Introduction to Aerospace Structures and Materials

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2. Environment & durability

2.1 Introduction

The material properties discussed in the previous chapter are considered to describe the behaviour of a specific material. However, this does not mean that the properties are constant under all conditions. Most material properties change for example with temperature. Increasing or decreasing the temperature will affect material properties like stiffness and strength.

Another aspect that should be considered is the duration of operation. An aircraft being operated for instance for 30 years will face degradation of structural and mechanical behaviour due to environment effects.

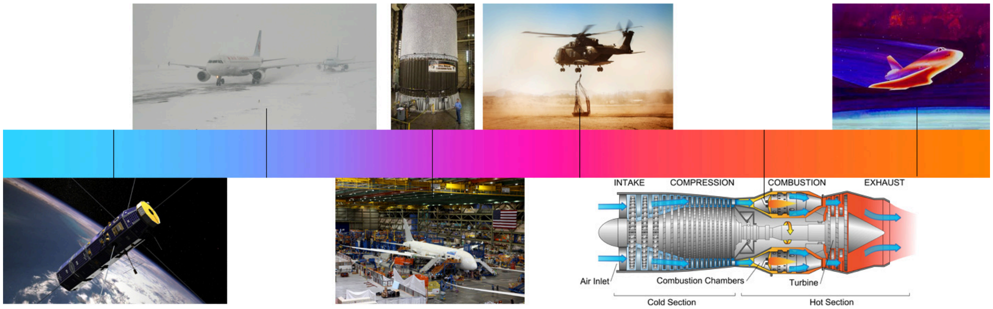

Figure 2.1
Illustration of structural aircraft and spacecraft applications and the temperature ranges in operation. Derivative from top left: Koul, (2008), CC-BY-NC 2.0, top middle: Deaton – NASA, (2013), Public Domain, top right: Stier, (2009) Open Government License, bottom left: NASA, (2006), Public Domain, bottom middle: NASA, (2011) Public Domain, bottom right: Jetstar Airways, (2013), CC-BY-SA 2.0.

The influence of the environment in which the structure or component will be operated is important to consider. For example, an engineer or designer should consider that if a structure is required to withstand certain loads during operation, the material strength may reduce for specific operating conditions. This may be either high temperatures of the environment, or degradation throughout the life of the structure due to aggressive environments. An illustration of typical applications and operationing (temperature) conditions is given in Figure 2.1.

This chapter tries to describe the effect of the environment on the material and structure, so as to increase awareness of this aspect to future engineers.

2.2 The effect of ambient temperature

The effect of the ambient temperature on the material properties can be illustrated with the data given in handbooks as for example Metallic Materials Properties Development and Standardization handbook [1]. In Figure 2.2, an example is given for the effect of ambient temperature on the ultimate and yield strength of 2024-T3 aluminium sheets in a temperature range below the melting temperature of the alloy (T_m = 500-640 °C).

In this figure it is also demonstrated that the duration of exposure to that temperature may have a considerable effect above certain temperatures. The 2024-T3 aluminium alloy is widely applied in aeronautical structures. The nominal maximum operational temperature for this alloy is often specified to be about 135°C. From Figure 2.2 it is evident that above this temperature, the mechanical properties will drop rapidly, especially when exposed for longer times.

Metallic materials are not the only materials that show dependency of mechanical properties on the ambient temperature. In general, all engineering materials exhibit temperature dependent material behaviour. Especially in polymers one may also observe a transition in the material response at a temperature below the melting temperature.

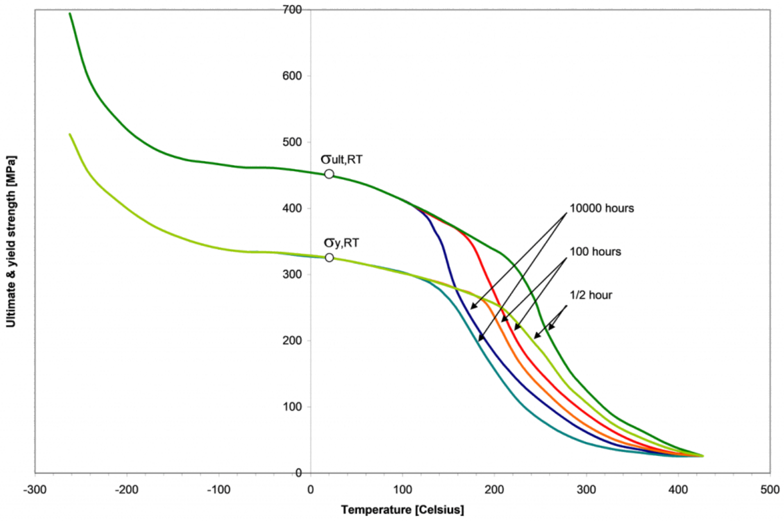

Figure 2.2
Effect of temperature on ultimate and yield strength for 2024-T3 sheets based on data from Rice et al., (2003). (Alderliesten, 2011. 2-2.jpg. Own Work.)

The transition in general relates to the transition from a solid state of the material into a rubbery state. The temperature at which this transition is observed is called the glass-transition temperature T_g. This refers to the transition glass exhibits at elevated temperatures, exploited in the glass blowing process. The phenomenon is illustrated in Figure 2.3 for the modulus of elasticity. However, the effect is also evident for the strength and strain to failure; increasing the temperature beyond the transition temperature decreases the strength of the material, while the strain to failure is often increased.

For structural applications this implies that operational temperature may never approach the glass transition temperature, otherwise the mechanical properties would drop significantly risking premature failure of the structure.

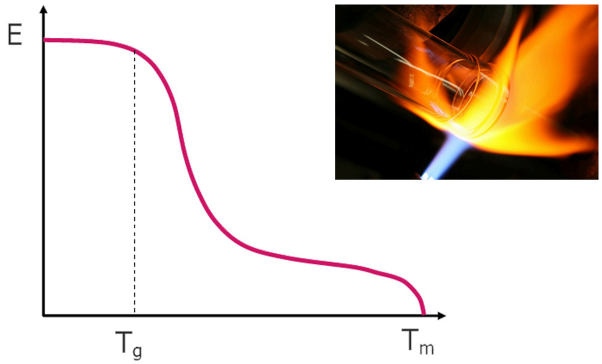

Figure 2.3
Illustration of the transition in modulus of elasticity near the glass transition temperature T_g*. Derivative from left: Alderliesten, (2011), 2-3a.jpg, Own Work, and right: Anon., (2006), CC-0.*

2.2.1 Effect of elevated temperature

In general, the effect of increasing the temperature is that most mechanical and fatigue properties of engineering materials deteriorate. This is also clearly illustrated in Figure 2.2. This means that it has to be verified that the mechanical properties of the selected materials remains above the specified levels within the full operational temperature range.
For the case of 2024-T3, this means that the specified ultimate and yield strength are minimum values that are lower than the values obtained at room temperature. To determine the minimum allowable strength of the material, knock-down factors are applied to the values obtained at room temperature.

For many metallic structures, the reduction of yield strength may not directly implicate a safety issue, because the ultimate strength may still be considerable. However, the application of stresses beyond the reduced yield strength may cause permanent (plastic) deformation.

Another aspect related to elevated temperature, especially high temperatures, is the creep phenomenon. Creep is a small, but steady ongoing deformation of materials under the application of constant stress. Although these stresses can be below the yield strength of the material, the ongoing deformation may still occur. At room temperature and low temperatures, this phenomenon is usually insignificant. At elevated temperatures, especially high temperatures near the melting temperatures, this phenomenon may cause permanent deformations within limited times of load application. The deformation rate is thus dependent on the applied load level, the temperature level, and the mechanical properties of the material.

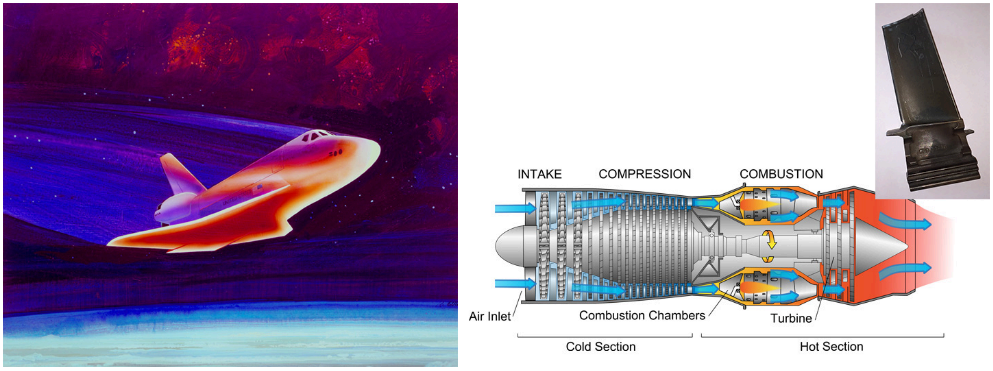

Figure 2.4
Illustration of high temperature applications; thermal protection systems and engine turbine blades. Derivative from left: NASA, (2006), Public Domain, middle: Dahl, (2007), CC-BY-SA 4.0 and right: Saunders-Smits, (2018), 2-4-c.jpg. Own Work.

For certain high temperature applications, see Figure 2.4, the creep phenomenon may significantly limit the amount of materials that can be applied. For example engine turbine blades are exposed for a long time (duration of a long distance flight) at high temperature, while constantly exposed to significant centrifugal loads. These components are therefore specifically designed against creep. For example, single crystal alloys (Ni-based alloys) are developed that have significant creep resistance.

2.2.2 Thermal stresses

Aside from the effect the environmental temperature has on the mechanical properties of the applied structural materials, the designer has to consider thermal stresses. The material will expand or contract with respectively increasing or decreasing temperatures. The relation between the temperature and the expansion is described by the volumetric thermal expansion coefficient.

$$\alpha = \frac{1}{V}\frac{dV}{dT} \tag{2.1}$$

which is considered a material property. In equation (2.1) V is the volume and dV/dT the expansions rate of the volume with the temperature. For isotropic materials, the coefficient of thermal expansion is identical in all principal material directions. However, for anisotropic materials, the coefficient is different for the different directions, like the other mechanical properties.

The different expansion coefficients for different materials, see Table 2.1, implies that a composite or hybrid structure, i.e. a structure comprising multiple materials, will face differences in expansion. Beside the mechanical loads and corresponding stresses that are excerted to the structure, these differences in thermal expansion may impose additional stresses once free expansion is prohibited.

Table 2.1
Linear coefficients of thermal expansion for different materials

Material	α_x [1/°C]	α_y [1/°C]
Titanium Ti-6Al-4V (Grade 5)	$9.2 \cdot 10^{-6}$	$9.2 \cdot 10^{-6}$
Aluminium 2024-T3	$22 \cdot 10^{-}6$	$22 \cdot 10^{-6}$
Magnesium AZ31-H24	$26 \cdot 10^{-6}$	$26 \cdot 10^{-6}$
S2-glass epoxy UD-60%	$26.2 \cdot 10^{-6}$	$6.1 \cdot 10^{-6}$
Carbon epoxy UD-60%	$-0.4 \cdot 10^{-6}$	$27 \cdot 10^{-6}$

The significance of this aspect may be illustrated with press releases on the Boeing 787, where it was reported that the aluminium shear ties that fixate the fuselage frames to the composite skin in the rear fuselage section had to be replaced (Cohen 2010). The initial design did not account for the repeated cooling and warming of the unpressurized aft fuselage section 48. As result of these temperature cycles, the shear ties may repeatedly pull away from the skin with potential influence on the integrity of the structure.

Although this design flaw was detected prior to any 787 delivery, it emphasizes the importance of accounting for potential additional loading due to thermal stresses.

Example: Fibre Metal Laminates

A Fibre Metal Laminate (FML) is a composite material consisting of thin aluminium sheets with fibre/epoxy plies in-between. The laminates are cured at an elevated curing temperature in a stress-free condition. This means that due to the different coefficients of thermal expansion residual stresses occur when the laminate is cooling down at the end of the cure cycle. The magnitude of these stresses is dependent on temperature and laminate composition.

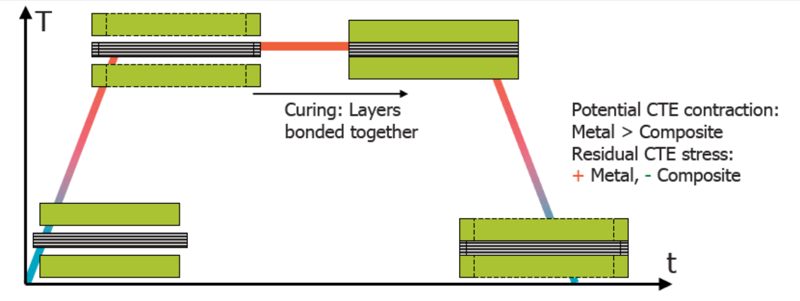

Figure 2.5
Illustration of thermally induced residual stresses in a FML (TU Delft, n.d. 2-5.jpg. Own Work)

2.2.3 Effect of low temperatures

Obviously, the effect of thermally induced residual stresses is also present when ambient temperatures are decreased to low temperatures. For the Fibre Metal Laminate Glare for instance, the residual stresses increase further with decreasing temperatures. This is because the difference with the curing temperature, i.e. $\Delta T = T_{cure} - T$ is further increasing.
However, in these laminates the mechanical and fatigue properties are becoming better despite the increasing residual stresses. This is related to the general influence low temperatures have on metallic materials.

At lower temperatures, the micromechanical response of materials results in higher resistance against elastic and plastic deformation. A higher resistance against

deformation relates to an increase in modulus of elasticity and yield strength of materials.
In addition, the chemical reaction and diffusion rates decrease at lower temperatures. To some extent this is the consequence of the lower water vapour pressure. Because there is less water vapour in the air at low temperatures, the chemical reaction with materials reduces.

A special case of the effect of low temperatures is the transition in fracture and impact toughness observed in some low carbon steel alloys. This transition relates to the change in fracture appearance. Where at room temperature, the fracture is completely ductile (high toughness) the fracture changes to brittle at low temperatures (low toughness). Examples of this phenomenon are the failures of the Liberty ships and T2 tankers, shown in Figure 2.6.

2.3 The effect of humidity

In general, a humid environment has a detrimental effect on the structural properties of both metallic and composite structures. However, the reason for the deterioration of both material types is different. Metallic materials in a humid environment may be more affected by corrosion attacks that damage the material and reduce the effective thickness of the structure or component. However, a composite structure in a humid environment faces ingress of moisture into the polymer matrix, which deteriorates both the cohesive strength of the polymer, but also the adhesive strength of the bond between fibre and matrix. Thus where in metallic materials the strength relates to reduction of cross-section because corrosion has eaten away the material, the strength of composites reduces due to the reduction in chemical bonding and softening of the matrix.
In both cases, time is an important parameter. The longer a structure is exposed to a humid environment, the more time there is to either corrode a structure, or for moisture to ingress the composite. In general, the reduction in strength due to environmental attacks and humidity is dependent on the exposure time.
Here an interesting difference can be observed between the performance of a fibre reinforced polymer composite and a Fibre Metal Laminate. Because the metallic sheets do not allow moisture to penetrate the material, the moisture ingress in FMLs

is in general limited to edges of panels and cut-outs and drilled holes (for riveting for example). The problem then reduces to a 2-dimentional problem. A fibre reinforced polymer, or carbon fibre composite material is sensitive to moisture ingress from all sides, which implies a 3-dimensional problem. Where FMLs required additional protection (coating) for edges only, the composite structures require specific coating applied to the structure.

Example: T2 and Liberty ships

On 16 January 1943, 24 hours after being released from the shipyard, the T2 tanker S.S. Schenectady broke mid ships into 2 pieces in the docks near Portland, Oregon. This ship was the first ship of a new series built. Although hull fractures had occurred occasionally before, this failure occurred with a brand new ship while being in the docks.

The T2 tankers and Liberty ships where ships that were manufactured quickly, within about 5 days, to provide transport to the fleet at a higher rate than German submarines could destroy. Where in the years 1930-1937 about 71 merchants ships were built in the USA, 5777 ships were built between 1939 and 1945.

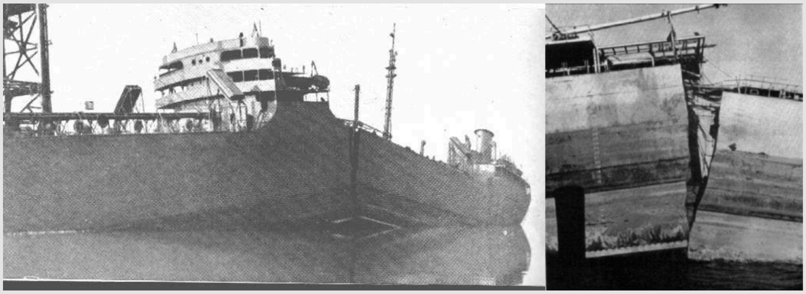

Figure 2.6

The T2 tanker S.S. Schenectady broke in 2 pieces on 16 January 1943, being 24 hours old (Derivative from US GPO, 1943, Public Domain)

Instead of riveting, welding was applied, which did not only increase the speed of production, but also enabled reduction of structural weight. Initially, the main reason was considered to be bad welding, but further investigation made clear that the steel used for construction appeared to be sensitive to low temperature. At certain temperature levels, the impact and fracture toughness exhibit a significant transition. The reduction in toughness relates to the transition from ductile fracture (evidence of high energy absorption) to brittle failure (low energy absorption prior to fracture). This phenomenon is illustrated in Figure 2.7.

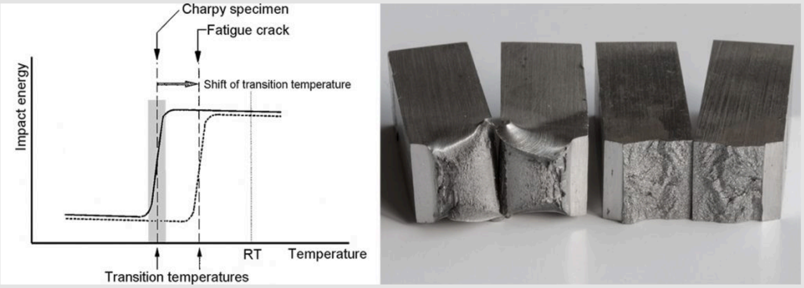

Figure 2.7
Illustration of the transition in impact energy (left) and the corresponding ductile and brittle fracture (right). Derivative from left: TU Delft, (n.d.), Own Work, and right: Broekhuis, (2018), Own Work.

2.4 Environmental aspects

The discussion in this chapter has been limited up until now to the effect of temperature and humidity. However, for both aeronautical and space structures various environments can be distinguished that each have their particular influence on the mechanical performance of a material or a structure.

The following typical environments may be identified:

- Air/moisture/salty environment

- Space and re-entry
- Fuel exposure
- Exposure to hydraulics
- Exposure to cleaning agents

2.4.1 Air, moisture and/or salty environment

Depending on the type of material, there can be different environments considered to be harmful or detrimental. In general, the detrimental processes due to aggressive environments are accelerated with increasing temperatures.

For most metal alloys the combination of moisture and salty environment forms the aggressive environment that may lead to corrosion. Corrosion is the electrochemical reaction that metallic atoms have with oxidants in the environment. This rate at which this process may occur depends on the environment. In a humid environment or water, corrosion occurs generally faster than in (dry) air. The oxidant may be for instance oxygen.

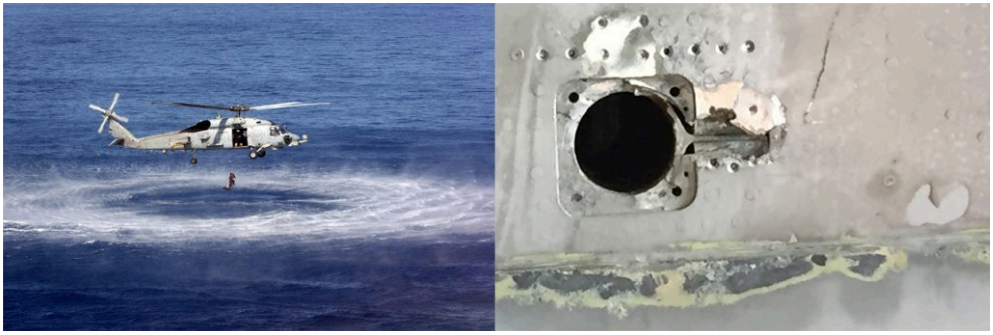

Figure 2.8
Illustration of a humid and salty environment (left) and the consequence of corrosion for an aluminium structure (right). Derivative from left: Skeeze, (2008), CC0, and right: Saunders-Smits, (2017), Own Work.)

For fibre reinforced composites usually the combination of humidity with higher temperatures forms the environment that may lead to material degradation or loss of structural properties. The earlier mentioned glass transition temperature may reduce to lower temperatures under the influence of moisture, with reduction in strength and stiffness at lower temperatures.

2.4.2 Space and re-entry

Space structures operate under different conditions as for example aircraft structures. To begin with, the temperature range under which most space structures operate is significantly larger than for aircraft structures, see Figure 2.1.

But aside from the temperature aspect, the environment and the relevant aspects to be considered are substantially different as well. Where in aircraft structures, environmental degradation may be attributed to moisture and oxygen in combination with temperature effects, typical environments and environmental aspects considered for space structures are;

- Radiation/UV exposure
- Free radicals, atomic Oxygen (O+)
- Vacuum (outgassing)

Ultraviolet (UV) light is electromagnetic radiation with a wavelength ranging between 10 nm and 400 nm (shorter than that of visible light). A lot of natural and synthetic polymers deteriorate under UV exposure. Here, fibres that are known to be sensitive to UV radiation are for example aramid fibres, like Kevlar.

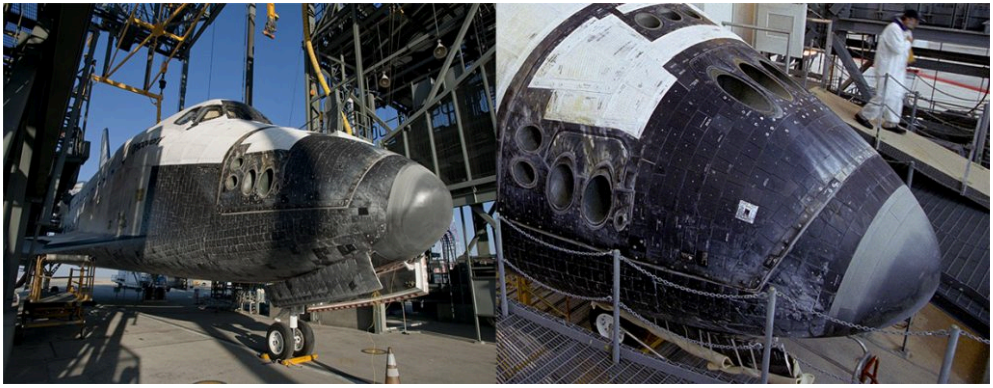

Figure 2.9
Illustration of surface of the Space shuttle (left) and the consequence of the aggressive environment on the structure's surface (right). Derivative from left: Landis – NASA, (2009) Public Domain, and right: Tschida – NASA (2005) , Public Domain.

In the outer atmosphere, free radicals, especially atomic oxygen, play an important role in the degradation of materials and structures. The amount of atomic oxygen relates to the altitude and the activity of the sun.
Different structural materials respond differently to the exposure to atomic oxygen. Aluminium for example erodes slowly under atomic oxygen exposure, while gold and platinum are highly resistant. A lot of polymers are known to be very sensitive and require the application of special coatings (for example silicon based coatings) and paints to protect the structure from atomic oxygen erosion.

Especially in vacuum, outgassing is an important topic of concern. Many materials, like for example polymers, composites, adhesives, are based on dissolvers, or contain substances that can evaporate from the material. But even metals may release gasses from cracks or impurities in the material.

In general, the consequence of degassing on the material or structure is that the mechanical properties of the material may deteriorate in time. Also the released gasses may condense on other cold surfaces causing trouble to the operation of certain components, for instance solar cells and telescope lenses.

Also here the temperature may have an acceleration effect; at higher temperatures, the chemical reaction rate with the material and the vapour pressure increase.

2.4.3 Exposure to fuel or hydraulics and cleaning agents

Other than air, moisture for aeronautical structures and the environments discussed in the previous section, environments should be considered that may cause degradation of structure and corrosion of materials. Especially for aircraft structures, several additional environmental aspects should be considered, of which some as listed below;

- Fuel
- Hydraulics
- Cleaning agents

In case of an integral fuel tank, see Figure 2.10, the fuel is kept inside the structure without use of additional fuel bags. All joints and structural connections are sealed air and liquid tight, to avoid leakage of the fuel.
This implies for that particular part of the structure, that the structural material is directly exposed to fuel. In order to avoid any degradation due to the fuel environment, one should then consider use of materials or coatings resistant to to this type of environment.

This is especially an aspect to consider for polymers and fibre reinforced composites. Here, the question will be whether the polymers applied in the structural material contains dissolvers that may react with the chemicals in the fuel.

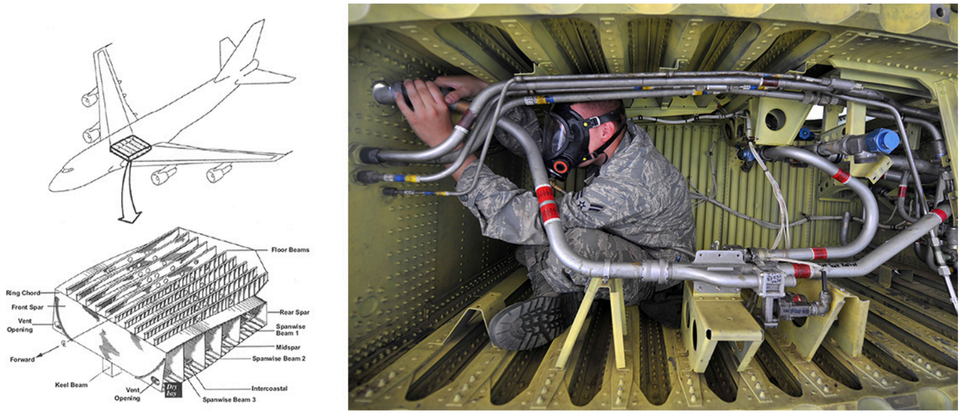

Figure 2.10
Illustration of integral fuel tanks, where the structure is directly exposed to kerosene fuel (left: NTSB, 2010, Public Domain; right: Britton – U.S. Airforce, 2010, Public Domain)

Another environmental aspect often not considered is related to operation and maintenance of structures. Often the selection of structural materials is thought of well, considering the environments and circumstances the structure will operate in with high probability.

However, for maintenance and operation one has to consider the materials applied in the structure. Use of cleaning agents to clean a dirty structure may impose structural degradation and impair the integrity of the structure, if the cleaning agents are based on a chemical composition that reacts with the structural material. One has to specify the cleaning agents or at least the chemical basis of such agents for particular structure. Here, the example given in Figure 2.11 (right) illustrates that the specification works both ways. It reads: “Do not use on glass or aluminium.” Manufacturers of cleaning agents define the restrictions to application of such cleaning agents.

In general, not only corrosion related to air and moisture, see section 2.4.1, should be considered in structural design, but also the deterioration due to other chemical environments. Here, one should consider that the general advantage claimed for carbon fibre composites is that this structural material does not corrode. However, depending on the epoxy system applied, it may deteriorate due to other environmental conditions, like for example UV exposure.

Figure 2.11
Photos of de-icing and cleaning procedures (extreme left: Brygg, 2009, CC-BY-2.0, middle left:Wollman – U.S.Navy, 2010, Public Domain) and an example of cleaning agent inappropriate for aluminium. (right, anon, n.d. Public Domain)

One type of corrosion should be added to the discussion here; galvanic corrosion. Galvanic corrosion is the electrochemical reaction process in which one metal may corrode due to electrical contact with another material or metal, while being in an environment that contains an electrolyte. This corrosion process forms the basis of batteries, where one metal corrodes to provide electrical current.
Especially in moisture rich environments, such contact between two materials may be easily made, which can cause corrosion of one of the metals involved. One example is given in Figure 2.13, where the aluminium rim corrodes in a wet, humid and potentially salty environment, due to the electrical connection with the chromium plated brass spoke.

It should be emphasized here however, that the contact does not necessarily be between two metals, it may also be between a metal and another material, of which the electric potential provides sufficient difference with the potential of the metal. For example, aluminium connected to carbon fibre reinforced composites, may lead to galvanic corrosion of the aluminium, due to the potential difference of these two structural materials. See for instance Figure 2.12, where the brass nipple of the spoke reacts with the aluminium rim.

The method to counteract galvanic corrosion is to isolate the different materials, avoiding the electrical connectivity, or to assure that the materials are not immersed in a solution containing an electrolyte.

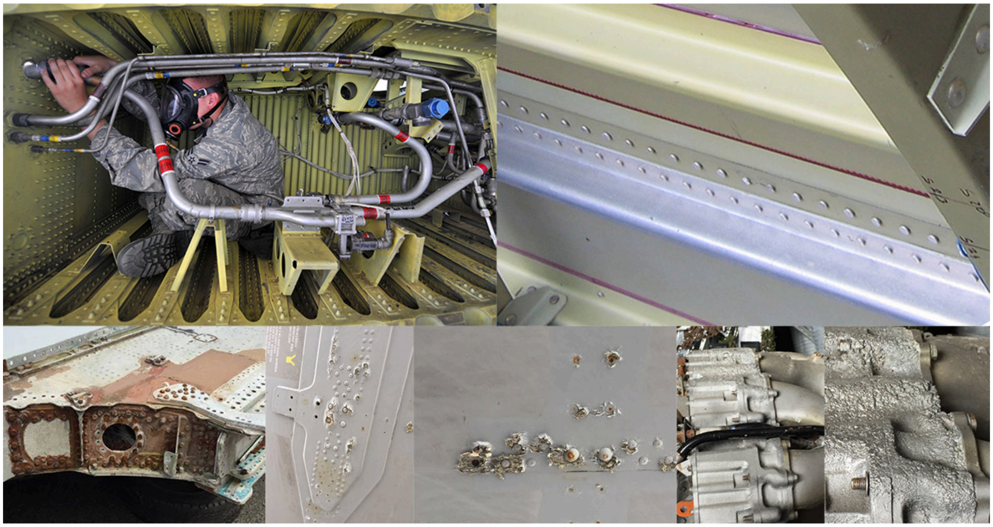

Figure 2.12
Examples of brand new virgin structures (upper row, left:Britton-U.S.Airforce, 2010, Public Domain, right TU Delft, n.d. Own Work.) and structures after decades of operational use (lower row: Saunders-Smits, 2017. Own Work.)

Figure 2.13
Example of galvanic corrosion on a bike in a corrosive (wet/humid/salty) environment (Hans, 2012, CC0); galvanic corrosion between chromium plated brass spoke nipple and aluminium rim (Open University, 2004, Copyright Open University)

Sometimes, the process is exploited as solution to counteract corrosion. Here, the example of placing zinc sacrifice material to steel (marine) structures could be mentioned. Since the zinc is less noble than steel, it will corrode first under a corrosive attack, protecting thereby the steel structure.

Introduction to Aerospace Structures and Materials

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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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