Introduction to Aerospace Structures and Materials

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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

3. Material types

3.1 Introduction

The key difference between the structures and materials discipline and other disciplines related to flight is that this discipline is about materialisation of concepts also developed within the other disciplines. To create an aircraft or spacecraft one must use materials. Materials in that sense can thus be defined as substances, matters, constituents or elements that are used to build parts, components and structures.
The properties of materials do not depend on their geometry, but on their composition only. The relation between the composition and the properties of a material can be further explored, but for the time being, one may consider the properties as an artefact of materials.

There is a wide variety of materials available to be used in materialisation of components and structures. Typical examples of materials are metals (steel, aluminium, magnesium, etc), wood, ceramics, and polymers. All these materials have properties which do not depend on their shape, like for example mechanical properties, electrical properties, physical properties, etc.

However, to materialise an aircraft or spacecraft structure, certain material properties are required. As a consequence, not all materials available in this world can be used, or are preferred to be used. Aerospace structures require materials that are solids with good mechanical properties but with a low density. This class of materials is often referred to as lightweight materials. Since there are numerous materials that are lighter than the materials currently used in aerospace structures, a more appropriate indication would be lightweight structural materials.
The performance of materials should be as high as possible for the lowest possible weight. This can be phrased alternatively by stating that the performance to weight ratio should be as high as possible. This leads to the use of specific mechanical

properties, which are the properties divided by the density or weight of the material. The use of those specific properties will be further discussed in chapter 8.

For application in aerospace structures, one can distinct the following material categories:

- Metal alloys
- Polymers
- Composites
- Ceramics

These categories are briefly discussed in the following sections. But before discussing these categories individually, one has to be aware that these materials have been retrieved from resources like ores (metal) and oil (composites and polymers). Once retrieved, they are transformed into semi-finished products like sheets, plates, bars, fibres, powder (polymers), etc. The semi-finished products are further processed into structural elements. For this transformation a huge number of processes are available that can be grouped into: casting, forming, machining, and joining processes. Subsequently, the structural elements are assembled into structures.

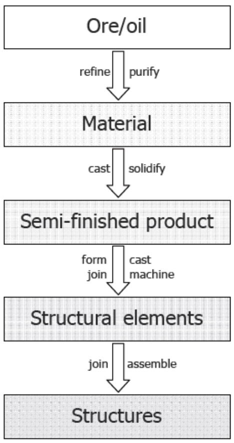

Figure 3.1
Illustration of subsequent production steps from raw material resources to structures (Alderliesten, 2011. Own Work.)

The properties of structures are directly related to the material properties although they are not identical: structural properties are often influenced by the shape and geometry (design) too. However, there is also another aspect to be considered when optimizing between material and structural shape; not every structure or shape can be made of any material. Consider for example the Eiffel tower, the Parthenon, or a surf board. The selected materials (resp. metal, marble and composites) and the shapes of these artefacts are compatible.
This also implies that if the shape is not adapted to or compatible with the material, the material properties are not optimally used and exploited.

A similar relationship exists between material and manufacturing process. Metals can be melted, so casting and welding are available production processes for metals. These production processes cannot be applied to ceramics or fibre reinforced composites for instance.

The last relationship to mention is the one between the shape (or structure) and the manufacturing process. To fabricate a sheet metal wing rib, one may use a forming process. Replacing the same rib by a machined rib will consequently result in different details of the wing shape (local radii, thickness, etc). To put it the other way around: To create a cylindrical shape and a double-curved shape, different manufacturing processes are needed.

In summary: there is a strong interrelationship between the three entities “material”, “structure or shape” and “manufacturing process”. Changing one entity often affects both others. For the best solutions to structural problems, i.e. to truly optimize the structure and its performance, one should include all three aspects in the design and its evaluation. This is illustrated in Figure 3.2 .

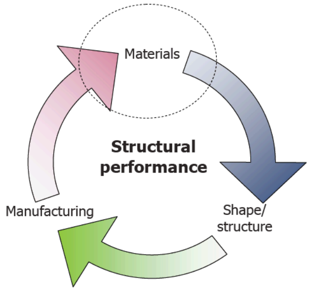

Figure 3.2
Illustration of the relation between Materials, Manufacturing and Design, with the topic of interest in this chapter highlighted (Alderliesten, 2011. Own Work.)

3.2 Metal alloys

An alloy is made by adding alloying elements to the purified metal in order to increase or modify the properties of the pure metal. For example, adding a few percent of copper and magnesium to aluminium (like in Al-2024) increases the yield strength and ultimate strength both with a factor of 4 to 6. In general, metal alloys have good processibility, show plastic behaviour, and are rather cheap.

3.2.1 Typical mechanical properties

Metal alloys typically are isotropic materials exhibiting similar elastic properties in all directions of the material. Because of this isotropic behaviour, the material specifications and the specifications of physical and mechanical properties are often given indifferent of the orientation. Only for specific metals that show anisotropic behaviour, like for example aluminium-lithium alloys, and for rolled sheet material sometimes properties are specified in two directions. The orientation dependency for the rolled products is related to the shape of the grains (severely elongated in rolling direction) as a result of the rolling process.

Because metal alloys are ductile materials that yield beyond the yield strength, both ultimate and yield strength are specified. This value indicates how far the material can be loaded elastically before permanent plastic deformation may occur.

Table 3.1 gives some mechanical and physical properties of typical steel, aluminium, titanium and magnesium alloys. It can be observed from the data in this table that there is some relation between strength and stiffness on the one hand and the density of the material on the other hand.
Steel exhibits high strength and stiffness, but at the cost of a high density, whereas magnesium (the lightest alloy in the table) shows the lowest mechanical properties.

Table 3.1
Typical mechanical properties some metals

Metal	Alloy	E [GPa]	G [GPa]	σ_y [MPa]	σ_{ult} [MPa]	ε_{ult} [%]	ν [-]	ρ [g/cm^3]
Steel	AISI 301	193	71	965	1275	40	0.3	8.00
	AISI 4340	205	80	470	745	22	0.29	7.85
	D6AC	210	84	1724	1931	7	0.32	7.87
Aluminium	AA 2024-T3	72	27	345	483	18	0.33	2.78
	AA 7475-T761	70	27	448	517	12	0.33	2.81
Titanium	Ti6Al-4V (5)	114	44	880	950	14	0.34	4.43
Magnesium	AZ31B-H24	45	17	221	290	15	0.35	1.78

3.2.2 Typical applications

Typical applications for metals are structures and components that require high strength both in tension and in compression, see the examples in Figure 3.3. Example applications for steel alloys are found in aircraft (landing gear components), train components and rails, bridges, towers and cranes.

Aluminium alloys are for instance applied in the main fuselage and wing structure of most aircraft, train structures, and car and engine components.

In aeronautical structures, titanium is applied in applications that require performance at elevated temperatures, like for example in the Concorde and military fighters. Most magnesium alloys are not applied in aircraft for flammability risks.

In general, metal alloys are applied in components and products that are produced in high volumes. Examples here are the cars and cans.

Steel is also often applied as reinforcement material in for example civil applications. The application of steel cables in suspension bridges is an evident example. But also concrete is reinforced with steel cables to increase the strength of the structure. Especially in case of high buildings the steel reinforcement is applied to pre-stress the structure, i.e. the steel reinforcement is put in tension (because of the excellent tensile properties), which by equilibrium puts the concrete in compression (for which concrete is known to perform excellent).

Figure 3.3

Typical applications of metals. Derivative from: Top left NI-CO-LE, (2017), CC0; Top right: Pingstone, (2004), Public Domain; Bottom left: KarinKarin, (2015), Public Domain; Bottom right: Bender, (2014), CC-BY-SA3.0.

3.3 Polymers

In general, polymers are not considered for structural applications. The polymers have relative low strength and stiffness and can therefore not be used as structural material. However, they are applied as structural adhesives to join other materials, and they are applied with additional reinforcement in composites.

3.3.1 Typical mechanical properties

Compared to rigid materials like metals, polymers exhibit significant lower stiffness and strength. Here, it should be noted that the stiffness of many polymers is not constant during loading. Whereas metals exhibit linear stress-strain behaviour during elastic deformation of the material, as illustrated in Figure 1.5, the stiffness of polymers often change with the amount of strain, see Figure 3.4. In case of such non-linear behaviour, the initial slope of the material is taken to determine the elastic modulus.

Although the strength and stiffness are generally very low, the elongation at failure can be quite high. Some rubbers, for example, may strain up to 500% before failure occurs.

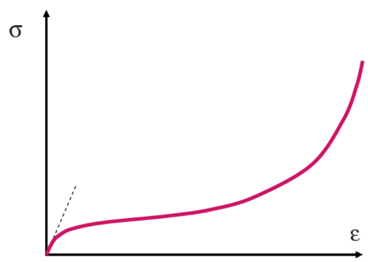

Figure 3.4
Qualitative illustration of the non-linear stress-strain behaviour of polymers (Alderliesten, 2011. 3-4.jpg. Own Work.)

In chapter 2, it has been explained that the temperature has an influence on the mechanical properties of materials. Although this is in general the case for all materials, it is quite significant for polymers. Depending on the temperature, materials may either behave like brittle materials or like elastic materials. Especially at low temperature, many polymers show brittle behaviour.

With increasing the temperature a gradual transition can be observed from brittle to elastic and rubbery behaviour, while further increasing to high temperatures the material may become viscous or even liquid like.

This transition to the viscous state is important for polymers, because it implies a significant reduction in the mechanical properties. A well known transition for polymers is the so-called glass transition temperature.

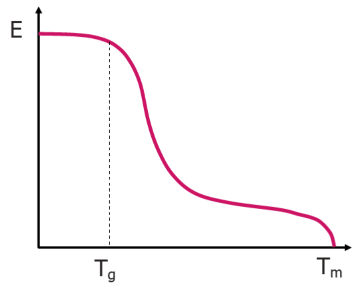

Figure 3.5
Transition in modulus of elasticity at the glass transition temperature, below the melting temperature (Alderliesten, 2011, 3-5.jpg. Own Work.)

Some polymers exhibit different mechanical behaviour, depending on the rate they are strained. Glass fibres for example, exhibit higher strengths when loaded at very high rates. This can be beneficial in case of impact for example.

3.3.2 Typical applications

Because of the wide variety of polymers that exist, the number of applications is numerous. Some main categories can be distinguished:

- Elastomers
- Plastics
- Fibres

Some well known examples of polymer applications are illustrated in Figure 3.6. Rubbers are elastomers that are typically applied in tires, sealing, coatings and liners. They are in general characterized by their flexibility and the large strain to failures. Plastics can be divided into two main categories:

- Thermoplastic
- Thermoset

Figure 3.6

Typical applications of polymers. Derivative from Top left: Saunders-Smits (2018), 3-6-b.jpg. Own Work.; Top right: Yogipurnama, (2017), CC0; Bottom left: Anon., (2017), CC0; Bottom middle: Pexels, (2016), CC0; Bottom right: Hans, (2013), CC0.

Thermoplastic polymers melt when heated to certain temperatures and return to their glassy state when cooled again. These materials are often associated with weak Van der Waals forces. This means that the material can be melted above their melting temperature and moulded into components. The process is reversible, as reheating will melt the material again.

Thermoset materials however, are cured irreversibly, which means that once the chains link during curing the process cannot be reversed. These materials usually do not melt at high temperatures, but may decompose or burn when heated too high.

The difference between these two materials is considered important, especially when addressing recyclability of the materials. Thermoplastic materials can be recycled relatively easy by heating above the melting temperature, while thermoset materials are in general not easy to recycle.

Example applications of thermoset materials are the old bakelite telephones and the epoxies used in fibre reinforced composites. Here, it should be mentioned that current developments seem to aim to replace, for certain composite applications, the thermoset matrix material by thermoplastic matrices.

Examples of fibre types are natural fibres, synthetic fibres and nylon. Application of these types of fibres in a fibre reinforced composite, implies that different polymers are combined into a structural material. The fibre is made of another polymer than the matrix material.

3.4 Ceramic materials

Ceramics are not suitable for structures. They are too brittle and have poor processing features. However, they are applied in some space applications, for instance for thermal protection of the metallic or composite structure. Ceramics often consist of (metal) oxides and metals, in which ionic bonds between the different atoms provide the material structure.

3.4.1 Typical mechanical properties

In general, ceramics are hard and brittle materials that have very limited toughness due to the lack of ductility (small failure strain). In certain cases a high strength and stiffness can be achieved, but that depends on the composition of the material and the level of porosity.

The reason why certain ceramics are considered for heat protection is that they are capable to sustain very high temperatures. Even at those temperature levels the bonds between the atoms remain very strong. This strong bond also implies that ceramics are often very resistant to wear.

3.4.1 Typical applications

A variety of typical applications for ceramics can be mentioned here. To start with the glass application, glass is applied in window panes, lenses, but also in fibres. Glass fibres are very stable fibres that have high mechanical properties both in tension and compression. At high strain rate levels, the glass often provides a higher strength than when quasi-statically loaded to failure.

Another example of ceramics is clay. Porcelain and bricks are well known examples of these ceramics. In civil applications not only bricks, but also cement and lime are being applied as ceramic applications.

Other examples are cutting tools and abrasive materials due to its high wear resistance, armour reinforcement because of its high puncture resistance, and in case of glass fibres, due to its high impact resistance. The previously mentioned high heat resistance (1600 – 1700 °C) results in many applications in engine components and heat protection systems for, for example, the Space Shuttle. A selection of applications are illustrated in Figure 3.9.

Figure 3.9
Typical applications of ceramics. Derivative from Extreme left: Cjp24, (2007), CC-BY-SA3.0; Left: Torr68, (2005); CC-BY-SA3.0; Right: Anon.(n.d.), Public Domain; Extreme right: Atkeison, (2003) CC-BY-SA2.0.

Example: Space Shuttle Columbia

A known application of ceramic materials is the thermal protection tiles on the Space Shuttle. The importance of this protection is illustrated with the tragic accident on February 1, 2003. During its launch a piece of foam became detached from the tank and hit the leading edge of the wing causing damage to the ceramic skin. Although during lift-off and mission no apparent problems were observed, the Shuttle disintegrated during re-entry. Analysis revealed that during re-entry hot gasses could enter the wing structure through the damage affecting the structure behind the ceramic tiles.

In this accident the crew of 7 people were all killed.

Figure 3.7
Space Shuttle Columbia (left) with indicated location of space debris (centre) and an image of the accident. Derivative from NASA, (2003), Public Domain.

Figure 3.8
Photos of the ceramic tiles shown intact, with damage, test panel with damage and test set up. Derivative from Volk, (2008), CC-BY-SA2.0, and NASA, (2003 2007), Public Domain.

3.5 Composite materials

Composite materials are, as the name already indicates, materials that are composed of different materials. A more accurate description or definition is given by:

Composites are engineering materials, in which two or more distinct and structurally complementary substances with different physical or chemical properties are combined, to produce structural or functional properties not present in any individual component.

An example of a composite is the fibre reinforced polymer composite, which consists of two distinct and complement materials, namely fibres and polymer. The function of the fibres is to reinforce the polymer providing strength and stiffness to the material and, by doing so, to carry the main portion of load. The function of the polymer is to support the fibres and to transfer the load to and from the fibres in shear. This is indicated in Figure 3.10.
Products and components made of fibre composites are fabricated with specific processes like filament winding, lay-up and curing, and press forming, discussed in the next chapter.

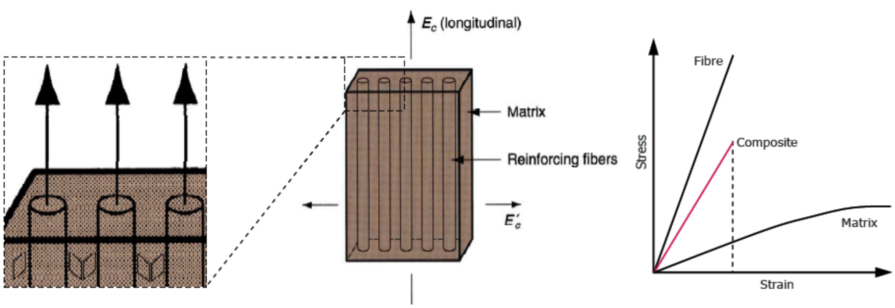

Figure 3.10
Illustration of a fibre reinforced polymer composite ply, and the related stress-strain behaviour of constituents and lamina (Alderliesten, 2011, 3-10.jpg. Own Work.)

3.5.1 Typical mechanical properties

As is evident from Figure 3.10, the stress-strain behaviour of the fibre reinforced polymer composite is determined by the constituents of which it is composed. The stiffness of the lamina is a function of the stiffness of the polymer and the fibre, which can be estimated by the rule of mixtures, discussed in section 3.6. However, whereas the stiffness may be directly related to stiffness and volume content of each constituent in the lamina, the strain to failure is solely determined by the strain to failure of the fibres. Once the fibres fail, the strength of the remaining polymer is too low to carry the load.

One should pay attention to the definition given here for 'composites', because this definition states that any type of engineering structural material that satisfies this definition is considered to be a 'composite'. These days, people use the wording 'composites' often to indicate only one specific type of composites, namely the one constituted of carbon fibres and polymer. However, one should be aware that this is an inaccurate use of the definition of composites.

To illustrate the meaning of the definition of composites, another example of a composite is given by the category of hybrid materials, such as for example Fibre Metal Laminates (Vlot and Gunnink, 2001), see Figure (3.11). These structural materials consist of alternating metal and composite layers combining the benefit of each constituent material, while compensating each other's disadvantages.

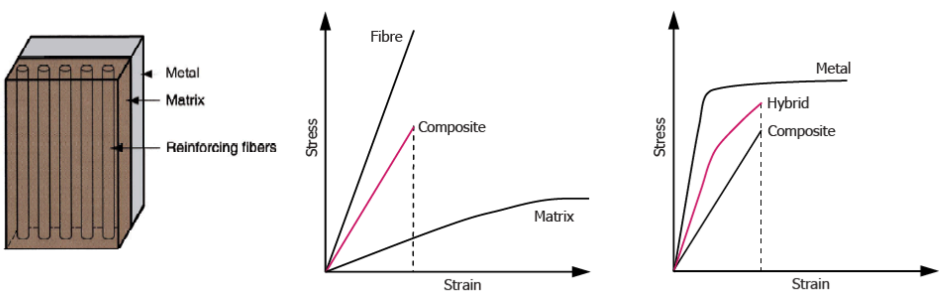

Figure 3.11
Illustration of a fibre metal reinforced polymer composite ply, and the related stress-strain behaviour of constituents and lamina (Alderliesten, 2011, 3-11.jpg. Own Work.)

In general, fibre reinforced polymers are characterized by their high specific properties. The strength and stiffness to weight ratio is considerable. However, most composites behave elastic until failure, without showing any ductile behaviour. Despite the often very high strength and stiffness, this limits the toughness of these materials.

Due to the high directionality (fibre orientation) these materials enable tailoring to specific load applications (beams, cables, columns), but require multiple orientations to cope with bi-axial load applications.

Table 3.2
Qualitative comparison of typical properties of several composites

Material	Specific strength	Failure strength	Electrical conductivity	Flame resistance	UV resistance	Chemical resistance
Glass fibre reinforced composite	High	Medium	Low	High	Medium	Low
Carbon fibre reinforced composite	High	Low	High	High	Medium	Low
Aramid fibre reinforced composite	High	Medium	Low	High	Low	Low
Fibre Metal Laminate	High	Medium	High	High	High	Medium

3.5.2 Typical applications

Typical applications are illustrated in Figure 3.12. Wind turbine blades are commonly made of glass fibre composites. Other applications are sail planes and pressure tanks and vessels.

Carbon fibre composites are often applied in automotive and aerospace structures for their high stiffness. A well known application in sailboats is for example the mast. But also (motor) bikes are made of carbon fibre composites since the stiffness and rigidity of the frame is important in such design. Similarly certain sport equipment is made of these materials.

Aramid and Kevlar based composites often find applications in armour and bullet proof protection systems, like bullet proof vests and cockpit doors that should resist terrorists. Also heat and flame resistant products are often made from aramid fibre reinforced composites.

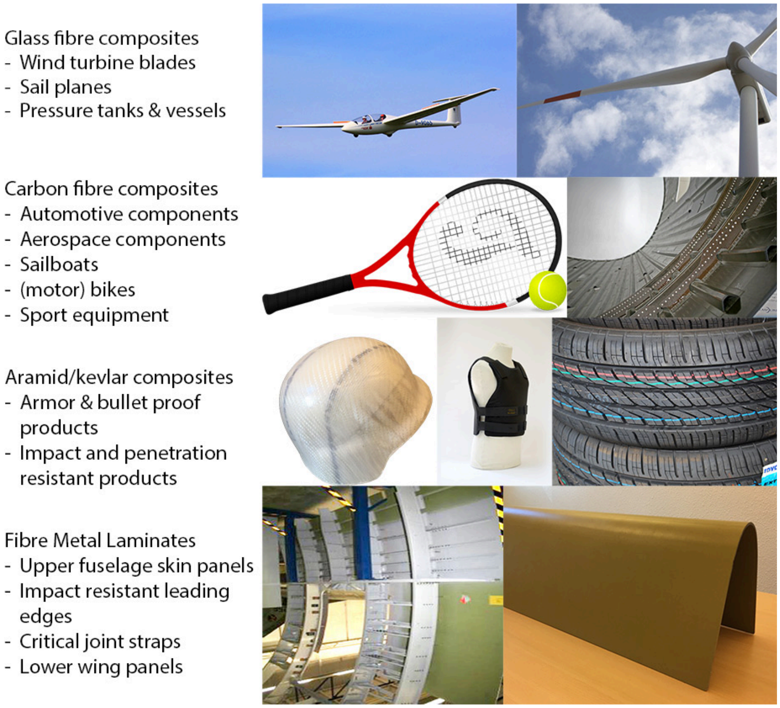

Figure 3.12

Typical applications of composites. Derivative from Top row, left: GuentherDillingen, (2012), CC0; Top row, right: medienluemmel, (2016), CC0; Second row, left: Gnokii, (2011), CC0; Second row, right: Boffoli, (2018), CC0; Third row left: Saunders-Smits, (2018), 3-12-f.jpg. Own Work.; Third row middle: PMulhalla, (2015), CC-BY-SA3.0; Third row right: Vinayr16, (2014), CC0; Bottow row: Saunders-Smits, (2018), 3-12-h.jpg and 3-12-i.jpg. Own Work.

Typical applications of the composite Fibre Metal Laminate (FML) concept are primarily found in aerospace applications. The reason is that these materials are specifically developed for their high strength and fracture toughness, which increases the damage tolerance of primary fuselage and wing structures, necessary for maintaining structural integrity. The FML Glare is currently applied as upper fuselage skin material and impact resistant empennage leading edges on the Airbus A380. The material is also applied as high damage tolerant butt strap joint material in the Airbus A340 fuselage.

3.6 Rule of mixtures

A simple method to estimate the composite ply properties of a composite material is the so-called rule of mixtures. This rule is a mean to *estimate* the lamina properties based on the properties of the individual constituents, i.e. fibre and matrix system. However, one should be aware that the method by no means is considered accurate.

$$M_{FRP} = M_F + M_M \rightarrow \rho_{FRP} V_{FRP} = \rho_F V_F + \rho_M V_M \tag{3.1}$$

where M indicates the mass of the constituent, V the volume and ρ the density.

This equation can be written as

$$\rho_{FRP} = \rho_F \frac{V_F}{V_{FRP}} + \rho_M \frac{V_M}{V_{FRP}} \rightarrow \rho_{FRP} = \rho_F v_F + \rho_M v_M \tag{3.2}$$

where v indicates the volume fraction of the constituent in the fibre reinforced laminate. This linear relationship is illustrated for the density of the laminate in Figure 3.13.

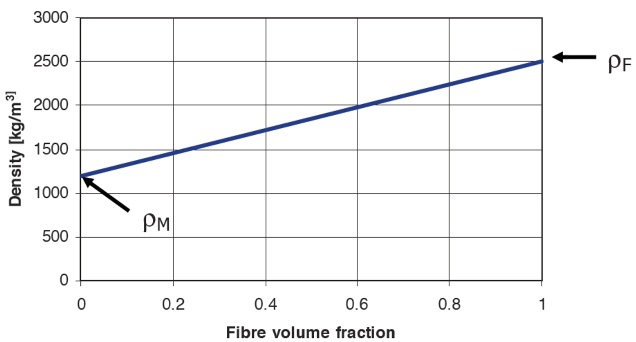

Figure 3.13
Rules of mixtures to estimate the composite ply properties based on the matrix and fibre properties relative to their volume content (Alderliesten, 2011, 3-13.jpg. Own Work.)

Similarly, this rule of mixtures relationship is illustrated in Figure 3.14 for a carbon fibre composite with various lay-up configurations. Here, it should be clear that the high fibre volume may improve the properties, but that the different orientations reduce the overall laminate properties significantly. The grey shaded area in this figure illustrates the common fibre volume fractions typically applied in composites.

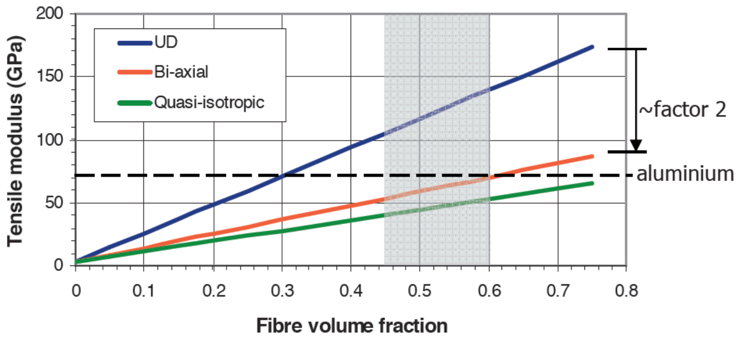

Figure 3.14
Illustration of the effect of fibre volume fraction of the individual composite plies and lay-up on the overall laminate stiffness (shaded area is typical range of fibre volume fractions). Alderliesten, (2011). 4-14.jpg. Own Work.

3.7 Requirements for structural materials

One could assemble a list of requirements for the engineering materials considered. Comparison between these material requirements and, for example, structural requirements would reveal a large overlap. However, here one should be careful: there are significant differences between these two.

Several requirements for structures are also mentioned for materials: high strength, high stiffness, low weight, durability, and costs. Nonetheless, one should keep in mind that for compliance to structural requirements the geometry of the structure could be changed.
For example, to increase the stiffness of a structure, one can select either a material with a higher stiffness, and/or create a stiffer geometry (shape/design). But, changing the stiffness of the material, represented by its Young's modulus, is not possible.
Likewise the density is a material constant. Other properties like the strength and the durability can be changed by (slightly) changing its composition (another alloy) or condition (temper).

In addition to these requirements, more requirements can be mentioned here that relate to the relation illustrated in Figure 3.2.

The manufacturability or workshop properties of materials relate materials to manufacturing aspects. To manufacture an aircraft, it is very important to have materials that have good workshop properties. For instance, aluminium alloys have good manufacturability, but titanium alloys don't. That means that processes like forming and machining (drilling, milling) are easy for aluminium alloys, but difficult for titanium alloys. In composites, glass and carbon fibre reinforced composites have good/adequate workshop properties, but aramid (Kevlar) fibre reinforced composites are very difficult to cut by machining operations, due to the very tough aramid fibres.

To emphasise the importance of the manufacturing aspects in relation to materials requirements, one should also consider that several manufacturing processes are relatively easy for one material, but impossible for other. For example, for manufacturing of a spar or stringer, extrusion and machining processes are available for metals, which are all inapplicable for fibre reinforced composites. Selection of the appropriate materials then relates to the available production processes.

Physical properties like electrical conductivity and the coefficient of thermal expansion (CTE) are important for specific features of the operation performance. The electrical conductivity of aluminium alloys make it easy to create a (safe) Faraday cage of the aircraft fuselage. For composites this is more difficult; sometimes extra strips or conductive meshes are required for this protection against lightning strike.
In this respect, the CTE is also important because aircraft operate between +80°C (a hot day on the airport) and -60°C (at cruise altitude). Large differences in values of CTE of applied materials could cause extra problems, like the thermal stresses explained in the previous chapter.

Therefore, meeting the requirements should be achieved both on a structural level and material level. Once dominant material requirements are met, discrepancies could be solved on a structural level. For example, the earlier mentioned differences in CTE could induce thermal stresses in a structure. This cannot always be solved by changing one of the applied materials. The structural design solution, i.e. type of joint, direct contact between materials or separation by intermediate layers, could solve those specific issues.

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.

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

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