Introduction to Aerospace Structures and Materials

Dr. ir. R.C. (René) Alderliesten

Introduction to Aerospace Structures and Materials

Introduction to Aerospace Structures and Materials

R.C. Alderliesten

Delft University of Technology
Delft, The Netherlands

Partly funded by the TU Delft Extension School (online-learning.tudelft.nl) as part of the development of a Massive Open Online Course in Introduction to Aerospace Structures and Materials.
ISBN E-Pub: 978-94-6366-077-8
ISBN hardcopy: 978-94-6366-074-7
ISBN PDF: 978-94-6366-075-4

11. Structural joints

11.1 Introduction

In previous chapters various aircraft and spacecraft structures have been discussed briefly with respect to their shape and functions. The analysis of general load paths and the way loads locally are translated into have been identified.

However, all these structures are constructed from parts that each often are build-up from smaller elements. All these elements and parts are jointed together to form the complete structure. These structural elements have been identified previously; sheets, stringers, ribs, frames, web plates, girders, clips, etc.

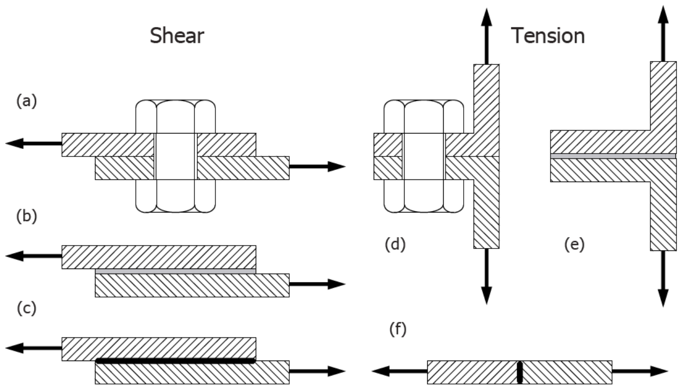

Figure 11.1
Two load transfer modes to classify the three major joining techniques in aerospace; shear (a-c) and tension (d-f). (TU Delft, n.d., 11-1.jpg. Own Work.)

There are quite a few joining techniques currently applied in engineering; only few of them are considered applicable in aerospace engineering. The most commonly applied joining techniques in aerospace are:

- Mechanically fastening (includes riveting and bolting)
- Welding
- Adhesive bonding

The three major joining techniques can be classified by the loading mode of the joint; the joint may either transfer load in tension, or in shear, see Figure 11.1. Although in principle each joining technique could be designed as either tensile or shear joint, the tensile load transfer is avoided for adhesive bonding.

This chapter provides general characteristics of each of these joining techniques. These characteristics may be used to identify the advantages and disadvantages of one joining technique over the other. Here, care must be taken, because the advantages and disadvantages are relative; what may be considered in one structure as advantage may imply a disadvantage in another structure. These considerations will be discussed in the next chapter.

11.2 Mechanically fastened joints

Different mechanical fasteners are used in engineering. The four major types are illustrated in Figure 11.2. The traditional nails often applied in wooden constructions, are considered inapplicable in aerospace, and will therefore not be discussed here. The three remaining fastener types are threaded fasteners, blind fasteners and rivets. Threaded fasteners are commonly referred to as bolts.

Figure 11.2
Illustration of the four major fastener types: threaded fasteners (top left), rivets (top right), blind fasteners (bottom left), and nails (bottom right). Derivative from top left: Alexas_Photos, (2016), Public Domain; top right: Saunders-Smits, (2018), 11-2-b.jpg. Own Work; bottom left: Cdang, (2010), Public Domain; bottom right: InspiredImages, (2015), CC0.

Example: Mechanically fastened joints in metals

Aeronautical structures contain numerous mechanically fastened joints. These joints are designed to transfer load by either tension or shear. Typical shear joints are for example illustrated in Figure 11.3.

The wing spar connection is bolted to the web plate of the spar close to the girders. The normal load in the girders must be introduced into the connection, where the bolts primarily transfer load in shear. The stepped configuration intends to slowly increase the stiffness of the connection to transfer load from girders and web plate gradually into the connection.

The lap joint and butt joint are typical shear joints applied in thin walled structures. The thickness step in the lap joint is oriented longitudinally in the fuselage structure, which implies no aerodynamic problem. The circumferential shear joint have to be smooth for aerodynamic reasons. Therefore, the butt joint is applied.

Figure 11.3
Wing spar connection (left), fuselage lap joint (centre) and fuselage butt joint (right). (TU Delft, n.d., 11-3.jpg. Own Work.)

Figure 11.4 illustrates typical tensile joints in aeronautical structures. The load into the horizontal stabilizer is introduced through the lower skin sheets into the ribs and spars. The joint exhibits a lot of tensile joints through several additional skin doublers. The channel fitting is a typical design feature to introduce tensile load by the bolt gradually into the skin sheets. The gradual reduction of the fitting's cross section by tapering the flanges implies stiffness reduction. The rivets in the fitting are typical shear joints.

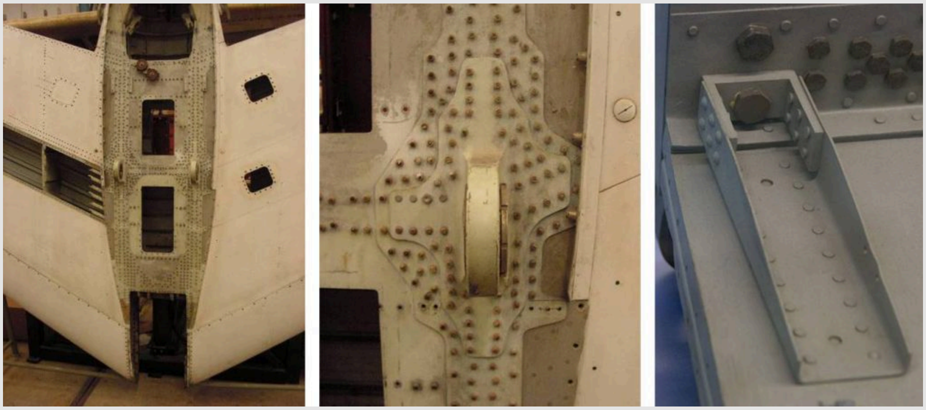

Figure 11.4
Fokker F28 horizontal stabilizer(left) with close-up from flange (centre), and channel fitting from MK8 Meteor (right). (TU Delft, n.d., 11-4.jpg. Own Work.)

11.2.1 Rivets

Riveting is generally applicable for joining sheet material in which the joint transfer the load from one sheet to the other in shear. Because the rivet is being forced into its final shape during installation, access from both sides is needed. In case access can be provided at only one side, blind rivets are used.

Riveting is a reliable joining method because it has been applied for many decades (lot of experience), but also because the joint can be well inspected and repaired. In case a riveted joint must be repaired rivets can be drilled out and replaced by a slightly larger rivet.

Riveting is often considered for its low cost; both the rivets and the installation per unit are fairly cheap. For rivet installation, only pneumatic hammers or rivet guns are necessary tooling to apply the riveting force, while bucking bars are needed to counteract the applied force. An alternative method for riveting with pneumatic hammers is the application of squeezing. The rivet is then pressed into its final shape by a force controlled machine. This method for rivet installation provides better quality and places rivets in a more reproducible manner.

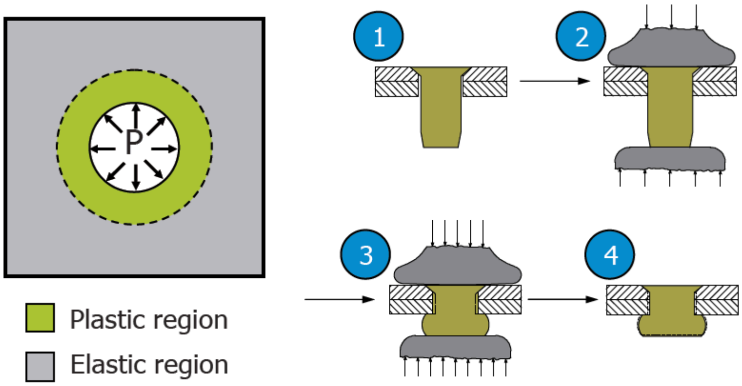

Figure 11.5
Illustration of the riveting principle: rivet placement (1), riveting squeeze force (2), rivet deformation (3) and final result (4).(TU Delft, n.d., 11-5.jpg. Own Work.)

Riveting is considered a permanent joining method. In case of repair the rivet could be drilled out and replaced by an oversized rivet (rivet with larger diameter), but this can only be done very few times. Each removal implies application of a larger rivet, which can only be done a limited amount of times. Another reason why riveting is considered permanent is that during operational loading the rivet cannot vibrate loose. Although the residual compressive stress may reduce over time, the rivet remains fixated in the hole.

Because the rivet is forced into the hole, it will fill the hole completely. During riveting, the shaft of the rivet will expand (see chapter 1), applying radial pressure to the sheet edges. As a consequence, the stress concentration factor induced by the holes, see chapter 10, is reduced by radial expansion of the rivet. The riveting principle is illustrated in Figure 11.5.

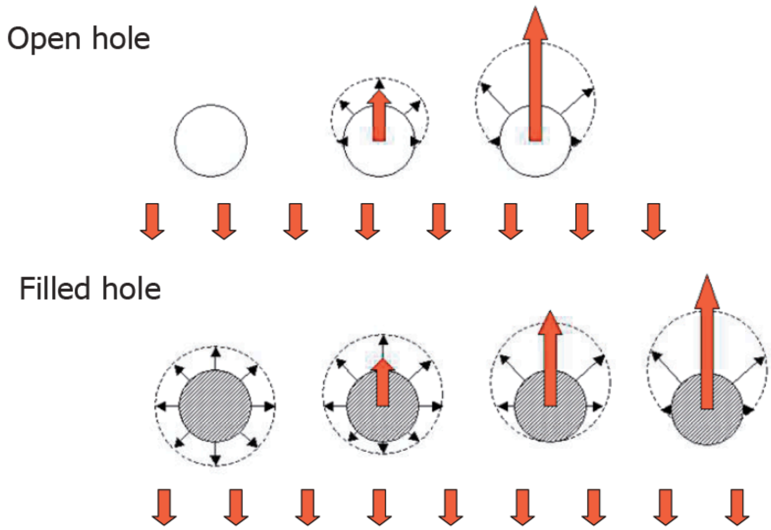

Figure 11.6
Difference in stress concentration due to load transfer induced by bearing pressure only (open hole) and load transfer by bearing and radial compression (filled hole). (TU Delft, n.d., 11-6.jpg. Own Work.)

The remaining residual stress is considered favourable for the load transfer, and therefore also for the fatigue properties of the riveted joint. The reason can be explained with the two cases illustrated in Figure 11.6. The open hole configuration could represent a bolted joint in which the bolt is placed free from the sheet edges, often denoted as clearance fit. The load applied by the bolt to the sheet edges is called bearing pressure. This bearing load must be in equilibrium with far field stresses further away in the sheet. As a consequence, all stress is concentrated near the hole edges, implicating a large stress concentration.

The filled hole represents a rivet that has been squeezed into the hole applying radial expansion to the sheet edges. Subsequent loading of the joint, would not only apply bearing pressure to the sheet edges, but would also reduce the radial compressive forces at the back side of the hole. As a consequence, the load around the hole edges to be in equilibrium with the far field stresses in the sheet is significantly less. In other words, riveting reduces the stress concentration factor K_t at the hole edge by radial expansion of the rivet shaft.

11.2.2 Threaded fasteners

The threaded fasteners have a wider range of application. First of all, they can be applied both in shear joints and tension joints, and in joints that comprise a combination of both loading modes. In addition, bolts can be applied not only to sheet material, but also to a wider variety of structural components.

A general characteristic is that threaded fasteners, often called bolt, allow disassembly after being assembled. In other words, they are not permanent but can be removed and re-installed again. Where a rivet after being drilled out is discarded and replaced, bolts can be used again.

Another characteristic of threaded fasteners is the wider range of materials that can be selected to manufacture the bolt. Rivets must be deformable during installation, which limits the type of materials from which it can be manufactured. For threaded fasteners, this limitation is not present, and as a result there is more freedom to select the appropriate bolt material.

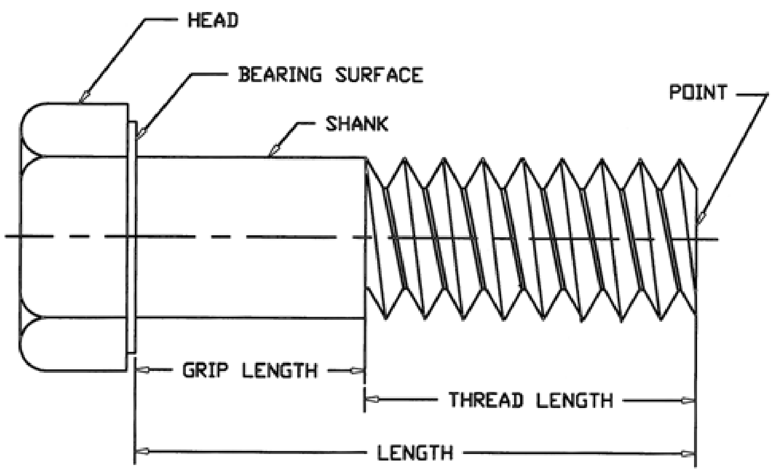

Figure 11.7
Definition of the bolt dimensions. (TU Delft, n.d., 11-7.jpg. Own Work.)

Therefore high strength joints are often bolted joints. The strength of bolts can be tailored by selecting the right material, the appropriate heat treatments, and convenient case hardening technique. The dimensions of the bolt can be chosen depending on the to-be-jointed components. An illustration of dimension definition is given in Figure 11.7.

11.2.3 Load transfer mechanisms

In mechanically fastened joints multiple load transfer mechanisms act together to provide the load path through the joint. Figure 11.8 illustrates the primary and secondary loads that act in a single sided shear joint.

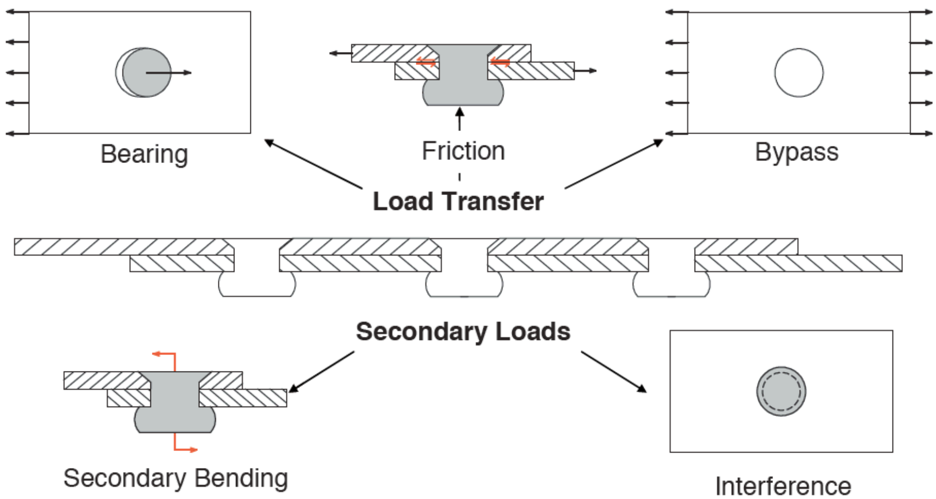

Figure 11.8
Illustration of the primary and secondary loads in mechanically fastened joints. (TU Delft, n.d., 11-8.jpg. Own Work.)

To evaluate a mechanically fastened joint, the individual load paths must be identified. In a single row joint, as illustrated in Figure 11.9 all load is transferred form one sheet to another by either bearing pressure on the sheet edges, or by friction between the sheets. The magnitude of friction depends on the clamping force that is provided by the bolts.

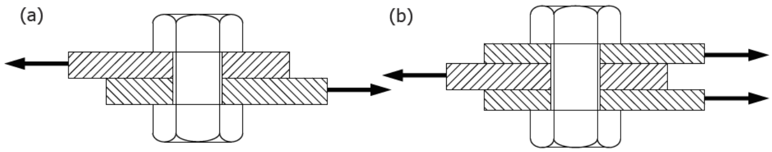

Figure 11.9
Illustration of a single sided shear joint (a) and double sided shear joint (b). (TU Delft, n.d., 11-9.jpg. Own Work.)

In case of a multiple row joint, for example three rows as illustrated in Figure 11.8, all load is distributed over the three rows. This implies that the load in the upper sheet in Figure 11.8 is partly transferred to the lower sheet at the first rivet row, by bearing and friction, while the remainder of the load continues through the upper sheet to the second and third rivet row. This part of the load must then go around the rivets in the first row, which is called by-pass load.

Secondary loads to be considered are the interference loads, which are created by rivets that expanded in the holes during riveting, or by bolts with an oversized shank diameter that have been forced into an undersized hole. These loads add to the bearing pressure as illustrated in Figure 11.6.

The main difference between the two shear joints in Figure 11.9 relates to symmetry. The single sided shear joint is an asymmetric joint, whereas the double-sided joint can be a symmetric joint. In case of a symmetric joint, equal load is transferred over both interfaces, which implies that the deformation of the joint remains symmetric. In an asymmetric joint, the load transfers through one interface, creating an asymmetric step in the load path. This load step induces an asymmetric deformation in addition to the longitudinal deformation induced by the applied load, which is called secondary bending, see Figure 11.10.

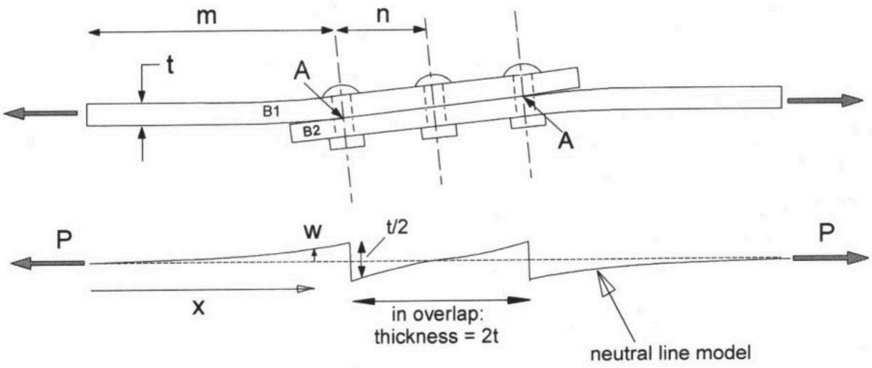

Figure 11.10
Illustration of secondary bending in a single sided shear joint; the deformation relates to the load step correlated to the neutral line through the joint. (TU Delft, n.d., 11-10.jpg. Own Work.)

Example: Effect of secondary bending

Consider load transferred by bearing in the joint in Figure 11.11. The bearing pressure is defined as:

$$p_b = \frac{F}{Dt}$$

where F is the load transferred by bearing, D is the diameter of the hole and t the sheet thickness. The bearing pressure, or bearing stress, has the units [N/mm^2] or [MPa]. This strength is considered characteristic for sheet materials, as it describes when sheets will deform and fail under bearing pressure.

In a symmetric joint, in absence of secondary bending, the bearing pressure is treated as a homogeneous stress distribution through the thickness of the sheet. Secondary bending implies a variation of stresses through the thickness of the sheet as illustrated in Figure 11.11. The superposition of two stress distributions implies that maximum stress is reached at one side first. Considering fatigue, it also implies that at one side the stress cycles are greater and higher than at the other side. The detrimental influence of secondary bending on the fatigue life is illustrated with the S-N curves in Figure 11.12.

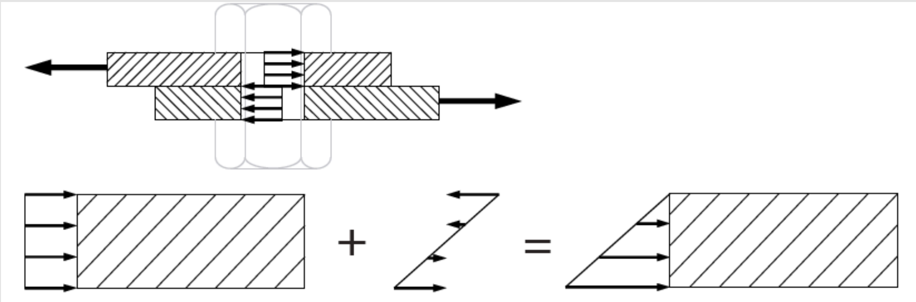

Figure 11.11
Peak stresses due to superposition of bearing stress and bending stress. (TU Delft, n.d., 11-11.jpg. Own Work.)

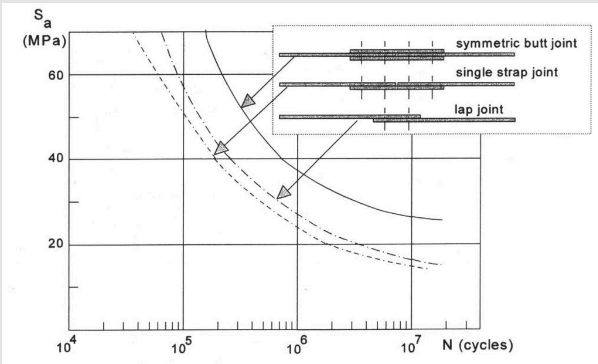

Figure 11.12
Effect of secondary bending on the fatigue performance of riveted joints. (Schijve, 2010, Copyright Schijve, used with permission)

11.2.4 Failure modes

The strength of mechanically fastened joints relates to both the fastener (type and material) and the jointed sheets. The joint can fail in different ways, which are identified as the joint failure modes, illustrated in Figure 11.13.

One failure mode relates to rivet failure; the shear load in the rivet exceeds the ultimate shear strength of the rivet material, causing shear failure of the rivet. In general, this failure mode should be avoided in aeronautical structures. Once the load on a riveted joint causes rivet failure, it can be expected that subsequent redistribution of load over the other rivets will cause failure of these rivets as well. As a consequence, the complete riveted joint may fail catastrophically.

The shear failure load on a rivet can be calculated for a single shear joint (see Figure 11.9) with

$$F_{ult} = \frac{\pi}{4} D^2 \tau_f \tag{11.1}$$

Where D is the diameter and τ_f is the failure shear strength of the material. For a double sided shear joint the load will be twice as high, because the load transfer takes place at two distinct interfaces.

The preferred failure modes relate to sheet failure. The three sheet failure modes in riveted joints are net-section failure, bearing failure and shear-out (or tear out) failure, see Figure 11.13. The net-section failure relates to load exceeding the ultimate tensile strength of the sheet in the cross-section between the rivets. For a single rivet that can be written as

$$F_{ult} = (W - D) t \sigma_f \tag{11.2}$$

where W is the width, t the sheet thickness, and σ_f the failure strength of the material.

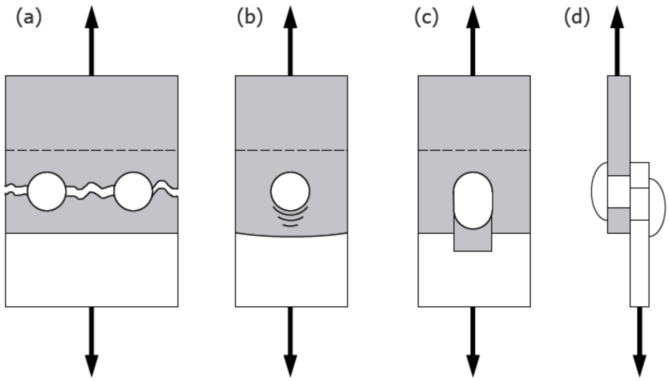

Figure 11.13
Four major failure modes for mechanically fastened joints. (Alderliesten, 2011, 11-13.jpg. Own Work.)

The second failure mode related to sheet failure is the bearing strength failure. The bearing strength failure can be calculated with (see example on the effect of secondary bending)

$$F_{ult} = Dtp_b \tag{11.3}$$

However, considering bearing strength in riveted joints, often the permanent deformation is considered for determining the nominal allowable load. Based on experience the maximum permanent deformation allowed is set to be 2% ovalisation of the hole, which is equal to 0.02D. The bearing pressure at which this deformation occurs is defined as $p_{2\%}$. Thus the nominal load should satisfy

$$F_{nom} \leq Dtp_{2\%} \tag{11.4}$$

The ultimate load is then obtained by multiplying both sides of the equation with the safety factor of 1.5, which yields

$$F_{ult} = 1.5Dtp_{2\%} \tag{11.5}$$

The last sheet failure mode is shear out of the sheet under the bearing pressure. This failure mode relates to the edge distance, i.e. the amount of material between the rivet and the edge of the sheet, see Figure 11.14.

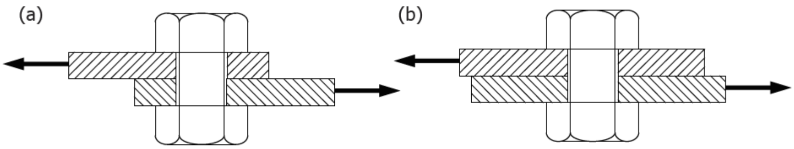

Figure 11.14
Small edge distance (a) will cause shear out failure, which can be avoided with greater edge distances (b). (TU Delft, n.d., 11-14.jpg. Own Work.)

Of course, the maximum load that a mechanically fastened joint can sustain is the smallest of the four failure loads.

11.3 Mechanically fastening in composites

Most of the discussion in the previous section applies to composite structures. However, several additional aspects should be considered. It was explained in chapter 1 that the orthotropic nature of composite panels implies that the strength depends on the orientation of the fibres within the panel.

This can be explained considering a single ply of fibre reinforced composite, illustrated in Figure 11.15. The longitudinal plies are strong in fibre direction, but the shear strength of the matrix material between the fibre is insufficient to resist the shear-out failure. Transverse plies have insufficient resistance against the bearing pressure, most likely causing net-section failure.

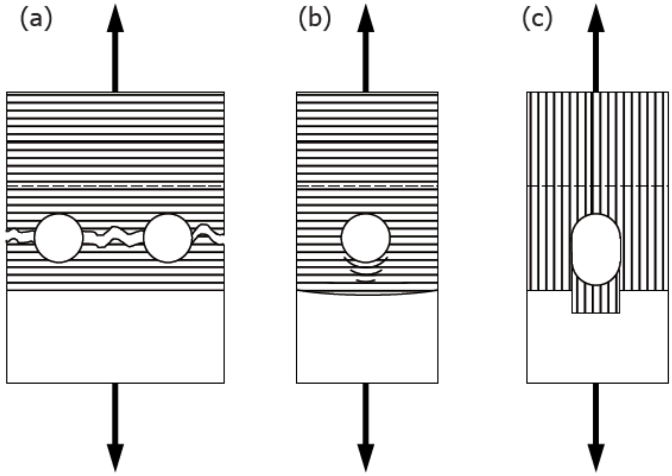

Figure 11.15
Relation between fibre orientation and failure mode; longitudinal plies are weak against shear-out, while transverse plies are weak against net-section failure and bearing. (Alderliesten, 2011, 11-15.jpg. Own Work.)

This implies that the composite laminates that are jointed together require plies oriented in several directions to create sufficient resistance against either of the three failure modes. Because the shear-out failure mode is induced by shear stresses between the fibres, see Figure 11.15 (c), often fibre layers are added oriented in ±45° orientation, because of their shear strength contribution.

To create sufficient bearing strength in composite panels, sufficient layers in 0°, 90°, and ±45° are needed. This implies that the thickness near the edges of composite panels often must increase to create sufficient quasi-isotropic thickness as is illustrated in Figure 11.16. As alternative, to limit the thickness increase often metallic inserts are added, because of their isotropic nature. Rather than applying multiple fibre layers in a quasi-isotropic lay-up (see definition in chapter 1), a single isotropic metal layer will suffice.

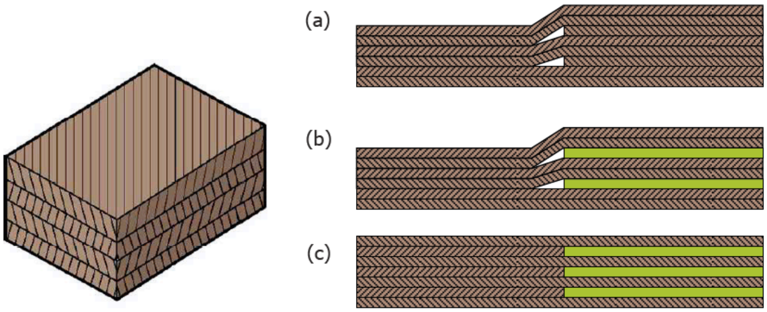

Figure 11.16
Illustration of increasing bearing strength in composite panels near the edge; increasing thickness (a), adding metallic inserts (b), and replacing layers with metallic inserts (c). (Alderliesten, 2011, 11-16.jpg. Own Work.)

11.4 Mechanically fastening in sandwich composites

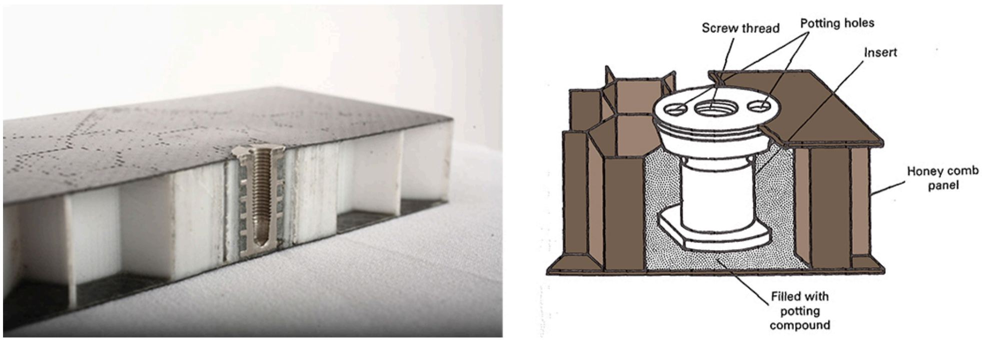

Figure 11.17
Application of inserts in the sandwich core to create sufficient bearing strength.(TU Delft, n.d., 11-17.jpg. Own Work.)

The application of mechanically fastening in composite sandwich panels is somewhat more complex compared to monolithic composite panels, discussed in the previous section. The complication is related to the characteristics of facing and core material; where the facings transfer all normal loads, the core only transfers the shear load. This means that the mechanical fastener in a sandwich panel has to transfer its load by bearing mainly to the two face sheets of the sandwich, as is illustrated in Figure 11.17 and 11.18

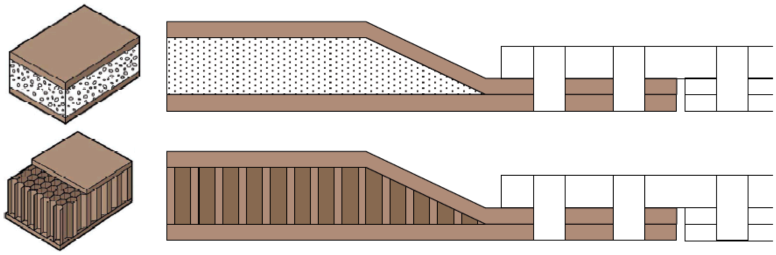

Figure 11.18
Reduction of sandwich panel to monolithic composite edges to create sufficient bearing strength. (Alderliesten, 2011, 11-18.jpg. Own Work.)

11.5 Welded joints

In this section the welding of joints is discussed for both metallic and composite structures.

11.5.1 Metallic structures

Welding is an attractive joining technique, because a good weld is almost as good as the parent material. In general, welding provides a so-called integral structure. After welding, the structural component can no longer identified as separate components.

For aeronautical purposes where fatigue and damage tolerance is of importance, this has a drawback. As illustrated in Figure 11.19, a crack propagating in the skin sheet, will sense no natural barrier against growth into the welded stringer, whereas the riveted and adhesive bonded joint provides a natural barrier for the propagating crack.

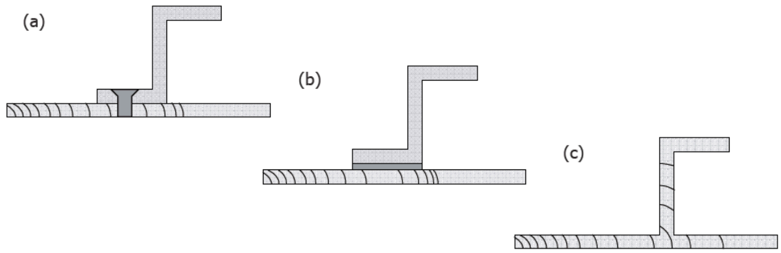

Figure 11.19
Comparison between mechanically fastened, bonded and integral structures; integral structures do not provide barriers against cracking. (Alderliesten, 2011, 11-19.jpg. Own Work.)

There are two major welding techniques applied in aerospace structures:

- Laser beam welding
- Friction stir welding

In both cases heat is added to the material, but the principle differs significantly. In case of laser beam welding, the laser beam is the heat source that very locally heats the material to melting temperature levels. Because of the welding rate and the local rapid rate of heating and cooling, only a small area is affected by the heat treatments, the so-called heat affected zone.

Friction stir welding is a different process. It is not based on heating material to melting temperature, but it is a process in which the material remains in its solid state. A cylindrical tool with shoulder is rotated and pressed with great force into the sheets. The friction between tool and sheet material generates sufficient amount of heat to soften the material and to allow mixing of the plasticized flow. Because of the limited amount of heat and the temperature levels, a smaller area of the weld is affected by the heat treatment. In addition, friction stir welding does not require addition of weld material, only the parent sheet materials are mixed during the process.

Whereas laser beam welding can only be applied to certain aluminium alloys because of the applied heat treatments, friction stir welding can be applied to more alloys including the high strength aeronautical alloys. It even has been proven that dissimilar alloys can be welded with friction stir welding.

11.5.2 Composite structures

In composite structures welding can only be performed with thermoplastic composites. The principle of welding is that the matrix material locally is heated above the glass transition temperature to bond parts together.

The following welding techniques are currently available:

- Resistance welding
- Induction welding
- Ultrasonic welding

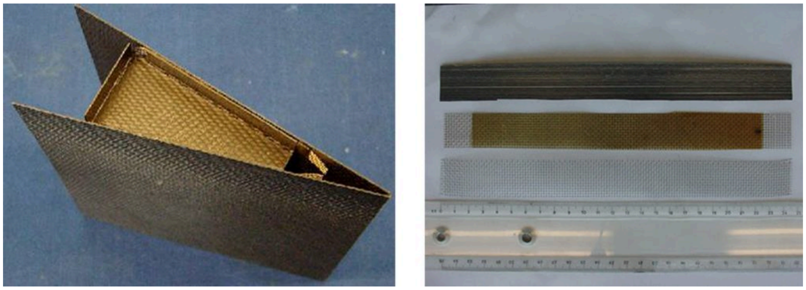

Figure 11.20
Examples of welding in thermoplastics; welding of ribs to the skin of flaps. (TU Delft, n.d., 11-20.jpg. Own Work.)

Resistance welding uses the principle of adding electrically resistive material between the surfaces that are welded together. By applying an electrical current through this material, the resistance generated heats up the material at the location of welding. An example application of resistance welding is given in Figure 11.20.

11.6 Adhesive bonding

Adhesive bonding is a permanent joining technique that can only be loaded in shear. Although, adhesive joints exhibit some tensile strength, loading in tension is generally not accepted and avoided. Adhesive bonding is characterised by the high durability. The absence of holes with corresponding stress concentrations makes these joints rather insensitive to fatigue, resulting in fatigue lives of order of magnitude greater than mechanically fastened joints. In addition, because the material is not weakened during the bonding process, the adhesive joint is generally stronger than the adherents, i.e. the materials bonded together.

A distinction can be made between hot bonding and cold bonding. The quality of cold bonding is generally lower than hot bonding, because of the adhesives that can be used. As a result, for bonding structural components hot bonding is generally applied. Because of the higher temperature and often higher required pressure autoclaves are necessary.

Because adhesive bonded joints cannot be inspected for their quality (How do you measure the quality of adhesive after curing?), the process is controlled in detail to guarantee reproducible adhesive joints. Once given process conditions have proven to give bonded joints with sufficient strength, the process can be repeated.

However, the reproducibility of high quality adhesive joints is not yet considered sufficient to assure that such joints will not fail prematurely or at lower stress levels than the failure strength. In addition, the measurement techniques to evaluate the adhesive joint strength non-destructively (without damaging the joint) are non-existent. Therefore, adhesive bonded joints are not allowed in primary structures as single load path solution. Adhesive bonding in these critical structures must always be accompanied with other load transfer paths, such as mechanical fasteners. Bonded stringers contain therefore always rivets at the stringer run-out; the adhesive joint is considered insufficient.

11.6.1 Metallic structures

To create a high quality adhesive bonded joint, the adherents must be pre-treated to provide a good chemical bond. In aluminium structures, the pre-treatment consists of anodising and priming the surfaces before bonding is applied. The anodisation process makes the adhesive joint resistant to corrosion (particularly bond line corrosion), while the primer creates the proper surface to bond the adhesive. These pre-treatment processes require monitoring of the process conditions in order to assure that the pre-treatment layers are applied according to the requirements.

Traditionally, these pre-treatment solutions contain chromates (chromate acid anodising), because of their excellence performance with respect to corrosion resistance. However, because of their detrimental impact on environment, these processes are required to become chromate free. This implies that currently a lot of research is being performed to identify alternative pre-treatment processes that have less impact on the environment, but are as good as the traditional chromate based solutions.

11.6.2 Composite structures

In composite structures the adhesive bonding can be applied in multiple ways. The reason is that the adhesive bonding process requires a curing step. This curing step implied an addition to the metallic production processes, but can be efficiently used in manufacturing of composites, because these materials already require a curing step.

As a consequence, cured composite stringers may be bonded to a composite skin panel that still has to be cured together with the adhesive joint. This combination is often referred to as co-bonding. Alternatively, the skin has been cured in a previous step and the stringers are cured while bonded to the skin at the same time. This combination is commonly referred to as co-curing.

In order to bond two skin panels together, other solutions may be applied that the overlap joint commonly used for metallic panels. The layered structure of the composite skin panel may be utilised to provide a more efficient overlap joint without the geometric step related to the overlap of panels. This solution is often called scarf joint, as illustrated in Figure 11.21. For example, each layer in the laminate may be terminated at a certain position to provide an overlap with the layer of the other panel. This stepped scarf joint is illustrated in Figure 11.21 (b).

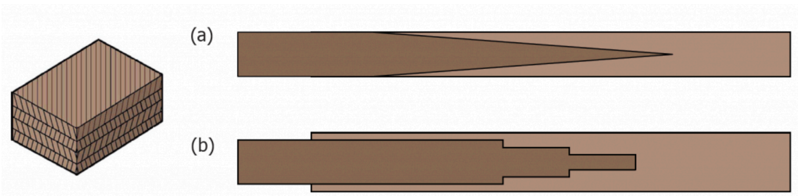

Figure 11.21
Illustration of bonding in composites: scarf joint (a) and stepped scarf joint (b). (Alderlieste 2011, 11-21.jpg. Own Work.)

11.6.3 Adhesive joint strength

The adhesive joint strength relates to the stress distribution throughout the adhesive joint. Although the adhesive joint creates an area of load transfer, rather than locations of load transfer (with rivets in a riveted joint for example), the stresses are not homogeneous.

Consider for example a simple overlap joint as illustrated in Figure 11.22. The primary mode of load transfer is via shear. The adhesive layer will deform by shear as illustrated in the figure. However, because the load is gradually transferred from one sheet to the other, the reduction of stress towards the end of the sheet implies a reduction of strain (or elongation). This is illustrated in the figure by the vertical marks in the sheets. Because the adhesive must deform in a compatible way with the sheets, it implies that peak stress levels occur at the edges of the joint. The shear stress exhibits a so-called bathtub shape.

However, because the two sheets in Figure 11.22 are not aligned, application of a tensile load on the joint will cause the joint to straighten itself. This causes a bending deformation of the sheets with additional tensile stresses in the adhesive, as illustrated in Figure 11.10. These tensile stresses are considered most critical concerning the overall joint strength. Estimating the joint strength therefore implies that not only the shear stresses are to be considered, but also peel stresses as result of these secondary deformation modes.

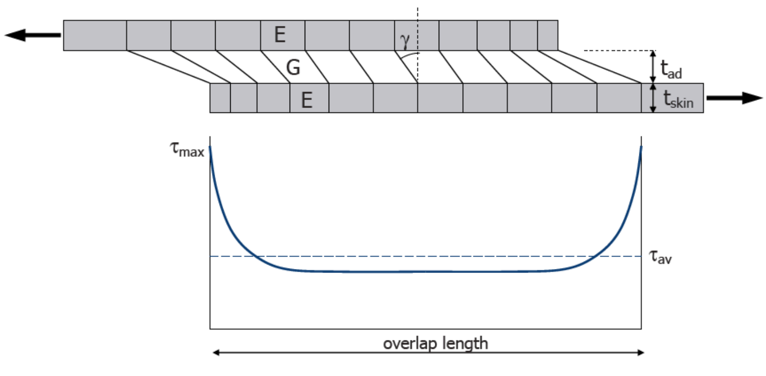

Figure 11.22
Shear stress distribution along the overlap length in a bonded joint. (Alderliesten, 2011, 11-22.jpg. Own Work.)

Introduction to Aerospace Structures and Materials

Dr.ir. R.C. (René) Alderliesten

This book provides an introduction to the discipline of aerospace structures and materials. It is the first book to date that includes all relevant aspects of this discipline within a single monologue. These aspects range from materials, manufacturing and processing techniques, to structures, design principles and structural performance, including aspects like durability and safety. With the purpose of introducing students into the basics of the entire discipline, the book presents the subjects broadly and loosely connected, adopting either a formal description or an informal walk around type of presentation. A key lessons conveyed within this book is the interplay between the exact science and engineering topics, like solid material physics and structural analysis, and the soft topics that are not easily captured by equations and formulas. Safety, manufacturability, availability and costing are some of these topics that are presented in this book to explain decisions and design solutions within this discipline.

Dr.ir. R.C. (René) Alderliesten
TU Delft | Faculty of Aerospace Engeneering

Dr. Alderliesten obtained his MSc and PhD degree both at TU Delft, and holds since 2012 the position of associated professor within the department of Aerospace Structures and Materials at the faculty of Aerospace Engineering, TU Delft. His expertise is fatigue and damage tolerance of metals, composites and hybrid materials, with the emphasis on proper understanding the physics of damage growth. Dr. Alderliesten introduces Aerospace Structures & Materials in the first semester of the BSc curriculum, while teaching Fatigue of Structures & Materials in the first semester of the MSc both at TU Delft and at the University di Bologna.

ISBN 978-94-6366-075-4
DOI https://doi.org/10.5074/t.2018.003

textbooks.open.tudelft.nl