acting on the throat section of a fillet weld

The effective length shall be taken as the total length of a fillet weld when:
- Run-on/run-off procedures are used.
- The length of the fillet weld is at least 8 times the throat thickness.
- The length of the fillet weld does not exceed 100 times the throat thickness with non-uniform stress distributions along the length of the weld. With uniform stress distributions a length restriction does not apply.

If the above requirements are not fulfilled an effective length has to be taken into account, see Eurocode 9. With non-uniform stress distributions and thin long welds the deformation capacity at the ends of the welds may be exhausted before the middle part of the weld yields; thus the connection fails by a kind of zipper-effect.

For the effective throat section of a fillet weld the height a of the largest triangle which can be inscribed within the weld, has to be applied, see fig. 30. When the qualification specimens show a consistent, positive root penetration, the throat thickness may be increased by 20 % with a maximum of 2 mm.
With deep penetration fillet welds the additional throat thickness may be taken into account provided that consistent penetration has been proved by test.

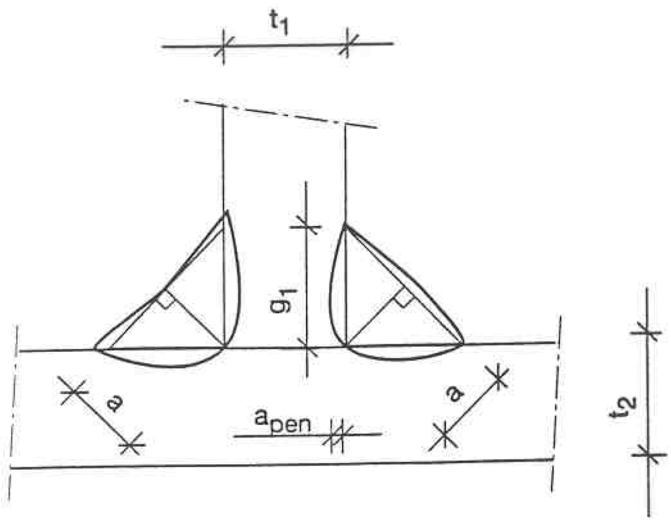

Fig. 30 Effective throat thickness a; positive root penetration a_{pen}.

As far as the design of fillet welds is concerned, the forces acting on fillet welded joints, should be resolved into stress components with respect to the throat section, see fig. 29.

This may result in a normal stress $\sigma_\perp$ perpendicular to the throat section, a shear stress $\tau_\perp$ acting on the throat section perpendicular to the weld axis, and a shear stress $\tau_{//}$ acting on the throat section parallel to the weld axis. A normal stress $\sigma_{//}$ acting along the weld axis does not have to be considered.
For the design the above stress components shall be combined to a comparison stress σ_c as follows:

$$\sigma_c = \beta\sqrt{\sigma_\perp^2 + 3(\tau_\perp^2 + \tau_{//}^2)}$$ where β = 1,0 for the alloys of fig. 27.

For the design the following shall be applied:

$$\sigma_c \leq \frac{f_w}{\gamma_M}$$ where f_w = limiting strength weld metal (fig. 27)

γ_M = partial safety factor; usually γ_M = 1,25

$$\sigma_\perp \leq \frac{f_w}{\gamma_M}$$

For the design of fillet welds the above β-formula can be used similarly to steel structures. Contrarily to steel where also simplified formulas are applied, for aluminium the β-formula is preferred since it allows for:

- A better approximation of the actual strength of a fillet weld which is more critical than with steel structures, where the weld strength exceeds the parent metal strength.
- A consistent approach towards the design of a fillet weld since the β-formula accounts for the direction of the forces acting on the weld. The difference in strength between transverse and longitudinal fillet welds is taken into account automatically.
- Simple calculations with simple joints. Often only one or two stress components govern the design and subsequently the β-formula reduces to a simple design formula.

3.2.4 *Design strength HAZ*

As stated earlier in 3.2.1. consideration should be given to the strength of the heat-affected zone (HAZ). Similarly to the design of welds the following applies:

- The forces acting on the failure plane F (see fig. 28) result in respective stress components.
- The design strength of the HAZ which is arrived at as follows:

$$\sigma_{HAZ} \leq \frac{f_{a,HAZ}}{\gamma_M}$$ for forces perpendicular to the failure plane

$$\tau_{HAZ} \leq \frac{f_{v,HAZ}}{\gamma_M}$$ for shear forces in the failure plane.

where:

$f_{a,HAZ} = \rho_{HAZ}\, f_u$

$f_{v.HAZ} = \rho_{HAZ}\, \frac{f_u}{\sqrt{3}}$

ρ_{HAZ} = softening factor (see 3.2.2)

γ_M = partial safety factor (see 3.2.1)

f_u = ultimate strength parent metal

It is noted that the above design guidance about the heat-affected zones is dealing with welded connections as such. With the design of members the effect of heat-input by welding shall be taken into account in a proper way.

3.2.5 *Design of connections with combined welds*

The design of connections with combined welds can be reduced to the design of the constituent welds by using one of the two following methods:

1. The loads acting on the joint are distributed to the respective welds, which are most suited to carry them (plastic design approach).
2. The welds are designed for the stresses occurring in the parent metal of the different parts of the joint (linear-elastic design approach).

With method 1 it has to be checked whether the welds possess sufficient deformation capacity to allow for such a simplified load distribution. Besides, the assumed loads in the welds should not give rise to overloading of the connected members.
With method 2 the above problem do not exist, but may be difficult to determine the stresses in the parent metal of the different parts of the joint.

Assuming a simplified load distribution (method 1) is the most commonly applied method. Since the actual distribution of loads between the welds is highly indeterminate, such assumptions have been found to be an acceptable and satisfactory design practice. However, these assumptions rely on the demonstrated ability of welds to redistribute loads by yielding.
Residual stresses and other stresses not participating in the transfer of loads need not be considered for the design.

3.3 Design of bolted and riveted connections

3.3.1 *General*

The design guidance given in this chapter applies to:

- Strength members under predominantly static loads;
- Mechanical fasteners in primary structures i.e. bolts and solid rivets, see also chapter 2.2.2.
- Positioning of holes as given in chapter 3.3.2.
- Elastic or plastic design of the connection.
- Non preloaded and preloaded bolts, the latter in slip resistant connections.

3.3.2 *Positioning of holes*

The positioning of holes for bolts and rivets shall be in conformity with the limits of validity of the rules used to determine the design resistances of the bolts and the rivets. The positioning shall also be such as to prevent corrosion and local buckling as well as to facilitate the installation of the bolts and the nuts.

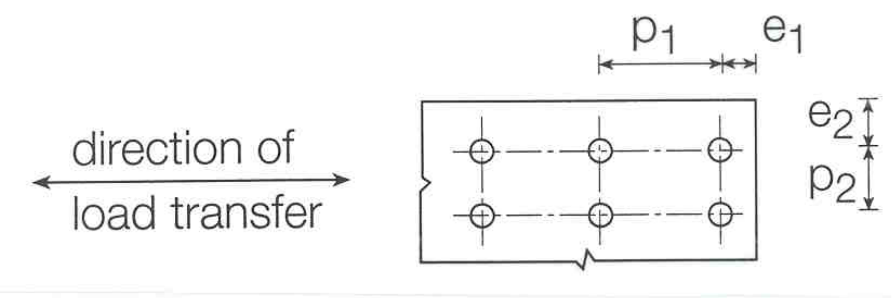

Fig. 31 Positioning of holes

To fulfil the above requirements the following distances shall be applied (see also fig. 31):

*	end distance e_1	minimum -	1,2 d	
	edge distance e_2	maximum -	4t + 40 mm	corrosive environment
			12t or 150 mm	no corrosive environment

*	spacing p_1:	minimum -	2,2 d	maximum – 14t or 200 mm
	spacing p_2:	minimum -	2,4 d	maximum – 14t or 200 mm

3.3.3 *Deductions for fasteners holes*

The net area of a member (A_{net}) is arrived at by deducting the maximum sum of the sectional areas of the holes in any cross section perpendicular to the member axis, provided the fastener holes are not staggered.

For staggered holes: $A_{net} = A - (2\,dt - s^2t/4p)$
(see fig. 32)

or $A_{net} = A - dt$

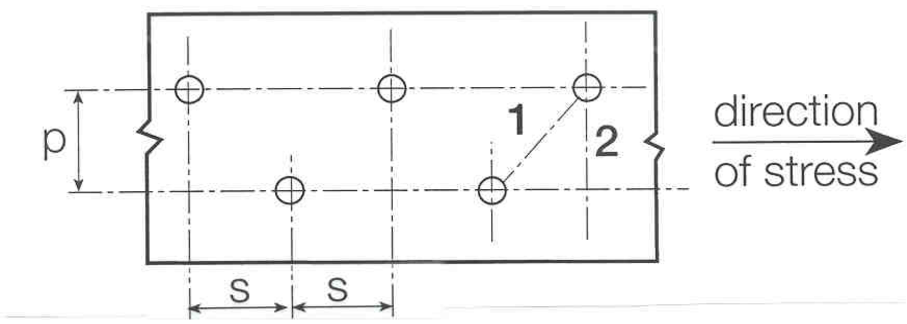

Fig. 32 Tension member, staggered holes

The above deductions hold for tension members; for compression members no deductions for fastener holes have to be applied. In case of holes in tension flanges as well as webs in beams specific rules apply. In case of shear usually A_{net} shall be taken into account. At the end of a member block shear should be verified.
In the case of unsymmetrical connected members such as angles specific guidance is given in Eurocode 9.

3.3.4 *Categories of bolted connections*

Two types of bolted connections can be distinguished:

- shear connections;
- tension connections.

Within <u>shear connections</u> 3 categories have been defined:

- <u>Category A: bearing type</u>. In this category (galvanised) steel, stainless steel, or aluminium bolts (or solid rivets) may be used.. The design ultimate shear load shall not exceed the design shear resistance nor the design bearing resistance of the bolt, see also 3.3.6.

- <u>Category B: slip resistant at serviceability limit state</u>. In this category preloaded high strength steel bolts with controlled tightening shall be used. The design serviceability shear load should not exceed the design slip resistance (see 3.3.7), while the design ultimate shear load shall not exceed the design shear resistance nor the design bearing resistance, see 3.3.6.

- <u>Category C: slip resistant at ultimate limit state</u>. In this category preloaded high strength steel bolts with controlled tightening shall be used. The design ultimate shear load shall not exceed the design slip resistance (see 3.3.7), nor the design bearing resistance obtained from 3.3.6.

In addition at the ultimate limit state the design resistance of the net section at bolt holes shall be taken as: $N_{net,Rd} = \dfrac{A_{net} \cdot f_{0,2}}{\gamma_{M1}}$

Within <u>tension connections</u> 2 categories have been defined:

- <u>Category D: non-preloaded bolts.</u> In this category low carbon or high strength (galvanised) steel, stainless steel, or aluminium bolts shall be used without preloading. The design ultimate tensile load shall not exceed the design tensile resistance of the bolt, see 3.3.6.
- <u>Category E: preloaded high strength steel bolts</u>. In this category preloaded high strength steel bolts with controlled tightening shall be used. The design ultimate tensile load shall not exceed the tensile resistance of the bolt, see 3.3.6. Such connections are often used to improve fatigue resistance; in that case the design tensile load shall should not disrupt the contact of the surfaces of the members connected.

3.3.5 *Distribution of forces between fasteners*

The distribution of forces between fasteners at the ultimate limit state due to the:

- bending moment shall be proportional to the distance from the centre of rotation;
- shear load shall be equally divided (see fig. 33a);

in the following cases:

- category C slip-resistant connections;
- other shear connections where the design shear resistance of a fastener ($F_{v,Rd}$) is less than the design bearing resistance ($F_{b,Rd}$).

In all other cases the distribution of forces between fasteners due to the bending moment and the shear load at the ultimate limit state may be assumed plastic as for example indicated in fig. 33b.

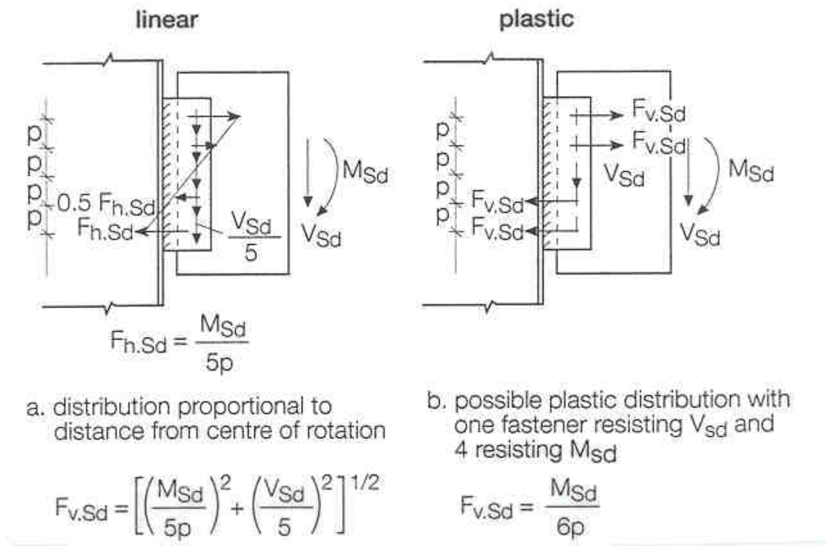

Fig. 33 Distribution of forces between fasteners.

In a lap joint the distribution of forces between fasteners may be assumed equal to a maximum length of L = 15d, where d is the nominal diameter of the bolt of rivet. For long joints (L > 15 d) a reduction of the force per fastener shall be applied as follows: the design shear resistance $F_{v,Rd}$ of all the fasteners as specified in 3.3.6 shall be multiplied by a reduction factor β_{Lf}.

Where: $\beta_{Lf} = 1 - \frac{L_j - 15d}{200}$ but $0{,}75 \le \beta_{Lf} \le 1{,}0$

L_j see fig. 34.

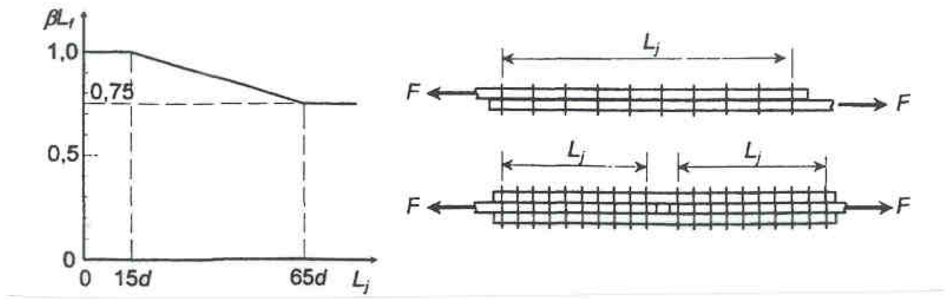

Fig. 34 Long lap joints

3.3.6 Design resistance of bolts and rivets

The design resistances given here apply to standard manufactured steel bolts of strength grades 4.6, 5.6, 8.8 and 10.9, or aluminium bolts, or stainless steel bolts. Bolts including nuts and washers shall conform with relevant standards.

At the ultimate limit state the design shear force $F_{v,Ed}$ on a bolt shall not exceed the lesser of:

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

At the ultimate limit state the design tensile force $F_{t,Ed}$ on a bolt, including any force due to prying action, shall not exceed the design tension resistance of the bolt $F_{t,Rd}$.

Bolts subjected in the ultimate limit state to both shear and tensile forces shall in addition satisfy:

$$\frac{F_{v,Ed}}{F_{v,Rd}} + \frac{F_{t,Ed}}{1{,}4F_{t,Rd}} \leq 1{,}0$$

For the design resistance of the bolts the following holds:

- Shear resistance per shear plane:

$F_{v,Rd} = \dfrac{0{,}6\, f_{ub} A}{\gamma_{Mb}}$ for strength grades lower than 10.9.

$F_{v,Rd} = \dfrac{0{,}5\, f_{ub} A}{\gamma_{Mb}}$ for strength grade 10.9, stainless steel and aluminium bolts.

- Bearing resistance:

$F_{b,Rd} = \dfrac{2{,}5 \alpha f_u d\ t}{\gamma_{Mb}}$ where α is the smallest of :

$$\frac{e_1}{3d_o} ; \frac{P_1}{3d_o} - \frac{1}{4} ; \frac{f_{ub}}{f_u} \ or\ 1{,}0$$

- Tension resistance:

$F_{t,Rd} = \dfrac{0{,}9\, f_{ub} A_s}{\gamma_{Mb}}$ where A_s is the stress area of the bolt.

For rivets similar formula apply. However, tension in aluminium rivets is not recommended.
Note that the bearing resistance is dependent on the edge distance as well as the spacing of the fasteners.

3.3.7 *High strength bolts in slip-resistant connections*

Design may be based on calculations for joints where the proof strength of the connected parts is higher than 200 N/mm^2. Otherwise, the strength of joints using high strength steel bolts should be proved by testing.

For the design of slip-resistant connections the following has to be distinguished:

a) In the ultimate limit state slip is not allowed (see also3.3.4, Category C). Thus, the design ultimate shear load shall not exceed:

- the design slip resistance $F_{s,Rd}$;
- the design bearing resistance $F_{b,Rd}$ (see 3.3.6).

b) In the serviceability limit state slip is not allowed (see also3.3.4, Category B). Thus, the design serviceability shear load shall not exceed the design slip resistance $F_{s,Rd}$; and the design ultimate shear load shall not exceed the design shear resistance $F_{v,Rd}$ nor the design bearing resistance $F_{b,Rd}$ (see 3.3.6).

In addition to the above at the ultimate limit state the design resistance of the net section at bolt holes shall be taken as:

$$N_{net,Rd} = \frac{A_{net} \cdot f_{0,2}}{\gamma_{M1}}$$

The design slip resistance of a preloaded high-strength bolt shall be taken as:

$$F_{s,Rd} = \frac{n\mu}{\gamma_{Ms}} \; F_{p,cd}$$ for shear connections

$$F_{s,Rd} = \frac{n\mu}{\gamma_{Ms}} \; (F_{p,cd} - 0{,}8\, F_{t,Ed})$$ for shear connections where the bolts are subjected to an additional tensile force $F_{t,Ed}$.

Where:

$F_{p,Cd}$ is the design preloading force.

μ is the slip factor.

n is the number of friction interfaces

γ_{Ms} is the partial safety factor for slip resistance and shall be taken as:

γ_{Ms} = 1,25 for the ultimate limit state.

γ_{Ms} = 1,10 for the serviceability limit state.

Note: slotted or oversized holes shall not be used; usual hole clearances for bolts apply.

The design preloading force $F_{p,Cd}$ for high strength bolts with controlled tightening shall be taken as:

$$F_{p,Cd} = 0,7\ f_{ub}\ A_s$$

Tightening procedures shall be such that the level of the design preloading force is arrived at.

The design value of the slip factor μ is dependent on the surface treatment applied. The value of μ for lightly shot blasted surfaces without surface protection treatments shall be taken as:

$$\mu = 0,3$$

In case of other surface treatments or when higher values of μ are wanted, a sufficient number of tests on representative test specimens has to be carried out.

3.4 Design of adhesive bonded connections

3.4.1 General

The design guidance given in this chapter applies under the condition that:

- Strength members are subjected to predominantly static loads;
- Adhesive bonding shall not be used for main structural joints unless considerable testing has established its validity.
- The joint design is such that only shear forces have to be transmitted (see 3.4.2).
- Appropriate adhesives are used (see 3.4.3)
- The surface preparation procedures before bonding do meet the specifications as required by the application (see 3.4.3).

3.4.2 Joint design

With the design of adhesive bonded joints shear forces should be looked after; tensile forces – in particular peeling or other forces tending to open the joint – should be avoided or should be transmitted by complementary structural means, see fig. 35.

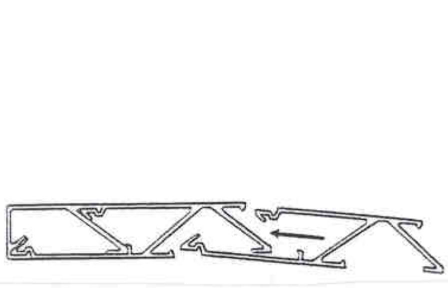

Fig. 35 Extruded members; in-plane tensile forces transmitted by snapping parts; out of plane shear loading transmitted by adhesive bonding.

Loads should be carried over as large an area as possible. Increasing the width of joints usually increases the strength pro rata. Increasing the length is beneficial only for short overlaps. Longer overlaps do result in more severe stress concentrations in particular at the ends of the laps, see fig. 36.

Furthermore, uniform distribution of stresses and sufficient deformation capacity to enable a ductile type of failure of the component are to be strived for. In case the design strength of the joint exceeds the yield strength of the connected member sufficient deformation capacity is ensured.

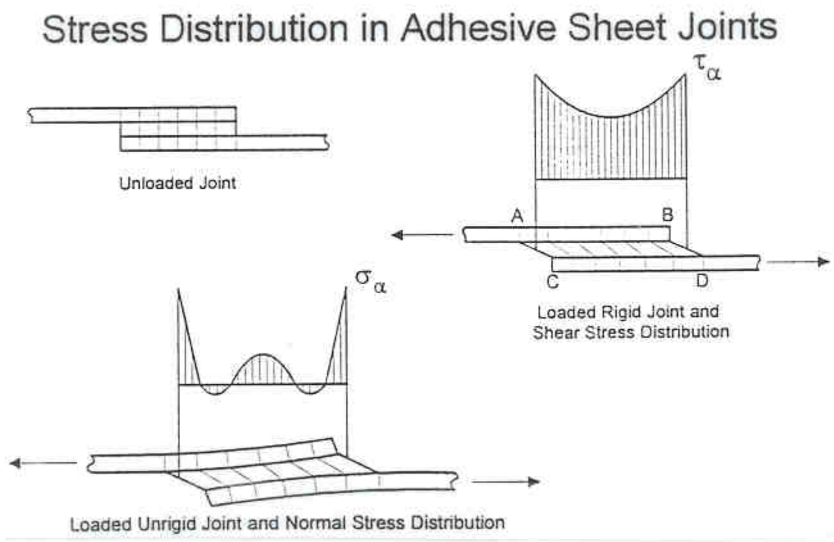

Fig. 36 Stress distribution in adhesive sheet joints.

3.4.3 *Limiting strength adhesives*

As far as the mechanical properties are concerned high strength adhesives should be used for structural applications, see fig. 37.
However, also the toughness should be sufficient to overcome stress/strain concentrations and to enable a ductile type of failure.
The influence of the adhesives 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 adhesives properties it is noted that in the temperature range –20° C up to +60° 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 service life of the structure. An overview of pre-treatments from simple degreasing up to very sophisticated chemical pre-treatments is given in 2.4.3.

For structural applications the limiting shear strength values of adhesives $f_{v,adh}$ as given in fig. 37, may be used.

Adhesive types	$f_{v,adh}$ N/mm^2
1-component, heat cured, modified epoxide	35
2-components, cold cured, modified epoxide	25
2-components, cold cured, modified acrylic	20

Fig. 37 Limited shear strength values of adhesives

The adhesive types as mentioned in fig. 37 may be used under the conditions as given earlier in 3.4.1 and 3.4.2. The values given are based on results of extensive research. However, it is allowed to use higher shear strength values than the ones given in fig. 37 provided that adequate tests are carried out, see 3.4.5.

3.4.4 *Design shear strength adhesives*

The design shear strength shall be taken as:

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

where:

τ is shear stress in the adhesive layer
$f_{v,adh}$ is limiting shear strength value adhesive, see fig. 37.
$\gamma_{M,adh}$ is the material factor for adhesive bonded and shall be taken as: $\gamma_{M,adh} = 3{,}0$

The above high value of $\gamma_{M,adh}$ has to be used since:

- 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;
- the mechanical properties of adhesive bonded joints suffer from ageing.

3.4.5 Design assisted by testing

Higher limiting shear strength values of adhesives than given in fig. 37 may be used when thick-adherend shear tests are carried out, see fig. 38. The results of these tests have to be evaluated as to arrive at reliable strength value of the applied adhesive.

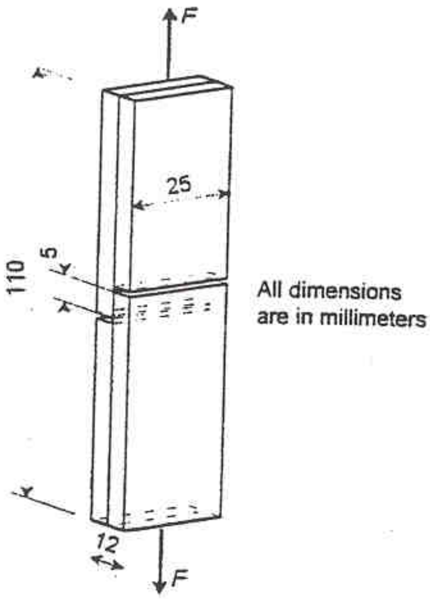

Fig. 38 Thick adherend shear test specimen

The strength of adhesive bonded joints or members may also be determined by testing. Sample joints should be made at full scale, using the same manufacturing procedure as for production joints. These sample joints should be tested with similar joint construction and loading to that occurring in the actual structure.

3.5 Hybrid connections

When different forms of fasteners are used to carry a shear load or when welding and fasteners are used in combination (see also 2.2.4 and 2.3.4) the designer shall verify that they act together.

In general the degree of collaboration may be evaluated through a consideration of the load-displacement curves of the particular connection with individual kind of joining, or also by adequate tests of the complete hybrid connection.

In particular normal bolts with hole clearance shall not collaborate with welding.
Preloaded high-strength bolts in connections designed as slip-resistant at the ultimate limit state (Category C) may be assumed to share load with welds, provided that the final tightening of the bolts is carried out after the welding is completed. The total design load should be given by the appropriate design load of each fastener with its corresponding γ_M value.

If not demonstrated that different fasteners act together only one type of fastener may be accounted for with the design of the joint.

4 Design examples structural applications

In the current practice still many concepts for aluminium structures are based on steel solutions. However, most of the time this is not the best solution for an aluminium structure.
In order to take advantage of the beneficial properties of aluminium it is important to ‘think in aluminium’ from the beginning of the design process. This attitude will result in aluminium structures better optimised with respect to structural design, material selection, fabrication, transport, erection and maintenance. Of course the connections play an important role in this process. When the connections are in mind from the beginning of the design process, the structure will be better optimised.
In this chapter the design of some typical aluminium structures is described, where the ‘thinking in aluminium’ has proven to work out very well in practice. The design of the structure is described generally, while the specific design of the connections is described in more detail.

4.1 Traffic gantries

The Dutch Ministry of Transport and Water Management has initiated the development of traffic gantries focused on durable materials, low maintenance costs and aesthetic aspects. Alcoa Masten, a subsidiary of Alcoa USA, has taken up this opportunity in designing and manufacturing aluminium traffic gantries. Four aluminium gantries have already been realised in the south of the Netherlands (see figure 39).

Fig. 39 Aluminium traffic gantry

4.1.1 Design concept

The traffic gantries are constructed by using a triangular space frame supported by two X-shaped column frames. Slenderness and transparency were objectives in the architectonic design.
The gantries are designed according to the Dutch code for aluminium structures NEN 6710, which is similar to Eurocode 9. The predominant load is the wind load. This is

reflected in the overall size of the space frame structure: the horizontal dimension (depth) of the triangular cross-section is larger than its vertical dimension (height).
Apart from static requirements the traffic gantries are also evaluated for wind induced fatigue. This has had consequences for the design of the cross sections as well as the design of the connections.

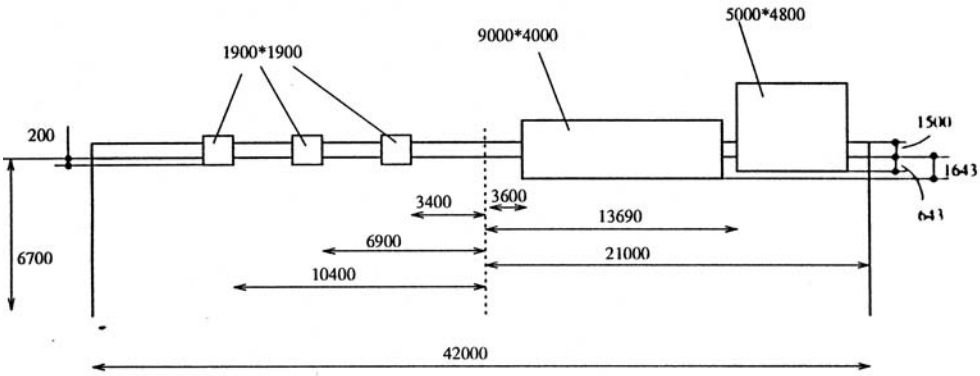

Fig. 40 Schematisation and positions of boarding

4.1.2 *Triangular space frame*

The triangular space frame has two upper chords and one base chord, which are interconnected by braces. Both chords and braces are fabricated by means of extrusion, allowing geometry and cross sections to be optimised with respect to load transfer and connections. The joints between the braces and chords are established by welding.
The upper chords and the base chord both have two flat surfaces to facilitate an easy welding procedure for these joints. The small external bulges and the flat surfaces of the braces are designed for an easy positioning, which also benefits the welding of the braces to the chords.

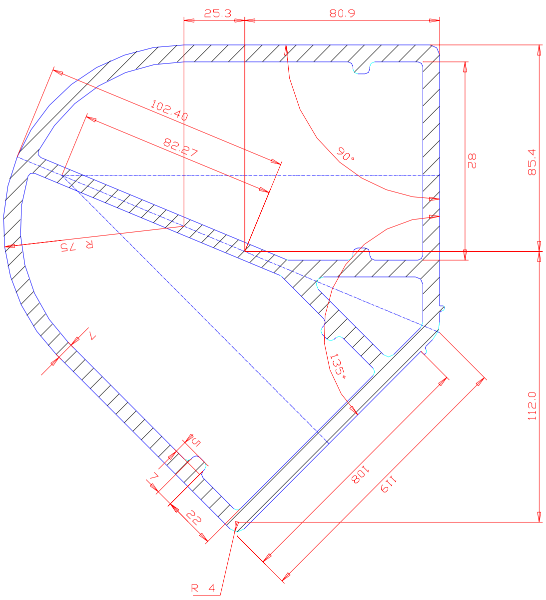

Fig. 41 Cross section upper chords

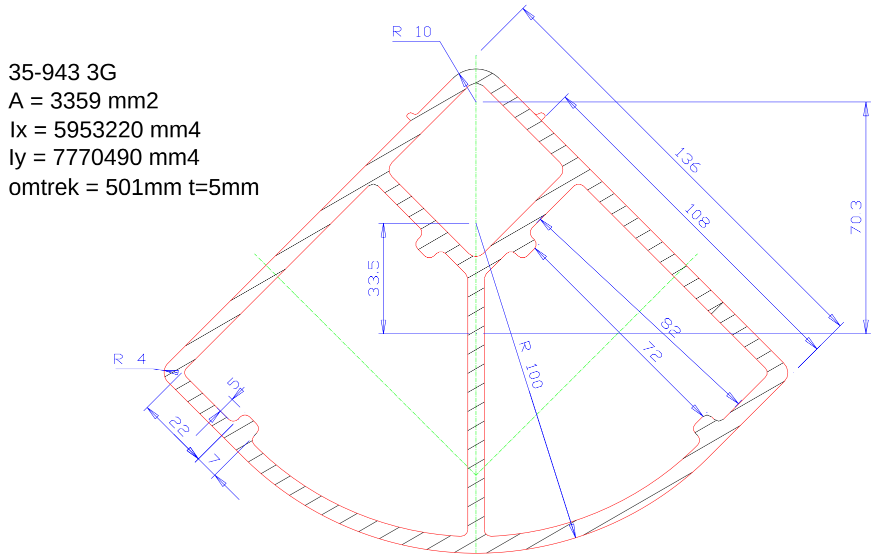

Fig. 42 Cross section base chord

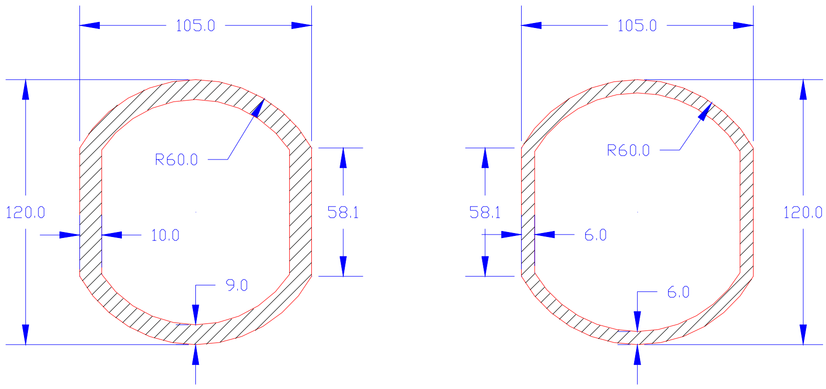

Fig. 43 Cross section braces

The internal bridges in the cross-section of the chord beams are designed for a reduction of the stress concentrations along the perimeter of the welded connection. Relatively low 'hot spot' stresses are important, especially when fatigue is governing for the design, which is the case for the traffic gantries. A detailed FEM analysis on the stress concentration of the multiplanar joint has shown that the internal bridge has indeed an important reducing influence on the stress concentrations. Chord sections without these internal bridges have shown up to 8 times higher SCF-values than the same sections with internal bridges.

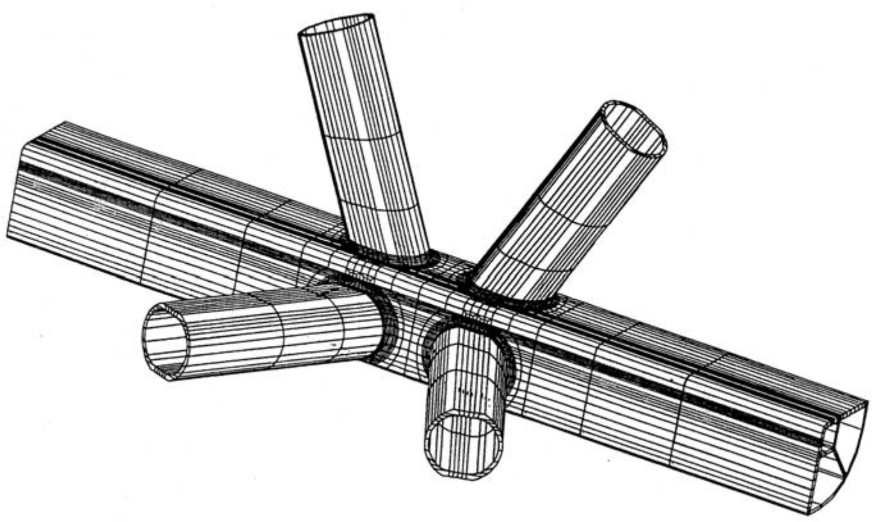

Fig.44 FEM-model of the welded multiplanar joint

The girder is prepared at the factory in sections up to 12 meters. The maximum span for which the gantry has been designed is 42 meters. So, depending on the actual length to be used, the sections are connected at the factory to the appropriate length and transported to the site. The internal legs in the aluminium chord sections are designed for the easy manufacturing of this section connection, which is realised by using two internal stainless steel strips for each connection between two chords. The stainless steel strips (width 80 mm, thickness 20 mm for the upper chords and 12 mm for the lower chord) are connected to the aluminium sections using M16 bolts. For the bolt gates a practical diameter of 18 mm is used, which is necessary to avoid problems during the assembly.

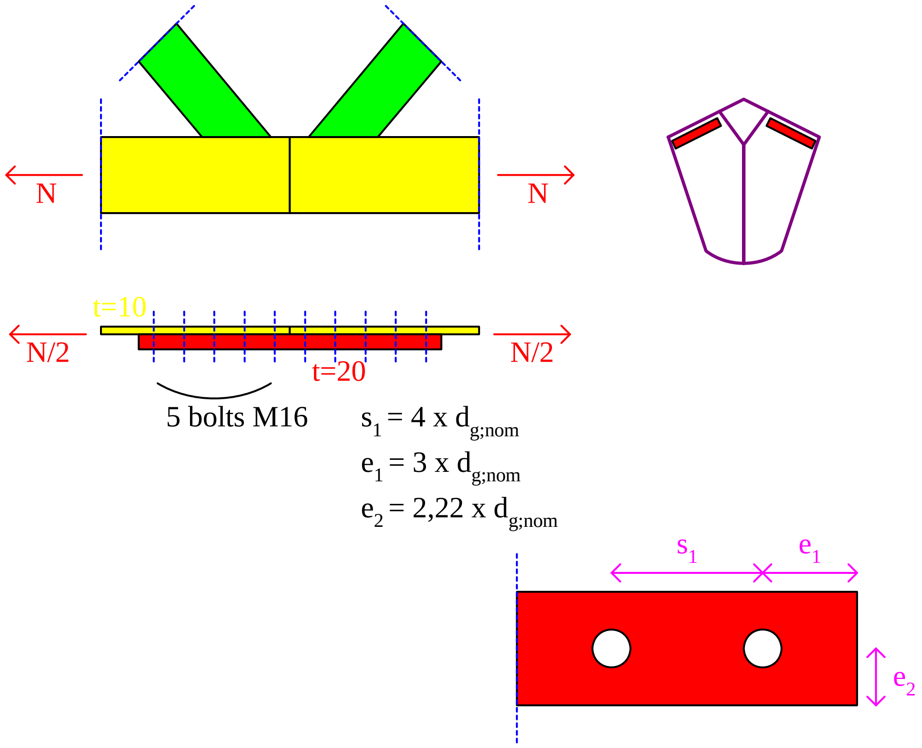

Fig. 45 Connection between girder sections

4.1.3 *X-shaped columns*

In the first designs the cross-section of the columns consisted of four parts (of which two and two are matching), to be welded to one profile in the factory (see figure 46). The columns of the four gantries already realised (see figure 39) have been constructed in this way.

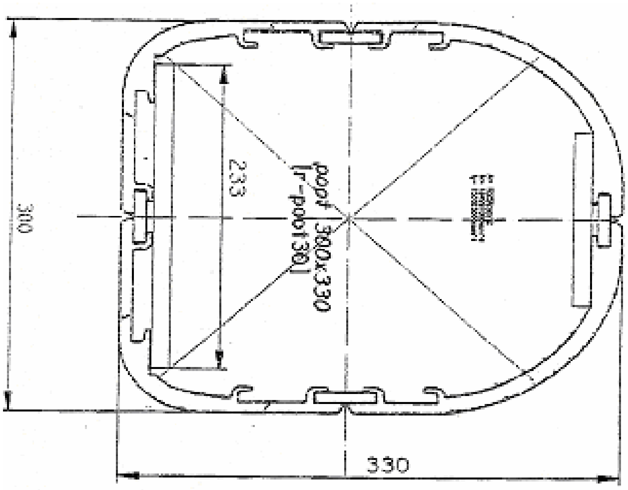

Fig. 46 Cross section of columns assembled by four parts

However, the fabrication of this column type seems to be very laborous and expensive, such that the aluminium gantry is not in good competition with the current steel gantries. In newer designs the column section contains only one extrusion, where the cross section for the column profile above the 'waist' is different from the column profile below the 'waist'.

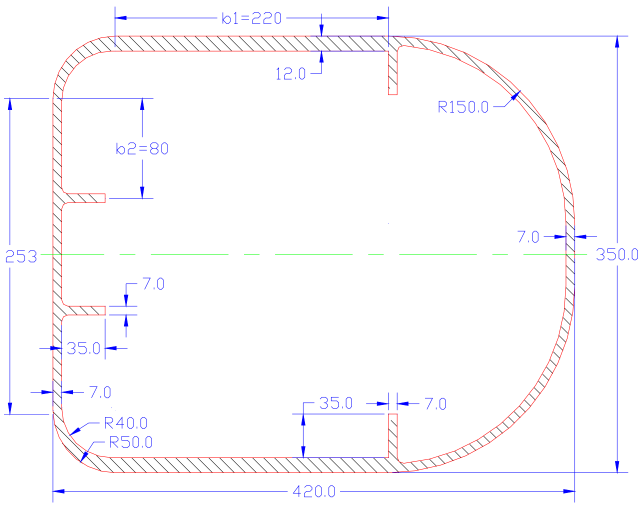

Fig. 47 Cross-section column profiles below the waist

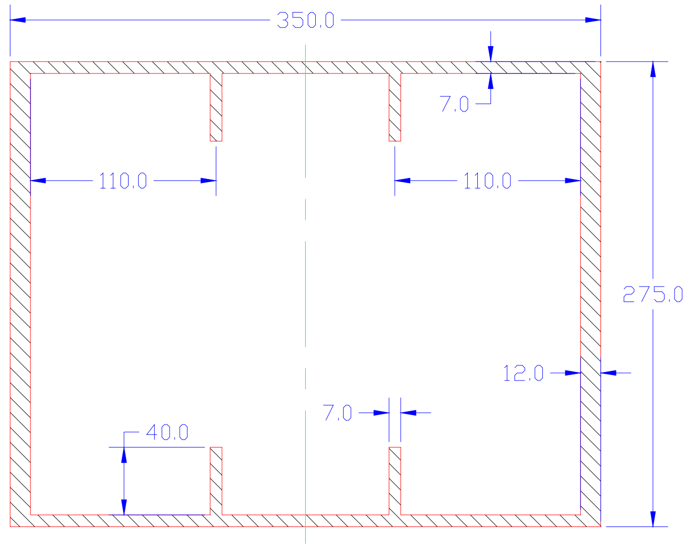

Fig. 48 Cross-section column profiles above the waist

For the assembly of the X-shape a special connection has been designed, which is able to transfer the high bending moments, horizontal shear forces and vertical axial forces. The ‘waist’ that forms the X-shape is realised by a preloaded slip resistant bolted connection between the two upper column sections and the two lower column sections. The ends of these profiles are provided with bolt holes previously. Stainless steel plates, which also have the X-shape, are placed inside the four column profiles to form the connection. These stainless steel plates are also provided with bolt holes as well as with pre-welded stainless steel nuts. In the factory one single connection is fixed by screwing, such that the X-shaped column can be transported to site. The actual connection is realised by preloaded friction grip bolts.

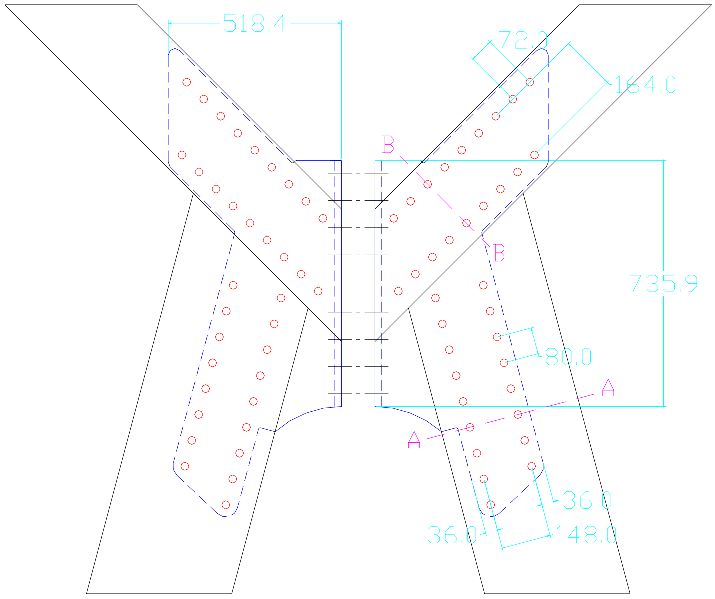

Fig. 49 Preloaded slip-resistant connection at the waist

The connection at the column foot is a standard moment connection using foot plates and M39 bolts for each connection.

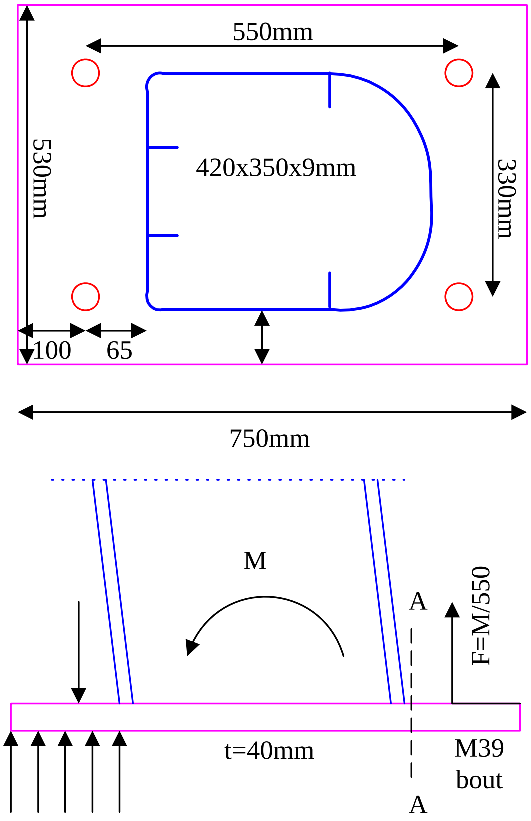

Fig. 50 Connection at column foot

When the girder is attached to the columns the traffic flow has to be stopped for some time. Special provisions, i.e. centre cams for the easy positioning of the girder, have been taken to reduce this conjugation of the traffic. In practice the assembly of girder and columns has taken place in a time span of only 10 minutes.

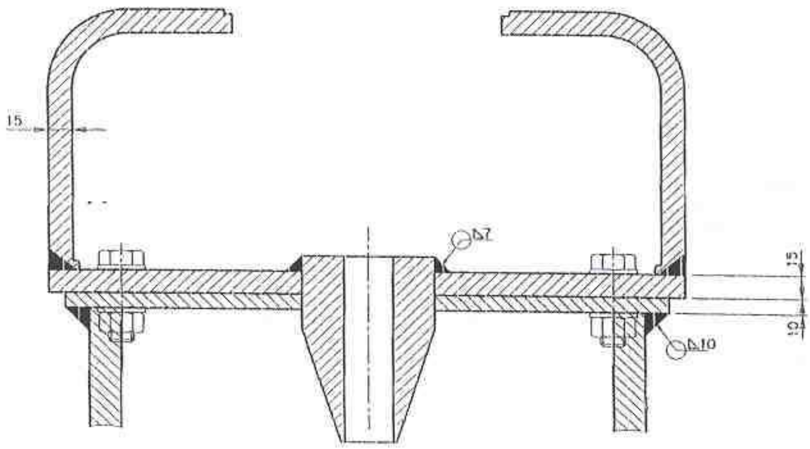

Fig. 51 Centre cams

4.2 Office building

The new office of the Dutch Aluminium Centre is settled in an all aluminium office building, which has recently been built in Houten in the Netherlands. The design concept of this building is rather exceptional: it is a one-storey building of about 1000 m^2 supported by more than 350 slender aluminium columns. The architect Micha de Haas was inspired by the rural landscape of the environment of Houten and called his design the ‘aluminium forest’ (see figure 52)

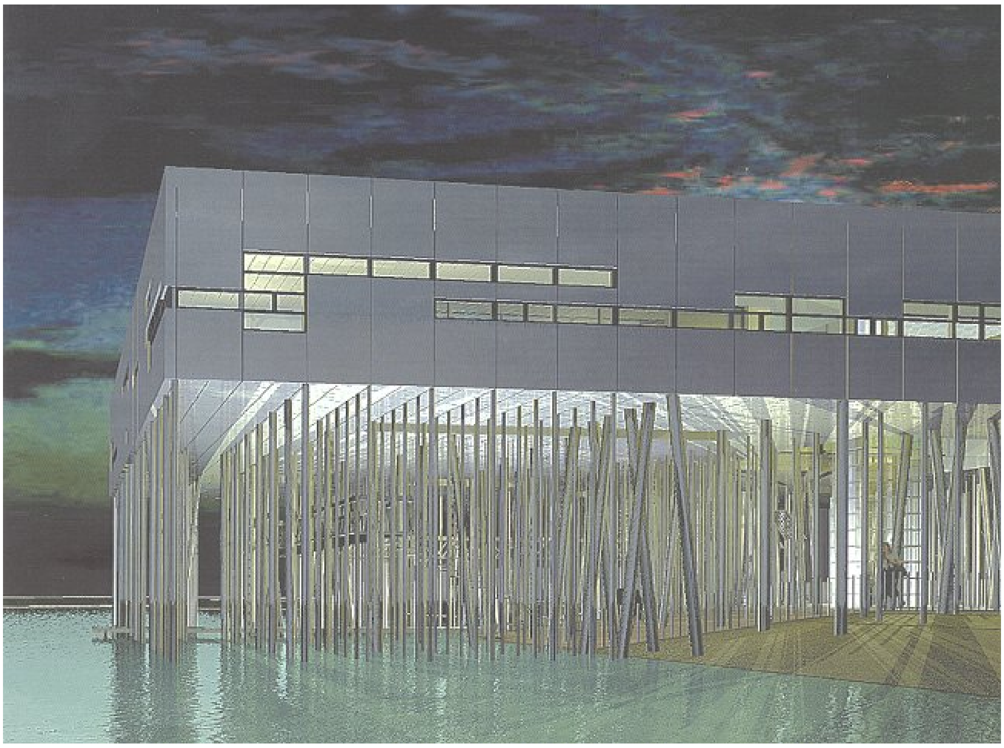

Fig. 52 View of the ‘aluminium forest’

4.2.1 Structural system of the building

The office layer has a plan of 31.2 meter by 36.0 meter and a height of 5 meter. The supporting columns have a length of 6 meter and range in diameter from 90 mm up to 210 mm, increasing in steps of 30 mm. The position of the columns is rather irregular, but such that the criteria for strength, stability and serviceability are satisfied. This is realised mainly by:

- rigid connection of the larger columns (diameter 210 mm) at the top as well as at the bottom;
- slight inclination (1:10) of these larger columns, which simulated a bracing system without destroying the ‘aluminium forest’ concept;
- concentration of the larger columns in three clusters, such that horizontal and rotational stability is satisfied.

The floor plan is constructed by primary beams at distances of 2400 mm. To include the supporting columns that are not located at this 2400 mm raster secundary beams are used lying under the primary beams. The aluminium beam section is similar to a steel HE160 beam. Where the span is too large two aluminium beams are placed above each other. These beams are connected by bolts which results in one assembled beam.

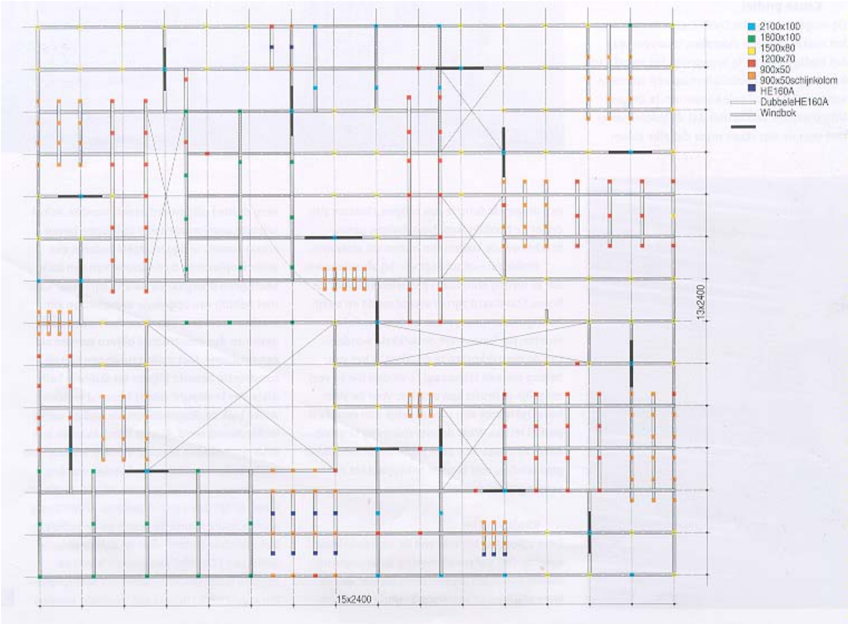

Fig. 53 Structural floor plan

Fig. 54 Floor beams and supporting columns during erection

Fig. 55 View of the bolted beam-column connection

For the roof structure the beams are assembled using two standard aluminium Π-profiles (150 mm width and 100 mm height) in combination with RHS profiles with varying heights. This results in assembled girders of 220 mm, 250 mm or 350 mm height, or in a lattice girder of 500 mm height (see figure 56). The assembly of the Π and RHS profiles is realised by welds in case of the girders and by bolts in case of the lattice girders. Where the span or the loading is too large for one lattice girder two of these girders are placed and coupled next to each other.

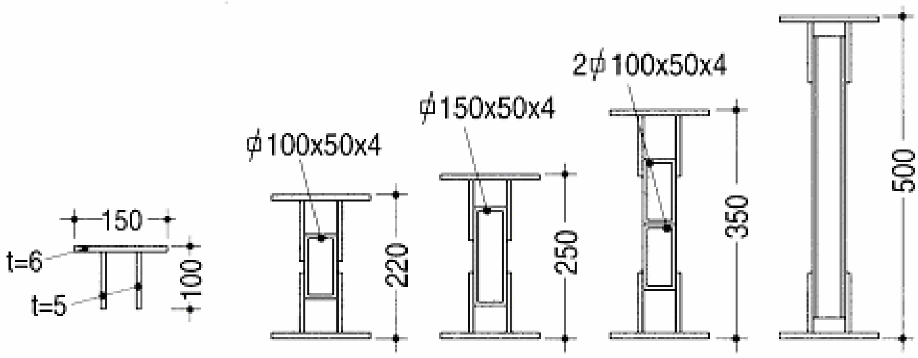

Fig. 56 Cross sections of the assembled beams in the roof structure

Fig. 57 View of single and double lattice girders

4.2.2 Bracing system

The bracing system, which is necessary for horizontal stability, is realised by slight inclination of the larger 210 mm columns. These columns have rigid connections at the bottom and at the top, which results in a satisfying horizontal deformation and a satisfying natural frequency.

It was required that the connection between the two inclined columns of the bracing system is located above the ceiling. Therefore the gusset plates, which are welded to the column top, have 'ears' to realise a bolted connection at the top of the inclined columns. The connection beneath the ceiling is realised by an in-welded bush.

Fig. 58 View of the simulated bracing system

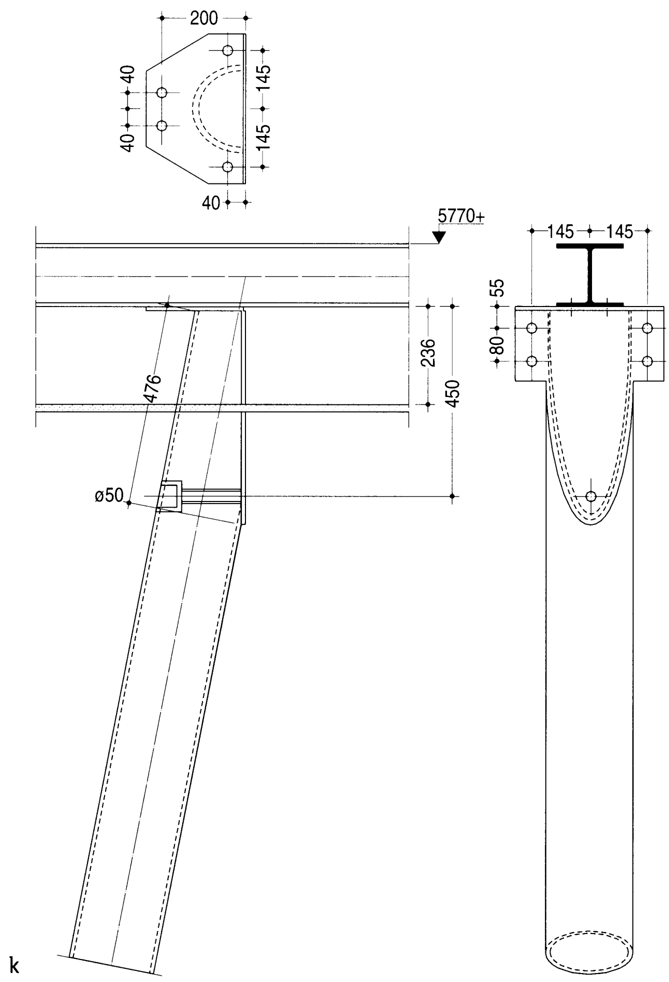

Fig. 59 Beam to column connection in case of inclined columns

4.2.3 *Exposition room*

The exposition room is settled inside the office building and has a floor plan of 14.4 meter by 12.0 meter. The roof structure of this exposition room consists of two whole and two half triangular aluminium truss girders spanning 14.4 meter. This aluminium structure can be considered as very innovative because of the special requirements and development of:

- an esthetical ‘streamline’ design for the connection between elements and nodes,
- an industrial method for the production of the girders,
- an industrial method for the production of variable aluminium casted node elements in low serie numbers,
- an adhesive bonded connection suitable for the primary load transfer between nodes and elements.

The requirement for a ‘streamline’ detail has been governing for the truss design. The lower part of the trusses is only 3.5 meter above floor level, which involves that elements and details have to be designed for architectonic qualities as well as structural properties. An adhesive bonded connection between nodes and elements fulfils both requirements, because then no visible connectors have to be applied.

Fig. 60 Triangular truss girders

An industrial production of the structure is met by using single truss girders as a basic structure. These single truss girders are located at the sides of the roof structure. The triangular girders, which are situated in the middle part of the roof structure, are constructed by two of these single truss girders. Together with the roof girders, which are located 50 mm above the nodes, the truss girders create a stable triangular system. The two bottom chords of the triangular truss are horizontally connected at the nodes. For esthetical reasons the upper chords are placed along a curved line.

Fig. 61 Shop fabrication of the triangular truss girder

For the casted nodes a production method with ‘lost foam’ has been developed. At first a simple polystyrene basic part, representing the connection of one element to the node, has been made. This has been done by producing one light aluminium expansion mould with loose screw thread inserts. This has resulted in polystyrene basic parts with left and right screw threads.
After this the polystyrene nodes have been assembled by manually cutting two or three or four polystyrene basic parts under the right angle and connecting these parts by adhesive bonding. Then the nodes are provided with a coating and bedded in sand by vibration.
After this the nodes are casted by fluid aluminium. During the casting the polystyrene mould, which contains 99% air, is melting and the residue disappears through the coating into the sand. The casted product has the typical polystyrene surface, but the inside is fully aluminium. Finally, the nodes were heat-treated for improvement of the strength.

Fig. 62 Fabrication of nodes

The connection between elements and nodes is realised by adhesive bonding. However, a direct connection between nodes and elements is not possible due to differing tolerances. Adhesive bonded connections require very strict tolerances, and the product tolerances of the nodes are not small enough due to the manual assembly of the polystyrene moulds. This problem is tackled by taking single sleeves which are adhesively bonded in the tubes. At the ends these sleeves have right and left screw threads which fit to the screw threads of the nodes.
The adhesive chosen for this application (two component epoxy) has already proven its quality in airplanes. Before the adhesive is applied a special cleaning treatment is used.

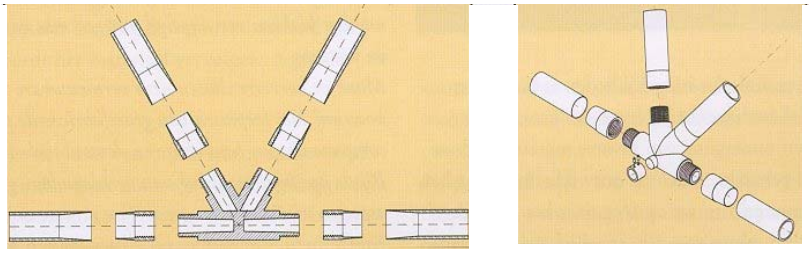

Fig. 63 Assembly of nodes and elements

The assembly of the truss girders, including the transverse roof girders, took only one day.

Fig. 64 One day erection at location

4.3 Bridges

Since 1995 world wide initiatives have been taken in the design of aluminium bridges. In Europe, particularly in Norway and Sweden, approximately 30 bridges have been built over the last couple of years. This revival of aluminium bridges is mainly due to the market-pull to lightweight and sustainable bridges. A proper design of the connections in aluminium bridges is important, because it may simplify the assembly and erection, which benefits the initial costs of aluminium bridges.
Also in the Netherlands several new initiatives have been taken in the design and construction of aluminium bridges. Three of these initiatives are described in this subchapter.

4.3.1 Leidschenveen bridges

During 1997 and 1998 an international contest has been held for the building of 58 pedestrian and traffic bridges in the planned area of Leidschenveen, near The Hague. In the tradition of Dutch city planning the area is criss-crossed with canals. To accommodate traffic circulation, a bridge system has been designed for 15 different bridge types, consisting of 45 pedestrian/cycling bridges and 13 traffic bridges.

Fig. 65 Leidschenveen traffic bridge

The initial concept of the aluminium bridge is a lens-shaped bridge, build up out of longitudinal beams of extruded elements. The lens shape accommodates both architectural and constructive requirements, providing a slender ‘wing’ to cross the water and adapting itself to the change in bending moment in the bridge girders. In addition the concept of longitudinal beams provides a modular system that can be used for any required bridge width.

The cross-section of the longitudinal beam is assembled by two identical extruded flanges separated by a flat web plate. The bridge height is varied by means of variation the heigth of the web plates. The triangular shape of the extrusions provides a torsion-stiff profile, is able to withstand concentrated loads and prevents local buckling. The extruded shapes are designed to accommodate adhesive bonded connections, which simplifies the assembly of the bridge girders.

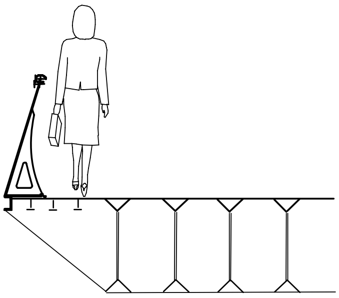

Fig. 66 Initial design

In the final concept of the aluminium bridge the design differed highly from the initial design. Aluminium bridge deck sections in transverse direction replace the triangular extruded flanges (in longitudinal direction) of the initial design. This kind of bridge decks have shown to be able to withstand concentrated wheel loads.

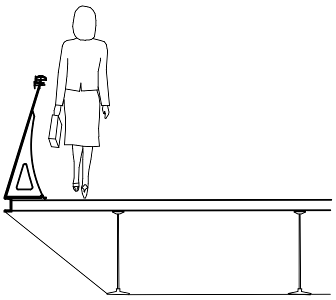

Fig. 67 Detailed design

The deck elements can also be applied in longitudinal direction. In this case the stiffness of the bridge decks reduces the number of beams to be applied. The typical top flange extrusion and the larger bottom flange extrusion have been designed for this situation.

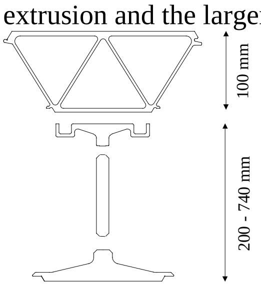

Fig. 68 Extrusions

Connections between extrusions, web plates, etcetera are established by welding. Some concept details are shown in figure 69.

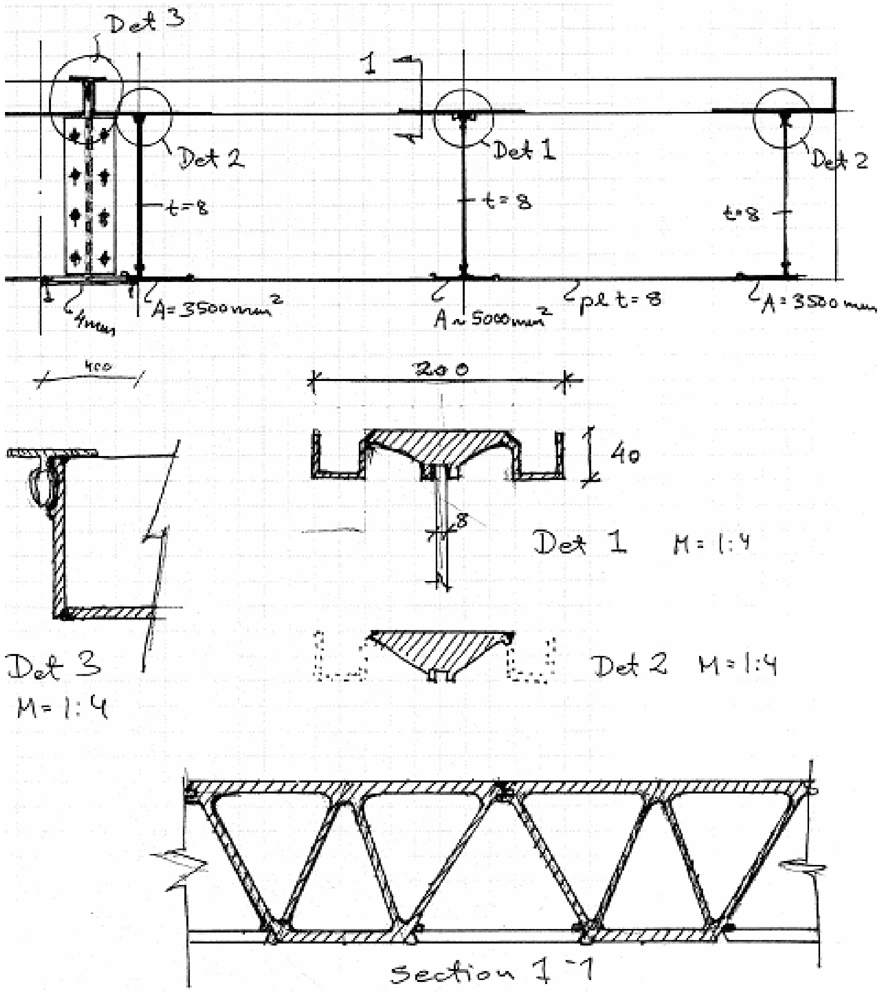

Fig. 69 Details

4.3.2 Vinex bridges

In 1999 a three year joint industry project has been started which aims at further stimulating the use of aluminium for bridges. One of the four subprojects that is dealt with is called ‘Vinex bridges’. Vinex bridges are pedestrian, cycling and traffic bridges in new-built residential areas, like the Leidschenveen bridges described before.

In this subproject a modular system of bridges has been developed for spans from 8 to 16 meter. This modular system is based on three different standard sections of 3 meter width, which can be easily connected to a total bridge width of 12 meter when necessary.

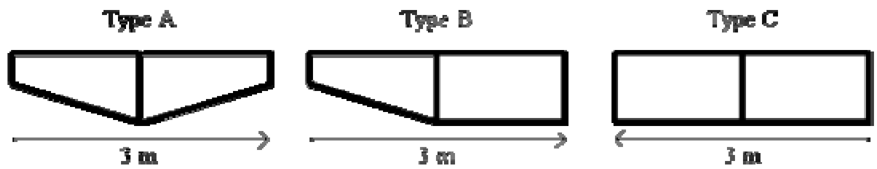

Fig. 70 Vinex bridges: three types of standard sections

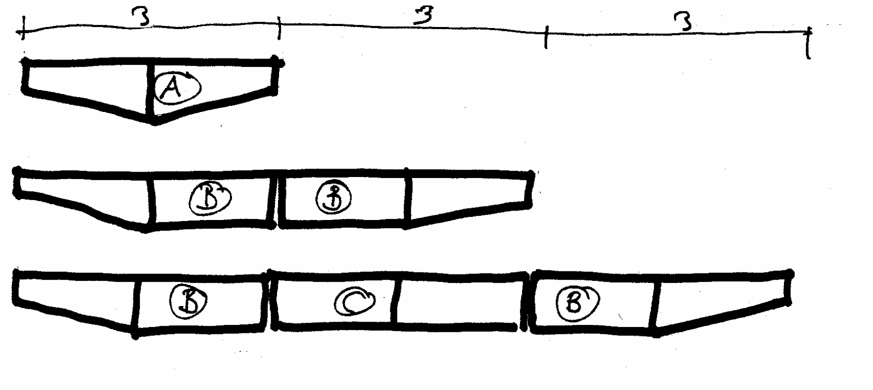

Fig. 71 Combinations of standard sections

The deck in the Vinex bridges is a standard aluminium deck profile, for example the deck as shown in figure 72. The bridge deck is used in longitudinal direction of the bridge, which involves simple connections for the coupling between standard bridge sections. Besides this the deck profile is taken into account for the main bearing structure, i.e. the deck profile forms the top flange of a rectangular hollow structure.

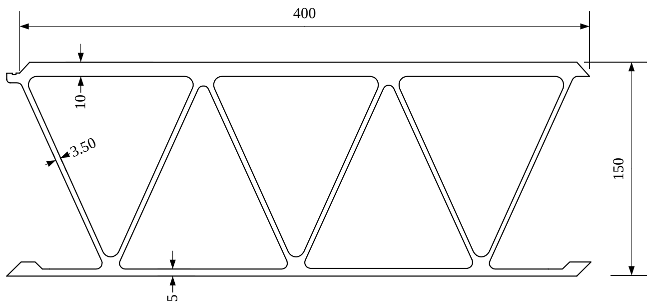

Fig. 72 Bridge deck

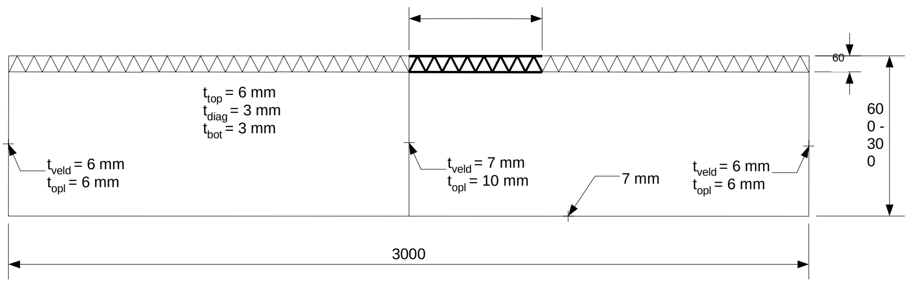

Fig. 73 Example of a rectangular standard bridge section

The three standard sections have been worked out for different situations. In the next figures a possible cross section including details are given for bridge section A. For better welding of the thin-walled bridge deck profiles to the relatively thick web plates it is advised to use thick bearing strips, that are locally supported by transverse strips.

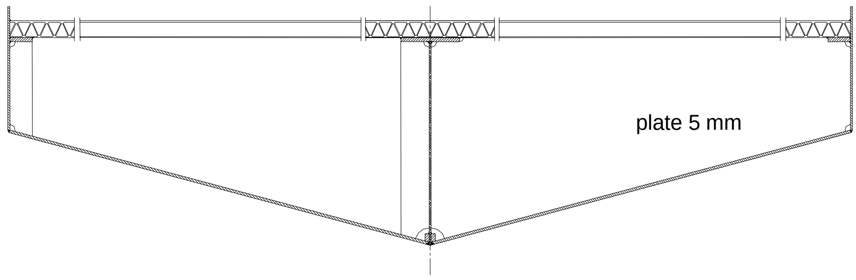

Fig. 74 Bridge section A

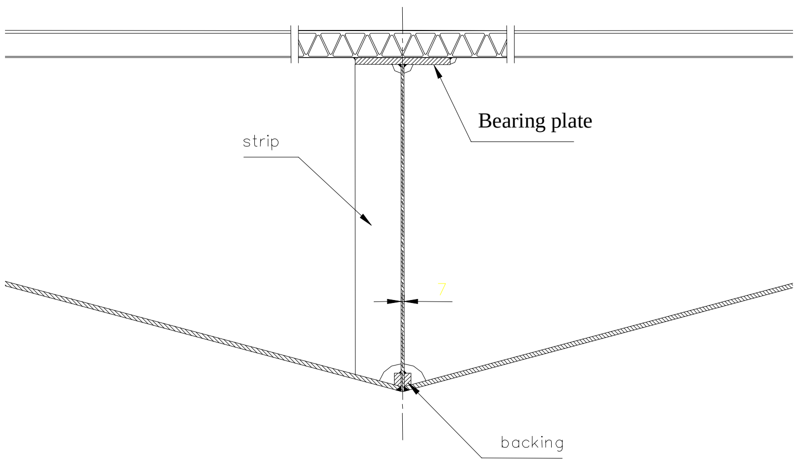

Fig. 75 Detail of the connection between bridge deck and web

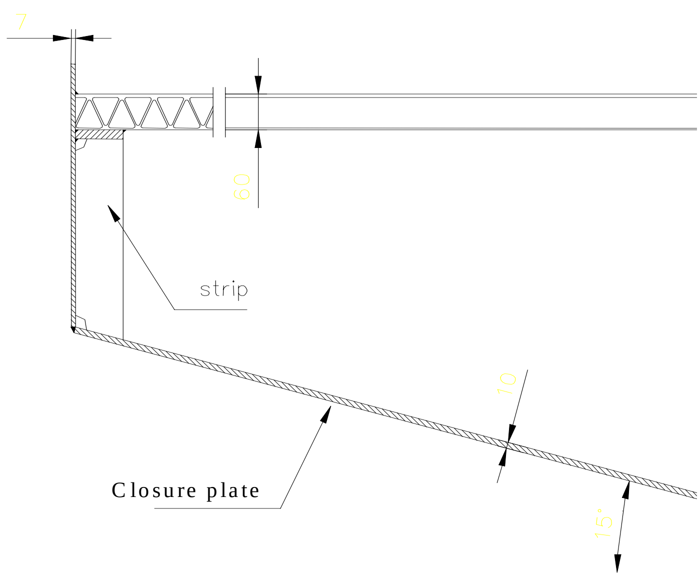

Fig. 76 Detail for edges of bridge section A

4.3.3 *Bridge decks*

In 2000 a fundamental study on the optimal cross-section for aluminium bridge deck profiles has been started. For so far existing extruded bridge deck profiles, using a triangular core between a top plate and a bottom plate, seems to be a well designed cross-section, especially when concentrated wheel loads are governing for the structural design.

The geometry of such a bridge deck section has been worked out for different situations. The cross-section in figure 77 is the optimised design for a deck span of 2 meter. The detailed design meets various requirements, where fabrication method and connections are as important as other aspects (strength, stiffness, local buckling, fatigue, vibrations, et cetera).

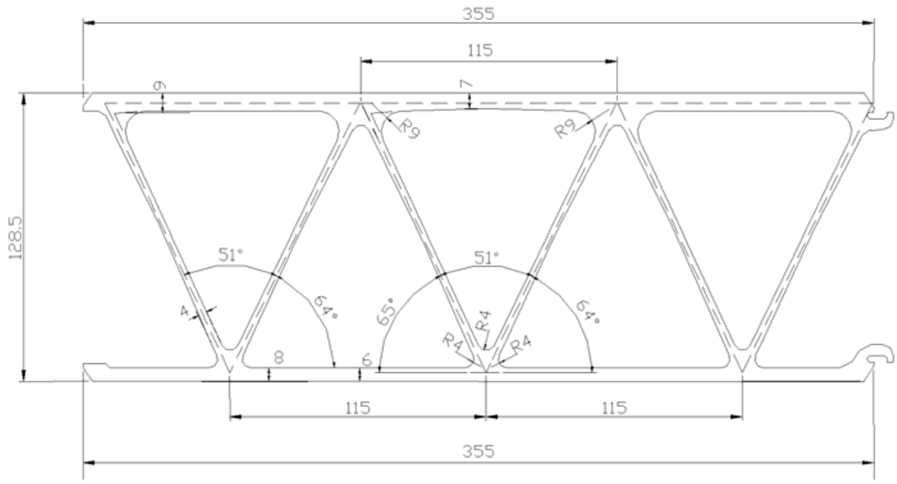

Fig. 77 Optimised bridge deck profile

The bridge deck profiles are welded together to larger bridge deck sections in the factory. The section width, which is dependent on transport requirements, is limited to 3 meter. On site the bridge deck sections are connected by means of bolts. Two alternative bolted connections, which satisfy the strength and stiffness requirements, have been worked out.

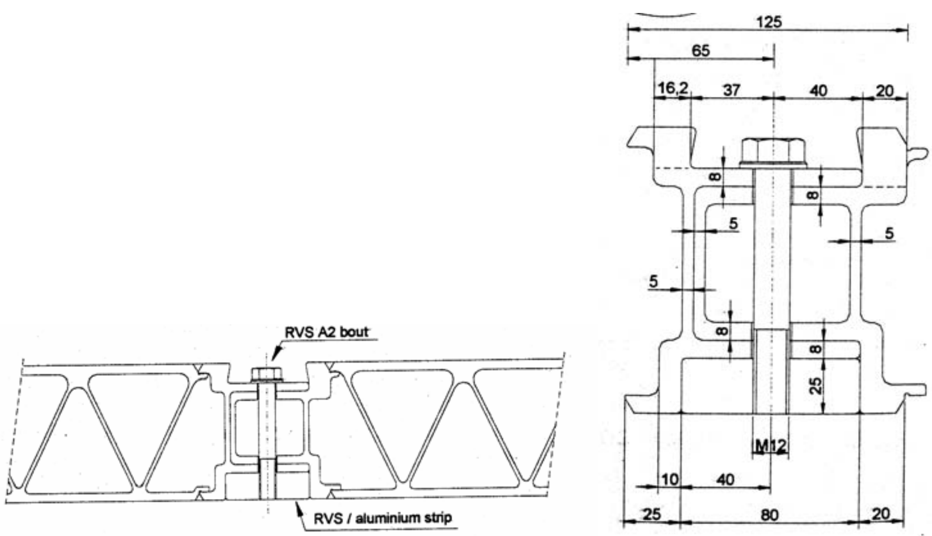

Fig. 78 Connection between deck sections – type 1

For the first type of connection two different extrusions are used, which are welded to the deck profile, shoved into each other and connected by means of stainless steel bolts. The design of this connection is such that the upper side of the bolts is beneath the upper side of the deck profiles, which enables a fully flat upper side of the bridge deck. Further a solid stainless steel or aluminium strip is used at the bottom side of the connection. This strip has screw thread inserts, which enables the connection to be assembled from the upper side only. This may be necessary in case of bridge deck renovations, where it is often not possible to reach the under side of the bridge deck.

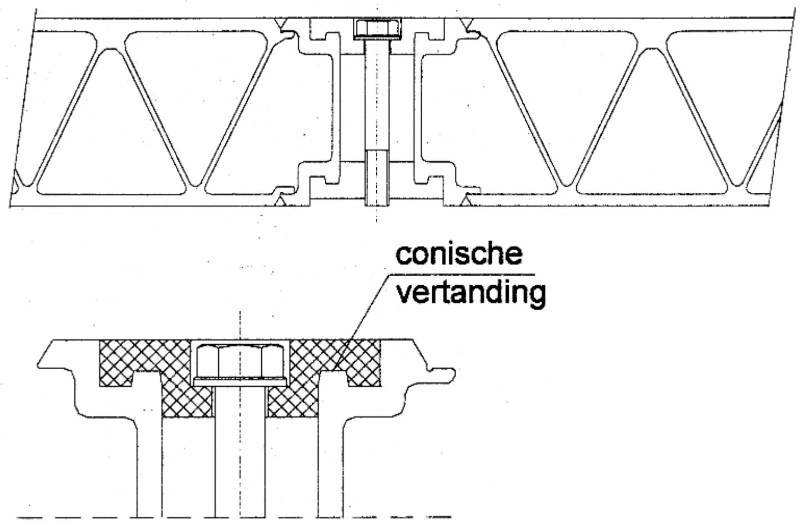

Fig. 79 Connection between deck sections – type 2

For the second type of connection also two extrusions are used to be welded to the deck profiles. At site the connection is realised by strips, which keep the deck profiles on its place while turning on the bolts. The extrusions have conic parts, which benefits the accurate and easy positioning of the strips. As in type 1 the solid strip at the bottom side has screw thread inserts, and the upper side of the bolted connections is beneath the upper side of the deck profiles.

5 Final Remarks

In the previous chapters joining of aluminium components is dealt with. After a short introduction of the subject attention is given to the joining technology both for primary as well as thin-walled structures. Subsequently welding, mechanical fastening, and adhesive bonding are reviewed.

Then, the design of connections is described following closely the design rules of Eurocode 9. The latter is regarded as the most up-to-date standard for structural aluminium applications.

Further, a number of recently designed – and some have been actually built – aluminium structures are reviewed with a focus on connections used with these structural designs.

The authors are of the opinion that the subject “connections in aluminium structures” is dealt with such that designers are aware of the main aspects to be looked after. For further reading a number of references is attached to this document.

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