Introduction to Aerospace Structures and Materials

Dr. ir. R.C. (René) Alderliesten

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R.C. Alderliesten

Delft University of Technology
Delft, The Netherlands

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4. Manufacturing

4.1 Introduction

The previous chapter provided a brief description of the different material categories relevant for the aeronautical industry, together with some characteristics and typical applications. As mentioned there, the performance of a structure is to be evaluated by means of trade-off between material aspects (discussed in previous chapter), structural aspects (discussed in the next chapters), and manufacturing aspects.

This means that despite being dealt with in individual chapters in this book, these aspects relate directly to each other. Considering material aspects together with structural aspects, but without addressing the manufacturing aspects will never lead to optimized structures.

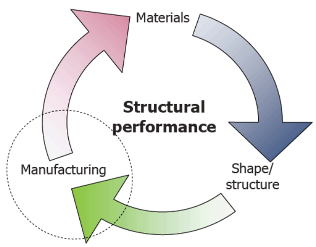

Figure 4.1
Illustration of the topic of interest in this chapter (Alderliesten, 2011. 4-1.jpg. Own Work.)

This chapter provides an overview of manufacturing techniques adopted in industry for manufacturing structures, components and products made of the materials presented in the previous chapter. The discussion on how manufacturing aspects are dealt with in practice is given in chapter 1. This chapter limits itself primarily to the manufacturing aspects of metallic and composite materials, because they are considered most relevant for the aerospace industry.

4.2 Metals

In general, three different manufacturing categories can be identified for metallic materials to create a component or product

- Casting
- Machining
- Forming

4.2.1 Casting

Casting is a production process in which liquid is poured into a mould containing the shape of the product. The shape of the cavity inside the mould defines the outer shape of the product. Although the principle is very old (it has been applied for over 5000 years), it is still often used for manufacturing complex parts. There are more materials that can be casted, like for example polymers, concrete and clays. The metals are heated above the melting temperature to provide a liquid that is subsequently poured into the mould. After cooling the part, the part is often retrieved by breaking the mould. An illustration of metal casting and of a typical product is given in Figure 4.2.

Figure 4.2
Casting: process (left) and typical product (right). Derivative from left: Marpockstudios, (2017), CC0 and right: CM_Photo (2016), CC0.

4.2.2 Machining

Machining is a solid state cutting and milling processes. This means that the process is applied to materials in their solid state at room temperature, which means that heating or melting of the material is not necessary. However, machining often required the use of a cooling agent, because cutting and milling create in itself heating of the material. The principle is illustrated in Figure 4.3. This figure illustrates the milling and cutting process. The first is a process that removes chips of material (milling, drilling, grinding, etc), while the latter is a does not remove chips, but separates (shearing) materials.

Machining is commonly used to produce large components for which small geometrical tolerances are required. Geometrical tolerances are defined as the maximum variation that is allowed in form or positioning of the product or component. Because the material can be fixed into its position in its solid state, machining can be performed with great accuracy, thus enabling small geometrical tolerances.

There are several types of tolerances possible:

- Form control
- Flatness
- Positioning
- Perpendicular or parallel

Although the machining process usually requires large and expensive equipment, the process is considered to be inexpensive for large quantities or large components, because it is relatively easy to automate. Especially high-speed machining enables production of components at high speeds with high accuracy and small tolerances in a relative short amount of time. Even thin-walled components can be easily manufactured with high accuracy.

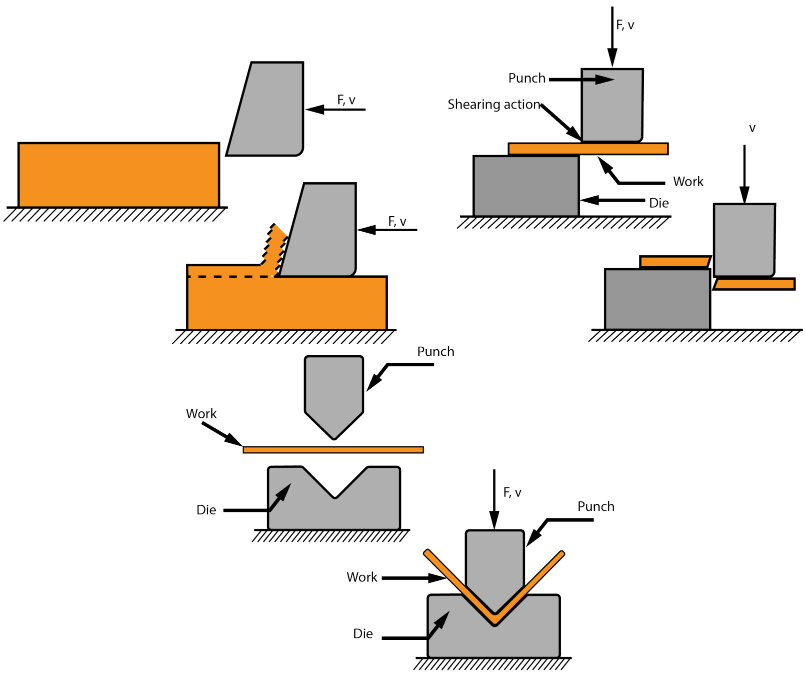

Figure 4.3
Illustration of the principles of machining (upper) and forming (lower). (TU Delft, 2018, 4-3.jpg. Own Work.)

4.2.3 Forming

The category of forming, of which an example (sheet bending) of the principle is provided in Figure 4.3, can be further divided into forming of bulk material and forming of sheet material. Examples of the first sub-category are

- Extrusion
- Forging

Examples for the second sub-category are

- Bending
- Deep drawing
- Roll bending

The forming principles of these processes are illustrated in Figure 4.4.

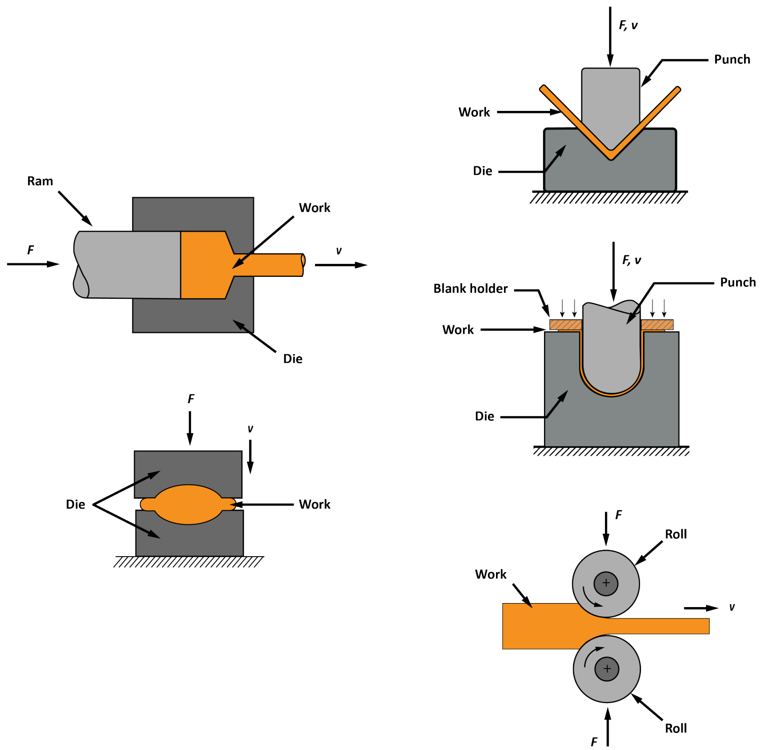

Figure 4.4
Illustration of the forming principles of bulk material (left) and sheet material (right). (TU Delft, 2018, 4-4.jpg. Own Work.)

An important aspect to forming is that in order to change the shape of the material permanently, the material is plastically deformed. However, before plastic deformation occurs, the material deforms elastic until it reaches the yield strength of the material, see chapter 1. The elastic deformation is reversible, which means that after the maximum deformation is reached and the forces are removed a small portion of the imposed deformation will be eliminated.

Consider sheet bending as illustrated in Figure 4.5. At the maximum bending deformation, the material has first gone through elastic deformation and subsequently plastic deformation. Thus once the bending force is removed, the material will spring back corresponding to the elastic deformation.

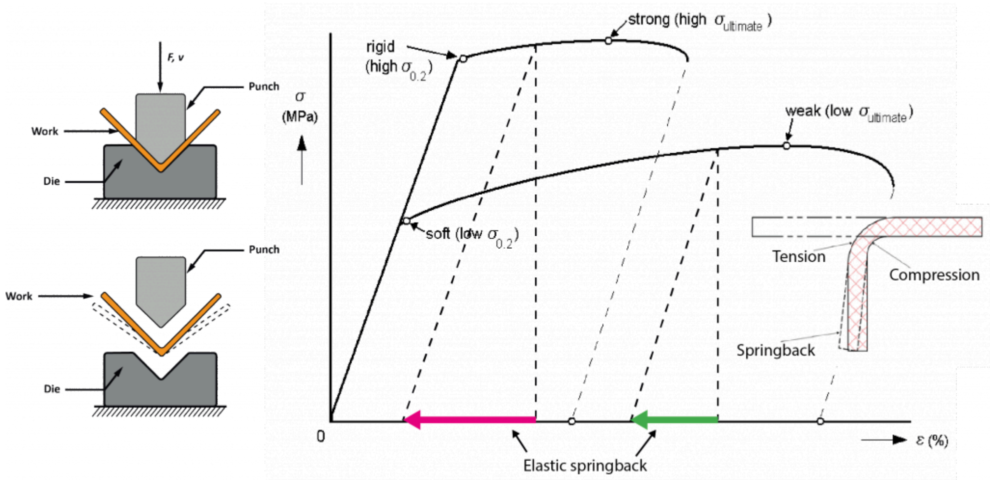

Figure 4.5
Illustration of spring back in sheet forming and relation to strength. TU Delft (2018), 4-5.jpg, Own Work.

There are two important aspects to this spring back. First, the amount of spring back is dependent on the level of the imposed stress. As illustrated in Figure 4.5, the spring back will be higher for higher yield strength, because higher yield strength implies more elastic deformation.

Here, one may observe the relation between material and manufacturing aspect in relation to the structural performance; often a high yield strength is preferred for a structure, to avoid permanent deformations at maximum operational loads. However, from a manufacturing perspective, high yield strength implies large spring back that needs to be accounted for.

That relates to the second aspect of spring back: tolerances. The final shape of the product is obtained after the forming forces are removed and elastic spring back has occurred. If small tolerances are required, this implies that the spring back must be known as accurate as possible. For the example of bending over a single line as illustrated in Figure 4.5, this may be very well achievable, but if the deformation is applied to double-curved shapes (3-dimensional), this becomes a complex calculation.

4.2.4 Forging

Forging is a forming process applied to bulk material. Special attention is given here to the production process. The interdependency between the material, manufacturing and geometrical aspects, illustrated in Figure 4.1, is clearly visible in the forging process.

Forging is a process where bulk material is deformed into another shape by applying compressive forces to the material. This process is be applied at elevated temperature. Obviously, at higher temperatures materials are easier to deform, because their resistance to deformation is lower.

The mould used to form the material into its new shape, defines with its inner contour the shape of the product. However, small tolerances cannot be achieved with this process, because the work applied to the material induces internal stresses. Together with little elastic deformation (see previous section), these residual stresses will find equilibrium while settling to its final shape after unloading. Because the level of detail achievable with forging is limited, machining is commonly applied after the forging process, to achieve the required geometry with the desired accuracy and tolerances.

However, this requires some additional considerations, because if internal residual stresses have obtained equilibrium after the forging process, this may imply that once material is removed with machining the equilibrium has changed and subsequently the shape. Therefore, either thorough analysis of the formation of residual stresses is required to predict potential 'spring back' after machining, or machining has to be applied carefully by removing in a symmetric manner and in small amounts. An example of a forged rid is illustrated in Figure 4.6.

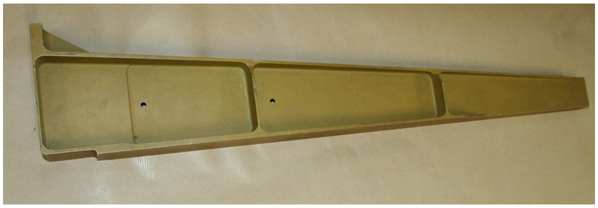

Figure 4.6
A forged rib of a control surface (Saunders-Smits, 2018, 4-6.jpg. Own Work.)

The example visualized in Figure 4.6 illustrates another relation shown in Figure 4.1, because the selection of the production steps in manufacturing a component, may imply that the residual stresses, that are in equilibrium in the product in its final shape, may or may not be significant. The lower the residual stresses in the final product, the less issues they may induce on the structural performance.

4.3 Composites

In manufacturing of composite structures, several production techniques can be identified that can be classified in three groups:

- Placement of fibres in dry condition
- Placement of fibres in wet condition
- Placement of fibres after pre-impregnation

4.3.1 Filament winding

Filament winding is a production technique that can be applied by placing the fibres either in dry or wet condition on a mould with a given geometry. Because of the rotational movement during winding, typical products are products containing a cylindrical geometry, like for example pressure vessels. Open geometries such as, for example, bath tubs cannot be made using filament winding. Products made using filament winding often have a textile appearance.

Characteristic for the filament winding process is that the placement of fibres is bound by the initial orientation and friction, with no free variable orientations possible.

The mould used to define the shape of the product over which the fibres are wound is called a mandrel. There are two options that can be applied for the mandrel:

- Removable mandrel; the mandrel should be solvable, collapsible or tapered in order to be removed
- Used as liner; the mandrel becomes part of the final product and serves for example as liquid and gas tight inner liner.

The windings that are possible are given by:

- Hoop $\alpha_i = 90°$
- Helical $\alpha_i = \pm n°$
- Polar $\alpha_i \approx 0°$

Figure 4.7
Filament winding machine (left) and a Schematic presentation of filament winding (right). Derivative from left: Gdipasquale1, (2018), CC-BY-SA4.0 and right: Esi.us1, (2001), Public Domain.

4.3.2 Pultrusion

Pultrusion is a process equivalent to extrusion, see Figure 4.4, but where the material is pulled through the mandrel rather than pushed. The material is pulled trough a mandrel that defines the shape of the product. Although the reinforcement with fibres is possible and commonly applied, there are limitations to the way fibres can be positioned in the product. This limitation is related to the process. The reinforcements that are possible are

- Rovings, strands or unidirectional material
- Chopped strands (fibre mats)
- Woven fibres

The first category is used the most. In any case, whatever category is selected, a certain amount of continuous fibres is necessary to provide the strength in longitudinal direction for pulling. For the matrix material thermoset polymers are applied, such as polyesters and vinyl esters.

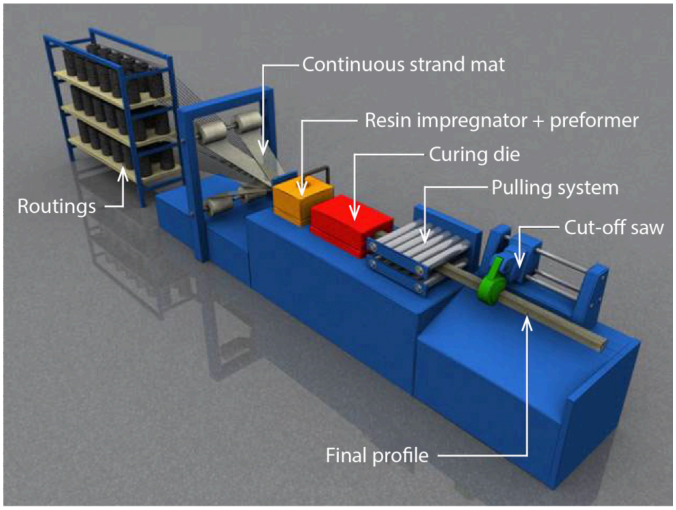

Figure 4.8
Schematic presentation of a pultrusion machine. Derivative from Arnd, (2005), CC-BY-SA3.0.

4.3.3 Lay-up

Lay-up is a manufacturing process that can either be applied manually, or fully automated. Manual lay-up is often used for small quantities of a product. Because of the relative low quantities of aerospace components (except for single aisle aircraft, most commercial aircraft are manufactured at a rate that is closer to prototyping than full scale industrial production) manual lay-up is often applied. However, with the introduction of composite fuselage structures (Boeing 787 and Airbus A350) the need for automation of the production process increases. This is especially the case, because circular shaped barrel components cannot easily be made with manual lay-up. The automated lay-up process is typically referred to as tape laying or fibre placement.

Comparing tape laying with manual lay-up, some benefits and drawbacks can be identified. Because automation implies numerical control, the placement usually is more accurate and more repeatable than manual lay-up. As a consequence the difference between identical parts is less for tape laying. For fibre reinforced composites, the improved accuracy in placement of fibres results often in better mechanical properties.

However, the apparent drawback is that it requires an expensive tape laying machine, which makes the automated process even more expensive. As a consequence, only large volumes or high end products, like for example space technology, justify the high investments.

In general, components made by lay-up can be very large but are limited by the time needed for impregnation and curing and the size of the autoclave. An autoclave is a pressure oven in which components can be cured at elevated temperature and pressure. For example, the fuselage barrels of the Boeing 787 require, because of their diameter, a very large autoclave.

Lay-up can be applied both using dry lay-up, which is then followed by impregnation and subsequent curing, and wet lay-up, which is only followed by curing.

A typical variant of lay-up is prepregging. This process uses pre-impregnated material (i.e. fibres that are impregnated with resin and subsequently consolidated as tape or prepreg), which is positioned on a mould either by manual or automated lay-up. After lay-up, the component is placed underneath a bag that is put in vacuum to remove the air from the component, before it is cured in, for instance, an autoclave. This lay-up variant enables manufacturing components with high quality, but in return implies a rather expensive process.

A quicker and cheaper process uses a spray up technique. Instead of long continuous fibres short chopped fibres (10-40 mm) are applied that are sprayed onto the mould. As a consequence, the fibres are positioned in a random orientation, which provides in-plane isotropic properties.

The disadvantage of this process is that it results in components with low mechanical properties compared to lay-up using continuous fibres, and the quality depends on craftsmanship. This implies that repeatability of this process is low from one worker to another.

4.3.4 Resin transfer moulding (RTM)

Resin transfer moulding is a manufacturing process where dry fibres are placed in a stiff and rigid mould, which is subsequently closed. With the use of pressure difference (i.e. high pressure at the entrance of the mould and low pressure at its exit) resin is drawn through the mould cavity impregnating the dry fibres. After this process step is completed, the impregnated component can be cured. The principle of the RTM process is illustrated in Figure 4.9.

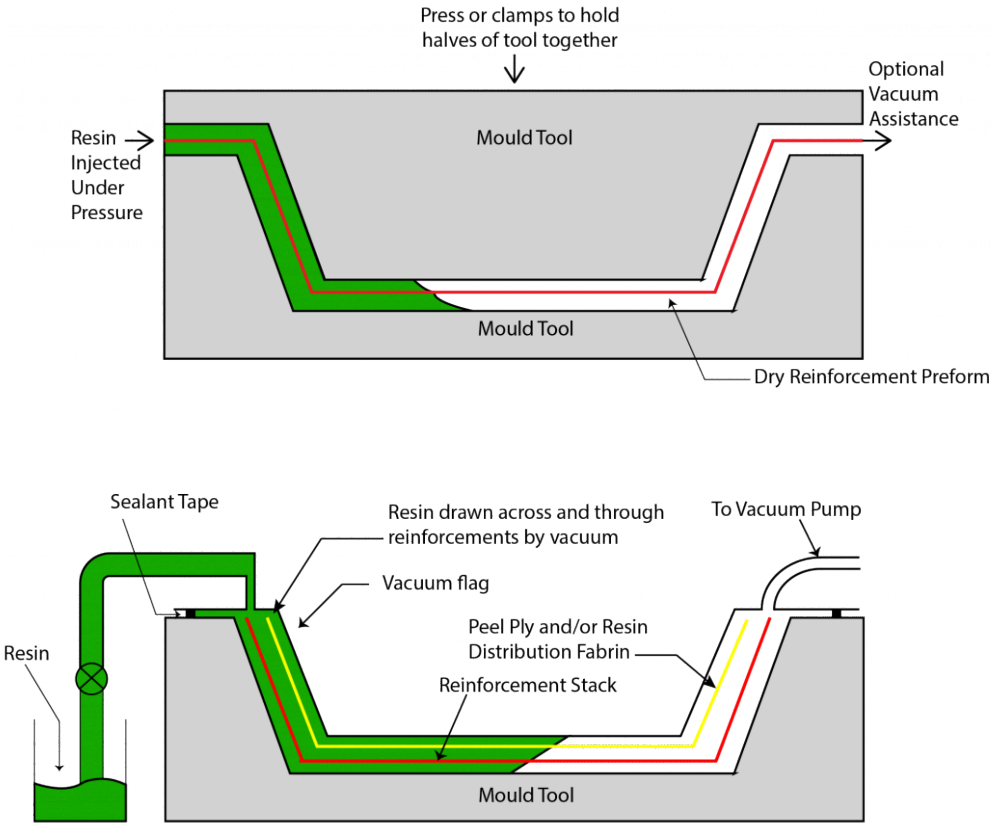

Figure 4.9
Principle of resin transfer moulding and vacuum infusion. (TU Delft, 2018, 4-9.jpg. Own Work.)

An alternative process, but closely related to RTM is vacuum infusion. In that process, dry fibres are also placed in a stiff and rigid mould, but the mould is closed with a flexible film. Putting the dry fibres underneath the film under vacuum will compress the material and pull the resin through the dry fibres in the mould.

The third variant is the vacuum assisted resin transfer moulding (VARTM). This process is in general similar to RTM, but the pressure differential is not only created by applying pressures higher than 1 bar at the injection side, but also by applying vacuum at the exit side.

The difference between the pressures used in the three processes is summarized in Table 4.1. Typical examples of applications manufactured with vacuum infusion are given in Figure 4.10.

Table 4.1
Typical pressures applied to obtained requires pressure differential

Pressure	P_1 (outside)	P_2 (inside)	ΔP
Resin Transfer Moulding	> 1 bar	1 bar	> 1 bar
Vacuum Assisted Resin Transfer Moulding	> 1 bar	< 1 bar	> 1 bar
Vacuum infusion	1 bar	< 1 bar	~ 1 bar

Figure 4.10
Example applications of vacuum infusion: Contest 67CS (upper row) and Eaglet rudder (lower row). Derivative from top left: Copyright 2016 by Contest Yachts, Reprinted with Permission.; Top middle and top right: Copyright 2006 by Lightweight Structures B.V., Reprinted with Permission; bottom row: TU Delft, (n.d.), 4.10-d.jpg and 4.10-e.jpg, Own Work.

4.4 Thermoset versus thermoplastic

With respect to composites manufacturing, some additional remarks shall be made. Traditionally, composite applications for aerospace structures were manufactured using thermoset resins, like for example epoxy and polyesters. However, the introduction of thermoplastic polymers as matrix material for composite structures has implications on the production aspects.

A qualitative comparison between the characteristics of thermoset and thermoplastic components and their manufacturing is given in Table 4.2.

In general, the advantage of thermoplastic composites is that they enable rapid manufacturing, producing components that can be recycled (melting the material again), welded (locally melting the material and cooling after components are pressed against each other), and that the process does not depend on chemical reactions. Compared to thermoset resins an important disadvantage is the required high temperatures and pressures, the limited storage life and out-gassing characteristics.

Aspects that must be considered before selecting the application of thermoplastic resins is that the melt processing used to produce thermoplastic composites limits the viscosity that can be achieved. A dimensional limitation due to the viscosity requirements can be illustrated using the example of wind turbine blades. Because these blades are very large and long, it is impossible to push the resin through the full length of the components even when applying high pressures. Therefore, the melt process of thermoplastic composites is considered an unsuitable process for manufacturing wind turbine blades.

Table 4.2
Comparison between thermoset and thermoplastic

Aspect	Thermoset	Thermoplastic
Material	Liquid components A and B	Single solid matrix
Melting step	No	Yes
Impregnating fibres	Yes	Yes
Chemical reaction	Yes	No
Material after cooling	Solid matrix	Solid matrix

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.

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