

Chapter 2

External Loads

2.1 Introduction

In the previous chapter, it has been indicated that a large number of load types exist. The most important load types are shown in Fig. 1.2. Each of these load types can originate from a number of specific sources, but the resulting generic load is unique for a certain load type, as is depicted in Fig. 2.1. For example, a mechanical load will always yield a force or a moment (generic load), but the specific source of that force can be diverse: centrifugal load caused by a rotation, gravity, torque provided by a drive shaft or thermal expansion.

In this chapter, the different external load types are discussed and the possible sources are indicated. Using practical examples, it is shown for each source how the loads can be calculated.

2.2 Mechanical Loads

The mechanical loading of a structure is caused by forces. That can be either forces that act directly on a structure, like a concentrated or distributed force or a moment, or forces caused by an indirect load like pressure or weight.

A *concentrated force* is a force that acts on a single point, while a *distributed force* is exerted on a certain area or volume. A towing line connected to a car, for example, exerts a concentrated force on the towing ring, whereas a book resting on a table exerts a distributed force on the table due to its weight. A *moment* is caused by a force that is acting on a line not passing through the centre of gravity or rotation point of a body. The magnitude of the moment (M) is determined by the product of the force and the perpendicular distance between the working line and the line through the rotation point (moment arm).

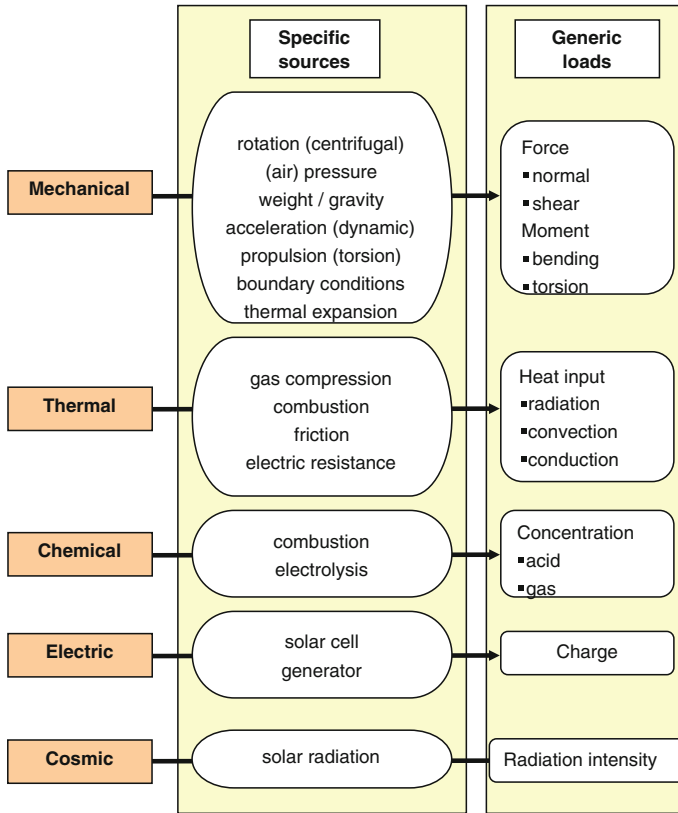


Fig. 2.1 Overview of load types, associated specific sources and resulting generic loads

Instead of acting directly on a body, forces can also originate from indirect loads, for example, caused by

- environment → (air) pressure
- weight → gravity
- accelerations → mass force
- drive/propulsion/guidance
- thermal expansion
- internal stress

In the next subsections, these sources will be discussed, and they will be illustrated using explicit examples.

A complete structure is generally loaded by a considerable set of concentrated and distributed forces, each acting at different locations. The combination of all these forces determines the total mechanical loading of the structure. As a result, one specific point in the structure can be loaded in tension or compression, bending or torsion. The translation of all the combined external forces into the local force at

a specific point is covered by the theory of statics. The basic principles of this theory will be treated in [Sect. 2.2.7](#).

2.2.1 Environment and Pressure

It is very common in practice that a body experiences a load from its environment. In most cases, this concerns a pressure load on a body residing in a gas or liquid environment. Examples are the loading of a pressure vessel by the large internal gas pressure or the buoyancy force exerted on the hull of a ship. Also, the loads on an aircraft wing by lift and drag are examples of this type of load.

A pressure load delivers a distributed load f (N/m²) acting on (part of) the surface of a body. The total exerted force F (N) can be calculated by integrating the distributed force over the surface area A (m²)

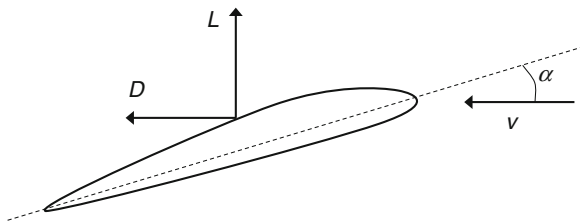
$$F = \int_A f dA \quad (2.1)$$

Example 2.1 (Pressure Loads on an Aircraft Wing) During flight, the loading of an aircraft wing is determined by the pressure loads on the wing and the weight distribution of the plane. Figure 2.2 shows an aircraft wing profile in an airflow with speed v and an angle of attack α . The flowing air causes two forces on the wing: the lift force L perpendicular to the airflow and the drag D in the direction of v . The magnitudes of L and D depend on the speed v and the angle α .

The basic lift distribution $l(y)$ across the span B of the wing is shown schematically in Fig. 2.3. It is assumed here that this distribution is known. The actual lift distribution at specified flight conditions (aircraft weight, flight altitude, air speed, etc.) is obtained by multiplying the basic lift distribution $l(y)$ with the intensity factor A . In case of a stationary flight condition, the magnitude of A can be determined from the balance between aircraft weight W and the total lift L_w of the wings:

$$W = L_w = A \int_{-B/2}^{+B/2} l(y) dy \quad (2.2)$$

Fig. 2.2 Lift and drag forces acting on an aircraft wing



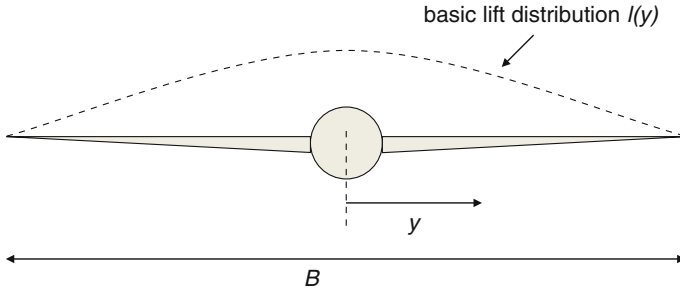


Fig. 2.3 Basic lift distribution across the span of the wings

In Fig. 2.4, a simplified basic lift distribution for an aeroplane is given. The mass of the plane, including fuel and payload, is $m = 45,200$ kg. The following values are assumed for the widths b_i of the sections: $b_1 = 1$ m; $b_2 = 7$ m; $b_3 = 3$ m; $b_4 = 2$ m, and for the corresponding basic lift forces: $l_1 = 0.3$ N/m; $l_2 = 1.0$ N/m; $l_3 = 0.7$ N/m; $l_4 = 0.4$ N/m. Using the gravity constant $g = 9.81$ m/s², the intensity factor A can be calculated from (2.2). This yields the value $A = 21,714$.

Since the mass of the aircraft is concentrated at the fuselage, the downward force (gravity) acts on that centre part of the plane. On the other hand, the upward force caused by the lift distribution acts on the wings of the aircraft. This difference in acting points results in bending of the wings, causing relatively high (bending) loads at the wing root.

In reality, the plane will not constantly be in a stationary situation with an exact balance between lift and weight. Due to air turbulence and gust, the lift distribution will change frequently (e.g. due to a change in entry angle α , Fig. 2.2), yielding an imbalance between the two forces and a resulting up- or downwards motion of the plane.

2.2.2 Weight

The weight of a structure generally causes a distributed load that depends on the mass distribution. The gravity force W is proportional to the mass of each volume element, with the gravity constant $g = 9.81$ m/s² as the proportionality constant,

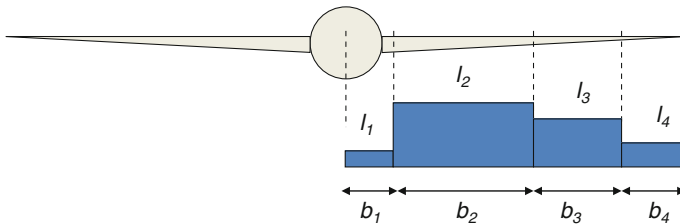


Fig. 2.4 Block wise basic lift distribution across the span of one wing

and acts on the centre of gravity of the element. The total gravity force, or weight, is obtained by integrating the distributed load over the complete volume

$$W = \int_V g \, dm \quad (2.3)$$

Example 2.2 (Gravity Loading of an Aircraft Wing) The wing of the aircraft from the previous example is not only loaded by the upward lift forces, but also by the downward gravity loading on the wings. This means that both the lift distribution and mass distribution across the span of the wing play a role. In this example, the mass distribution shown in Fig. 2.5 will be assumed.

The given mass distribution $m(y)$ (kg/m) is multiplied by the gravity constant g (m/s^2) to obtain the weight distribution $W(y)$ (N/m)

$$W(y) = m(y)g \quad (2.4)$$

Using values of $c_1 = 9$ m; $c_2 = 4$ m; $\xi_1 = 500$ kg/m; $\xi_2 = 150$ kg/m, the total gravity force or weight for one wing is obtained through

$$W = \sum_i m_i g = \sum_i c_i \xi_i g = 50 \text{ kN} \quad (2.5)$$

2.2.3 Acceleration

In Sect. 2.2.1, it was mentioned that gust loads cause an aircraft to move up- and downwards. According to Newton's law,

$$F = ma \quad (2.6)$$

the associated accelerations yield additional mass forces. A similar phenomenon is present in rotating machinery, in which rotating parts are subject to centripetal accelerations. To keep the parts in their rotating motion, the resulting centrifugal force (acting in an outward radial direction) must be balanced by an inward

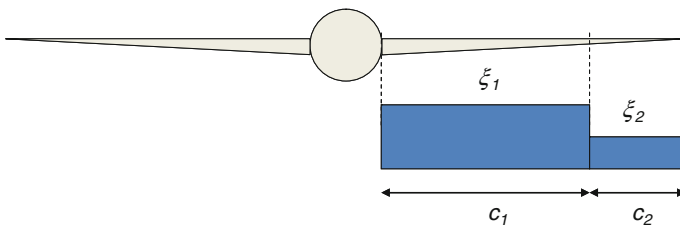


Fig. 2.5 Mass distribution across the span of the wing

centripetal force. The centrifugal force acting on a mass m rotating with an angular velocity ω (rad/s) in a circular motion with radius r is given by

$$F_{cf} = m\omega^2 r \quad (2.7)$$

Both these forces caused by different types of accelerations will be illustrated in the next two examples. In Example 2.5 in the next subsection, another case of mass forces is illustrated.

A final remark on this topic concerns the principle of balancing. In many rotating and reciprocating machines, the loads on the parts are reduced considerably by balancing the forces acting on these parts by equal (but oppositely directed) forces. During operation, defects in the machine can cause (partial) distortion of this balance, which may lead to loads that are considerably higher than the expected loads.

Example 2.3 (Mass Forces on an Aircraft Wing) In a stationary flight, the lift and gravity forces are in balance, that is, $L_0 = mg = W$. The ratio n of lift force over gravity force therefore equals 1. During a gust (e.g. a vertical upward wind blast), the lift is temporarily increased, resulting in a n -value greater than 1 and an upward movement of the aircraft. This means that the additional lift $\Delta L = L_0 \Delta n$ yields a vertical acceleration of the plane equal to

$$\ddot{z} = \frac{L_0 \Delta n}{m} = \frac{mg \Delta n}{m} = g \Delta n \quad (2.8)$$

Due to this acceleration, additional forces are acting on the wings with a magnitude of

$$F(y) = m(y)\ddot{z} = m(y)g \Delta n \quad (2.9)$$

Example 2.4 (Centrifugal Force on a Gas Turbine Blade) Figure 2.6 schematically shows the shaft of a gas turbine, to which a blade is attached. For a rotating element with mass dm located at a distance r from the centre of the axis, which is moving at a rotational speed ω , the centripetal acceleration is $\omega^2 r$. This acceleration yields a centrifugal force dF_{cf} on the element equal to

$$dF_{cf} = \omega^2 r dm \quad (2.10)$$

Assuming that the cross-sectional area A of the blade is constant across its length and that the mass density of the material is ρ , the mass of the element is

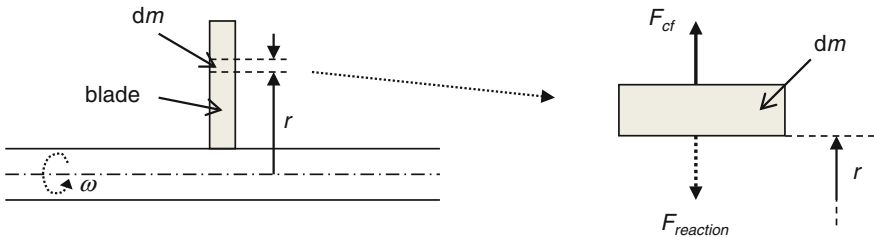


Fig. 2.6 Loading of a turbine blade by the centrifugal force

$dm = \rho A dr$. Therefore, the increase of the centrifugal force within the element is

$$dF_{cf} = \rho A \omega^2 r dr \quad (2.11)$$

The total centrifugal force at any radius is then obtained by integrating this expression to r and using the boundary condition that the centrifugal force is zero at the blade tip, that is, $F_{cf}(r = R_1) = 0$:

$$F_{cf} = \frac{1}{2} \rho A \omega^2 (R_1^2 - r^2) \quad (2.12)$$

The centrifugal force thus decreases quadratically with r and has a maximum value at the root of the blade ($r = R_0$).

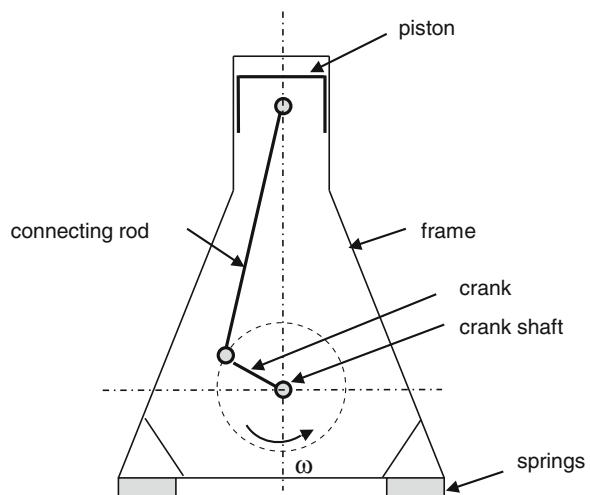
2.2.4 Drive/Propulsion/Guidance

In many machines, subsystems are driven by motors, where forces and moments are transferred with the purpose of getting or keeping parts of the subsystem in motion. On the other hand, the integrity of the system must be preserved, which means that at other parts of the machine motions must be prevented. Examples of components providing this restriction are bearings and movement limiters. In all these cases, mechanical loads are exerted on the different parts.

In the examples below, the loading of a piston engine crankshaft is discussed, as well as the support of the shaft by journal bearings. In the second example, the loads on the elements of a roller bearing are treated.

Example 2.5 (Piston Engine Crankshaft) Figure 2.7 schematically shows a cross section of one cylinder of a piston engine. The piston performs an oscillating

Fig. 2.7 One-cylinder piston engine



motion that is transferred by the connecting rod and the crank, resulting in a rotation of the crankshaft.

The loads acting in the machine are the gas pressure in the cylinder, the mass forces of the moving piston and connecting rod and the centrifugal forces on the rotating parts.

Gas Forces

The gas force F_{gas} acting on the piston is transferred through the piston pin to the connecting rod, while the frictionless cylinder wall exerts a (reaction) force F_{wall} on the side of the piston, see Fig. 2.8. As all forces acting on the piston must be in balance, it follows that

$$F_{\text{wall}} = F_{\text{gas}} \tan \beta \quad (2.13)$$

The forces F_{gas} and F_{wall} are transferred to the crankshaft and firstly yield the loads on the main bearing, which ensures the proper positioning of the crankshaft, and secondly the torque T_{gas} on the shaft. The forces on the bearing exactly equal the forces on the piston (force equilibrium, see Fig. 2.8a), and the torque is given by

$$T_{\text{gas}} = F_{\text{wall}} s \quad (2.14)$$

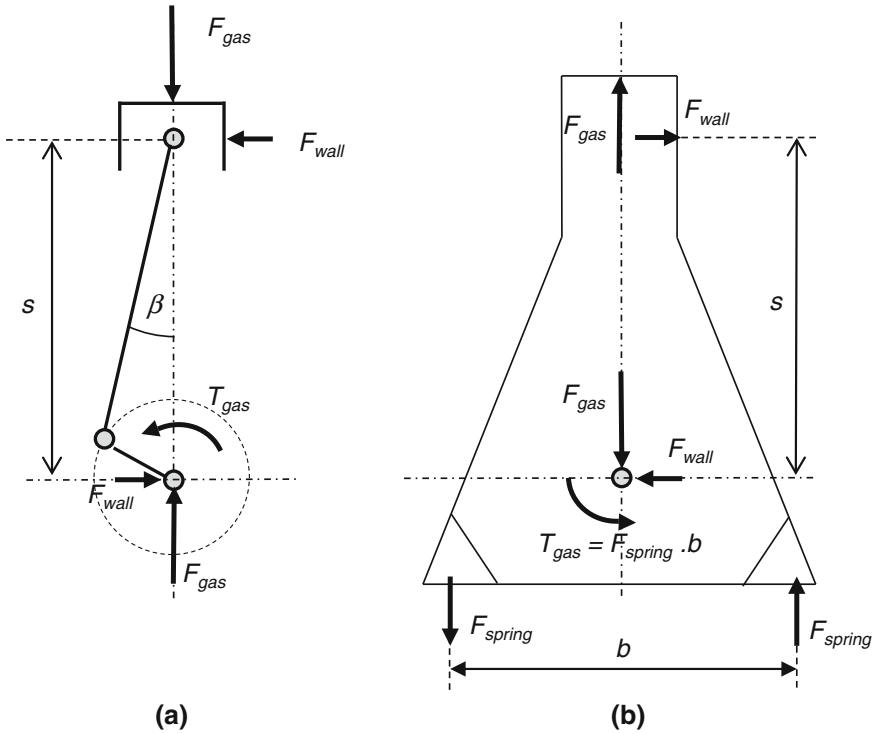


Fig. 2.8 Overview of loads on **a** driving mechanism and **b** frame

where s is the distance between the centre of the crankshaft and the piston pin. Note that the vertical forces (gas force and its reaction) are exactly on the line through the centre of the crankshaft, which means that no moments or torques are initiated by these forces.

To ensure structural integrity, all forces and moments on the driving mechanism (Fig. 2.8a) must be counterbalanced by forces on the frame of the engine. Figure 2.8b shows that force equilibrium can be attained within the frame, but the torque T_{gas} is transferred to the foundation of the engine by the springs.

Mass Forces

The motion of the driving mechanism is governed by an oscillating (vertical) movement of the piston and a rotating motion of the crankshaft. These motions also occur at the ends of the connecting rod. To be able to calculate the mass forces on the rod, the mass of this body is split into two separate mass points positioned at the piston pin and the crank pin, respectively. The total oscillating mass then equals the mass of the piston plus the *oscillating* mass of the connecting rod. The total rotating mass consists of the mass of the crank and the *rotating* mass of the connecting rod.

Oscillating Mass Force

Calculation of the oscillating mass force requires the acceleration of the piston to be known, which is calculated next (Fig. 2.9).

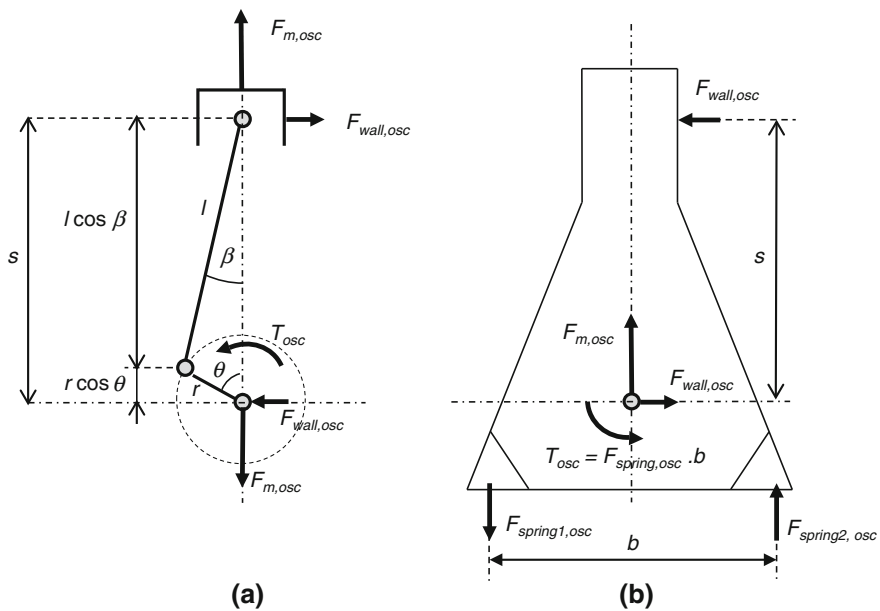


Fig. 2.9 Oscillating mass force acting on **a** the driving mechanism and **b** the frame

The position of the piston is given by the coordinate s defined as

$$s = r \cos \theta + l \cos \beta \quad (2.15)$$

Using $r \sin \theta = l \sin \beta$, $\cos \beta = \sqrt{1 - \sin^2 \beta}$ and $\lambda = \frac{r}{l}$, Eq. (2.15) yields

$$s = l \left(\lambda \cos \theta + \sqrt{1 - \lambda^2 \sin^2 \theta} \right) \quad (2.16)$$

Then, the time derivative of s is

$$\dot{s} = l \left(-\lambda \sin \theta - \frac{\lambda^2}{2} \frac{\sin 2\theta}{\sqrt{1 - \lambda^2 \sin^2 \theta}} \right) \dot{\theta} \quad (2.17)$$

And assuming a uniform motion, $\dot{\theta} = \text{constant} = \omega$, the acceleration (2nd time derivative of s) is given by

$$\ddot{s} = l \left[-\lambda \cos \theta - \frac{\lambda^2}{2} \left(\frac{2 \cos 2\theta}{\sqrt{1 - \lambda^2 \sin^2 \theta}} \right) + \frac{\lambda^2}{2} \frac{\sin^2 2\theta}{(1 - \lambda^2 \sin^2 \theta)^{3/2}} \right] \omega^2 \quad (2.18)$$

By neglecting the terms with λ^2 (since $\lambda^2 \ll 1$), the oscillating mass force can be approximated as

$$F_{m,\text{osc}} = m_{\text{osc}} \omega^2 r (\cos \theta + \lambda \cos 2\theta) = m_{\text{osc}} \omega^2 r (\cos(\omega t) + \lambda \cos(2\omega t)) \quad (2.19)$$

This mass force contains two harmonics that vary with the single and double rotational speed. The oscillating mass force is transferred to the main bearing in the same way as the gas force and also contributes to the torque

$$T_{\text{osc}} = F_{\text{wall, osc}} s \quad (2.20)$$

where

$$F_{\text{wall, osc}} = F_{m,\text{osc}} \tan \beta \quad (2.21)$$

A closer look at the loads on the frame due to the gas force and mass force, respectively, yields some remarkable observations (see Fig. 2.8). For the gas force, equilibrium exists between the forces (F_{gas}) on the cylinder head and on the main bearing. For the frame, also a force equilibrium exists, while the torque is transferred to the mounts of the frame. For the oscillating mass force, both the forces and the torque are transferred to the mounts.

Rotating Mass Force

The rotation of the mass m_{rot} yields a centrifugal force consisting of a horizontal and vertical component:

$$F_{\text{mrot}, h} = m_{\text{rot}} \omega^2 r \sin \theta \quad (2.22)$$

$$F_{\text{mrot},v} = m_{\text{rot}}\omega^2 r \cos \theta \quad (2.23)$$

The rotating mass force is also transferred to the mounts by the springs, see Fig. 2.10.

Summary of Loads

The total loading of one single cylinder of a piston engine thus consists of the following contributions:

- The crank shaft is loaded by a torque, given by

$$T = T_{\text{gas}} - T_{\text{osc}} \quad (2.24)$$

As a reaction force, this torque is also acting on the frame to provide the moment equilibrium.

- The main bearing is loaded by a combination of forces, where the horizontal and vertical components are given by

$$F_h = F_{\text{wall}} - F_{\text{wall,osc}} + F_{\text{rot},h} \quad (2.25)$$

$$F_v = F_{\text{gas}} - F_{m,\text{osc}} - F_{\text{rot},v} \quad (2.26)$$

- On the frame, the unbalanced mass forces are acting

$$F_h = -F_{\text{wall,osc}} + F_{\text{rot},h} \quad (2.27)$$

$$F_v = F_{\text{gas}} - F_{m,\text{osc}} - F_{\text{rot},v} \quad (2.28)$$

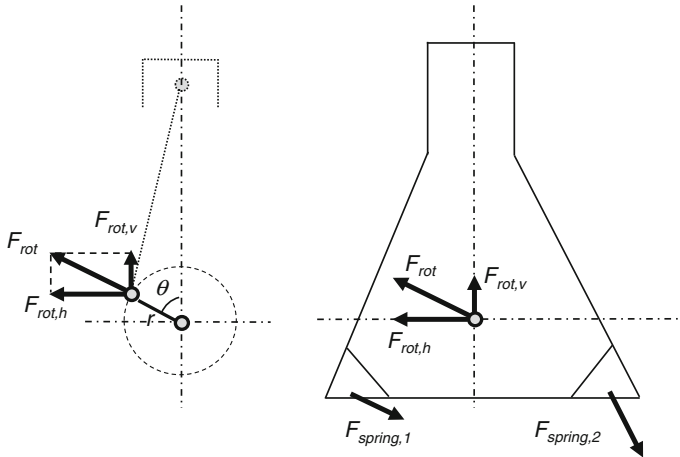


Fig. 2.10 Rotating mass force acting on the driving mechanism (*left*) and the frame (*right*)

Inline Piston Engine

An n -cylinder inline engine can be considered as a series of n connected single cylinder engines. To reduce the variations in torque applied to the crankshaft, the fuel in the separate cylinders is ignited equidistant in time. This is accomplished by varying the crank angles, as is shown for a three-cylinder engine in Fig. 2.11. The mass forces of the three cylinders and the corresponding moments around y - and x -axes are partly in balance. This will be illustrated next for the centrifugal forces.

Figure 2.12 shows the rotating mass forces of the three cylinders. Vectorial summation of these forces shows that the resultant force is zero, that is, the mass forces are balanced. The moment of these forces relative to the y - z plane (see also Fig. 2.11a) equals

$$M_{\text{rot},i} = F_{\text{rot},i}a \quad (2.29)$$

The direction of these moments in the y - z -plane is shown in Fig. 2.12b. The vectorial sum of the moments is

$$M_{\text{rot,tot}} = F_{\text{rot}}a\sqrt{3} \quad (2.30)$$

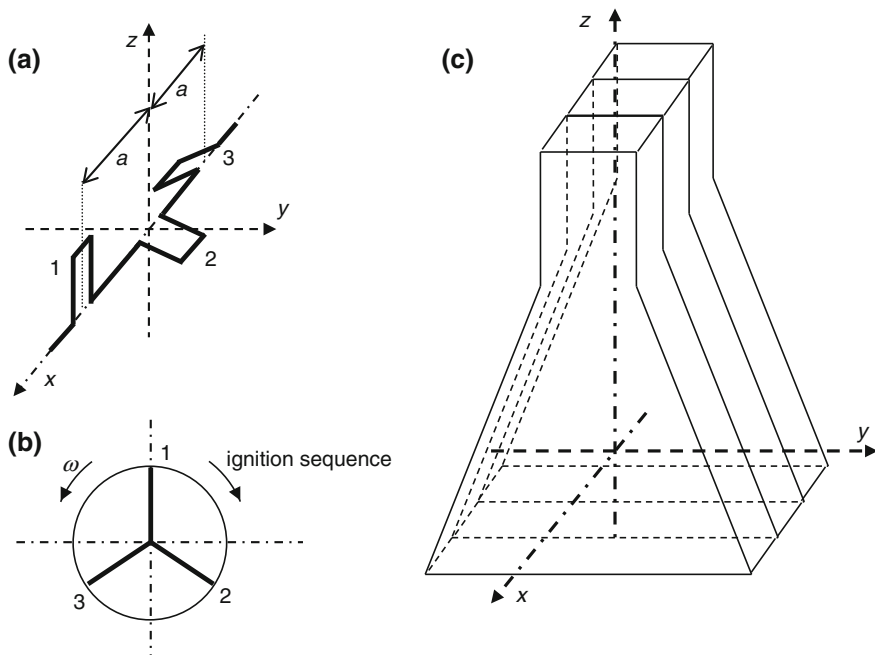


Fig. 2.11 Three-cylinder engine. **a** Crankshaft. **b** Diagram showing the ignition times of the separate cylinders. **c** The frame

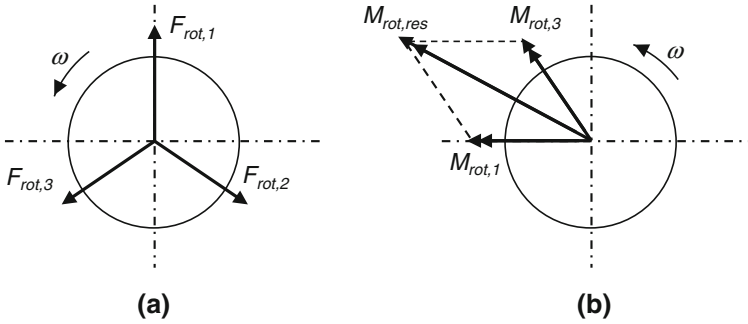


Fig. 2.12 Rotating mass forces **a** and torques **b** on the crankshaft, projected to the y - z plane

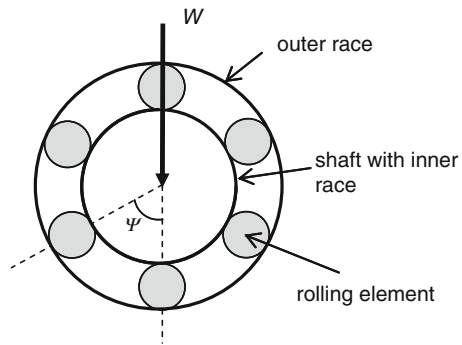
where $F_{rot} = F_{rot, i}$. This rotating moment is transferred through the frame to the mounts and causes vibrations in the supporting structures. To prevent this undesirable dynamic load, generally counter-masses are placed on the cranks of all cylinders. The mass forces generated by these masses eliminate the respective rotating forces and thus reduce the loading of the crank shaft. An alternative approach is the application of counter weights at the ends of the crankshaft that eliminate the rotating moment.

Example 2.6 (Ball Bearing) Figure 2.13 schematically shows a ball bearing, for which the shaft and inner race are loaded by a force W . This load is transferred to the outer race by the rolling elements.

The distribution of the load W over the different rolling elements will be derived using Fig. 2.14. Due to the elasticity of the bearing, the centre of the axis will undergo a small displacement δ , see Fig. 2.14a.

The displacement of the axis results in a distribution of the force W over the elements in the lower half of the bearing (Fig. 2.14b). For a displacement δ of the axis, the deformation of the lower rolling element is $\delta_0 = \delta$. For the other

Fig. 2.13 Schematic representation of a ball bearing



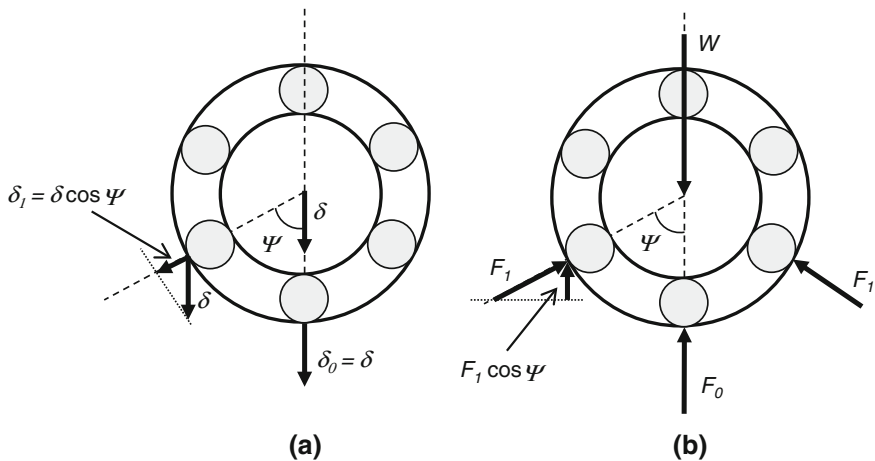


Fig. 2.14 Elastic deformation of a ball bearing; elastic displacements (*left*) and distribution of loads (*right*)

elements, the deformation is $\delta_1 = \delta_0 \cos \psi$. Assume that the rolling elements can be considered as a nonlinear springs with the following relation between force and displacement

$$F = c\delta^{1.1} \quad (2.31)$$

Then, the force on the lower rolling element is

$$F_0 = c(\delta_0)^{1.1} = c\delta^{1.1} \quad (2.32)$$

and on the other elements

$$F_1 = c(\delta_1)^{1.1} = c(\delta \cos \psi)^{1.1} \quad (2.33)$$

From the vertical force equilibrium, it follows that

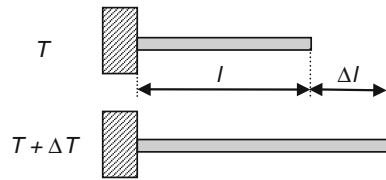
$$W = F_0 + 2F_1 \cos \psi = F_0 \left(1 + 2(\cos \psi)^{2.1} \right) \quad (2.34)$$

In this example, the angle ψ between the elements is 60° , which means that $F_0 = 0.682 W$ and $F_1 = 0.318 W$.

2.2.5 Thermal Expansion

In many cases, the thermal expansion of structures or parts yields mechanical loads in the structure. So although the origin of the load is thermal, that is, a heating or cooling process that causes a rise or drop in temperature, the nature of resulting forces is mechanical.

Fig. 2.15 Thermal expansion of an unrestrained bar



An increase in temperature of a certain material generally yields a thermal expansion of the body. The magnitude of the thermal expansion for an unrestrained body with original length l subjected to a temperature increase ΔT equals (Fig. 2.15)

$$\Delta l = \alpha \Delta T l \quad (2.35)$$

where α is the coefficient of thermal expansion, which is a material property. As the unrestrained bar in Fig. 2.15 can expand freely, no mechanical loads will be generated. That will be the case when the expansion is prohibited, for example, when the bar would be fixed in between two other parts. The generation and calculation of thermal stresses will be discussed in the next chapter.

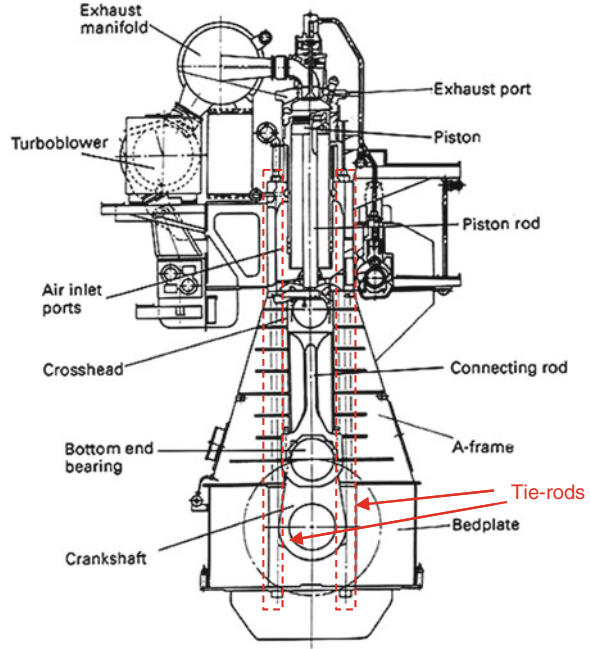
2.2.6 Internal Stress

Another common type of mechanical load is due to internal stresses that are already present in a structure. Examples of this type of load are deliberately applied pre-stresses and undesirable residual stresses due to plastic deformation. The origin of the latter type of internal stresses will be discussed in Sect. 3.2.6. The purpose of deliberately applied pre-stresses is to prevent that certain parts are overloaded or not loaded at all. The pre-stresses are applied during assembly of the system by the use of an external force. A well-known example is a bolt that is pre-stressed to avoid that it releases during use at high temperature due to thermal expansion. Another example concerns the tie-rods in a diesel engine, as will be shown in Example 2.7.

Example 2.7 (Tie-rods in a Diesel Engine) In diesel engines, as well as in other piston engines, very high pressures occur in the cylinders during combustion. In the 1970s, peak pressures were in the order of 100 bar, but in modern engines the values have increased to around 180 bar. These high pressures tend to lift the cylinder head. To avoid cylinder leakage, the head is attached to the frame of the engine with tie-rods (see Fig. 2.16), in which a considerable pre-stress is introduced. The loading of these tie-rods and the required pre-stress are discussed in this example. As the pressure in the cylinder increases during the compression phase of the cycle and reaches a maximum value during combustion, the loading of the tie-rods is a dynamic load (that varies in time).

To avoid cylinder leakage, a pre-stressing force F_v is applied to the tie-rods. The associated reaction force is a compressive force F_v on the cylinder liner. When

Fig. 2.16 Tie-rods attach the cylinder head to the frame of a diesel engine



the stiffness of the tie-rod and cylinder liner is k_{tr} and k_{cl} , respectively, then the force in the tie-rod for a certain elongation u_{tr} equals

$$F_{tr} = k_{tr}u_{tr} = \frac{EA}{l}u_{tr} \quad (2.36)$$

where the stiffness is expressed in terms of the elastic modulus E , cross-sectional area A and length l of the tie-rod. In the liner, the compressive force equals

$$F_{cl} = k_{cl}u_{cl} \quad (2.37)$$

where u_{cl} is the elongation of the liner.

As the forces in the tie-rod and the liner both equal the pre-stressing force F_v , the elongations can be expressed as

$$u_{tr} = \frac{F_v}{k_{tr}} \quad \text{and} \quad u_{cl} = -\frac{F_v}{k_{cl}} \quad (2.38)$$

In Fig. 2.17, the application of the pre-stressing force is visualized. The force–displacement curve for the liner has been copied and translated to the right-hand side of the figure, as will be explained later.

Due to the loading by a gas force F_{gas} , the cylinder head is lifted over a small distance Δu (Fig. 2.18). As a result, both the tie-rod and the cylinder liner are subject to an elongation Δu that causes additional forces in both parts equal to

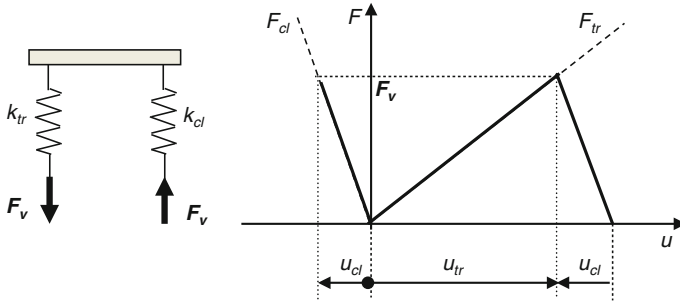


Fig. 2.17 Pre-stress in a cylinder head and the associated stiffness diagram

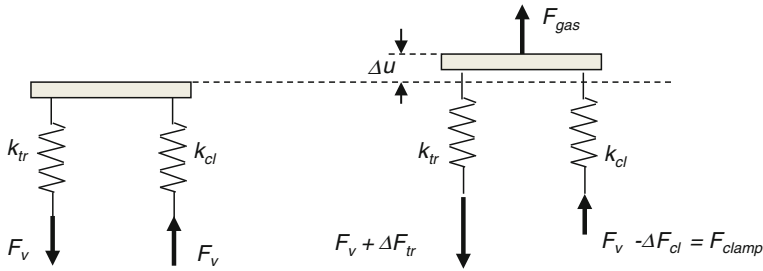


Fig. 2.18 Pre-stressed cylinder head and the loading due to the gas force

$$\Delta F_{tr} = k_{tr} \Delta u \quad (2.39)$$

$$\Delta F_{cl} = k_{cl} \Delta u \quad (2.40)$$

These forces must be in equilibrium with the gas force F_{gas}

$$F_{gas} = \Delta F_{tr} + \Delta F_{cl} \quad (2.41)$$

From these equations, it follows that

$$\Delta F_{tr} = \frac{k_{tr}}{k_{cl}} \Delta F_{cl} \quad ; \quad \Delta F_{cl} = \frac{k_{cl}}{k_{tr}} \Delta F_{tr} \quad (2.42)$$

$$\Delta F_{cl} = \frac{k_{cl}}{k_{tr} + k_{cl}} F_{gas} \quad ; \quad \Delta F_{tr} = \frac{k_{tr}}{k_{tr} + k_{cl}} F_{gas} \quad (2.43)$$

which means that the clamping force F_{clamp} is given by

$$F_{clamp} = F_v - \Delta F_{cl} = F_v - \frac{k_{cl}}{k_{tr} + k_{cl}} F_{gas} \quad (2.44)$$

and the total loading of the tie-rod is

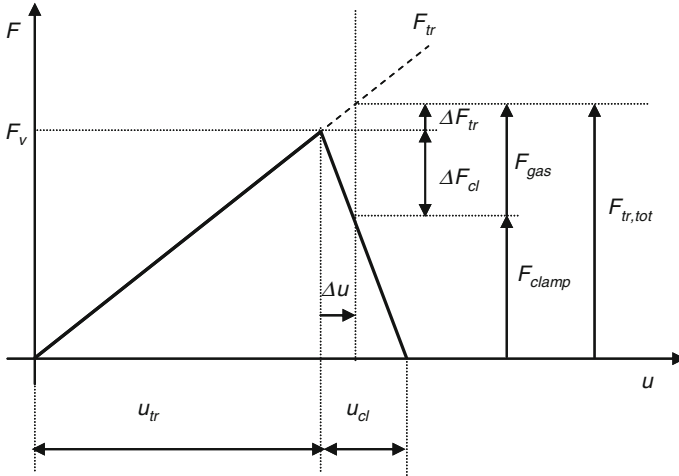


Fig. 2.19 Stiffness diagram of a pre-stressed cylinder head

$$F_{tr,tot} = F_v + \Delta F_{tr} = F_v + \frac{k_{tr}}{k_{tr} + k_{cl}} F_{gas} = F_{clamp} + F_{gas} \quad (2.45)$$

The Eqs. (2.42) to (2.45) are visualized in the stiffness diagram in Fig. 2.19. This diagram shows that the load on the tie-rods can be reduced by choosing a low stiffness (i.e. using rods with a large length); especially the dynamic part of the load, ΔF_{tr} , is reduced considerably in a flexible tie-rod, which is particularly important to avoid fatigue failures. To prevent the lifting of the cylinder head, the clamping force F_{clamp} should always have a positive value ($F_{clamp} > 0$), which requires a large pre-stressing force F_v . The magnitude of this force largely determines the cross section of the tie-rods in a specific engine.

2.2.7 Internal Forces

Generally a complete structure is loaded by a number of concentrated and distributed forces acting on different locations. The combined action of all these forces eventually determines the total mechanical load on the system or structure. As a result, a certain location in the structure can be loaded in tension or compression, in bending or in torsion. The translation of the set of individual forces into their combined action is governed by the laws of *statics*. In simple one- or two-dimensional structures (e.g. beams, trusses), the resulting normal force, transverse force and bending moment on certain cross sections of the structure can be calculated rather easily. For more complex, three-dimensional structures generally numerical analyses like finite element analysis (FEA) are applied.

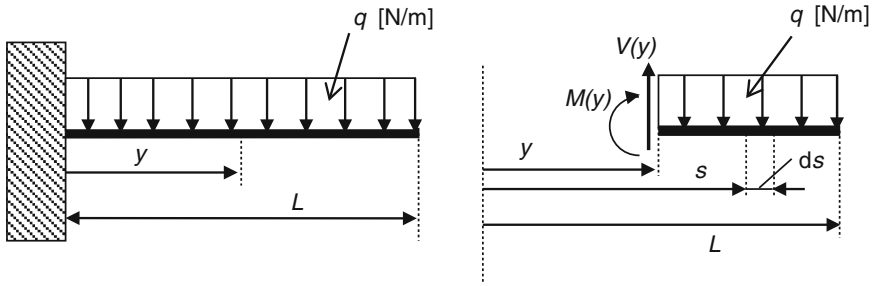


Fig. 2.20 Calculation of the internal forces in a one side fixed beam

Transverse Force and Bending Moment

When a load is applied in a direction perpendicular to the structure, a certain distribution of the transverse force V and bending moment M will exist in the body. This will be illustrated using the simple example of a beam that is fixed on one side and loaded by a uniformly distributed load q normal to the beam, see Fig. 2.20.

To calculate the internal forces, a fictitious section is made at a distance y from the fixation. The effect of the removed part of the beam is represented by a transverse force $V(y)$ and a bending moment $M(y)$ at the section plane. Since for the remaining part of the beam the forces and moments must be in equilibrium, the magnitudes of $V(y)$ and $M(y)$ can be calculated. The transverse force balances the resultant of the distributed load q

$$V(y) = \int_y^L q \, ds \quad (2.46)$$

and the bending moment should be in equilibrium with the total moment generated by the distributed load

$$M(y) = - \int_y^L (s - y) q \, ds \quad (2.47)$$

The calculation of internal forces and moments in more realistic components and structures is illustrated further in two examples: an aircraft wing and a gas turbine rotor blade.

Example 2.8 (Internal Forces in an Aircraft Wing) During stationary flight conditions, the distributed load $q_0(y)$ on an aircraft wing is a combination of (upward) lift forces and (downward) gravity forces

$$q_0(y) = -A l(y) + m(y)g \quad (2.48)$$

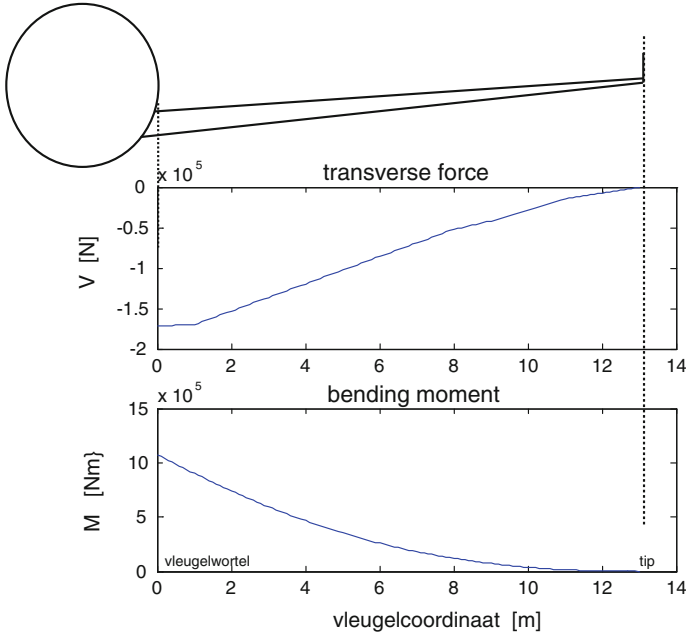


Fig. 2.21 Variations of transverse force and bending moment across the wing

Assume that the lift force and mass distribution are given by the block wise distributions in Figs. 2.4 and 2.5 and $A = 21,714$. Using Eqs. (2.46) and (2.47), the variations of the transverse force and bending moment across the wing can be calculated. The result is shown in Fig. 2.21.

Example 2.9 (Normal Force in a Gas Turbine Rotor Blade) The centrifugal force acting on a rotating gas turbine blade (see Sect. 2.2.3) yields a tensile force in the blade. This load is the normal force N , which is directed normal to the blade cross section.

A centrifugal force equal to $\omega^2 r dm$ acts on the element with height dr and mass dm (see Fig. 2.22). This force must be balanced by the increase of the normal force dN across the height dr . When the cross-sectional area of the blade equals A along the whole length of the blade and the mass density is ρ , then

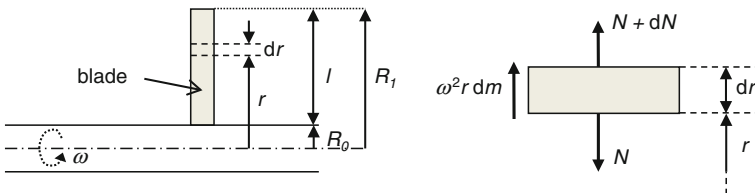


Fig. 2.22 Internal normal force in a rotating turbine blade

$$dm = \rho A dr \quad (2.49)$$

and

$$dN = -\rho A dr \omega^2 r \quad (2.50)$$

Integrating this expression to the radius r with the boundary condition $N(r = R_1) = 0$ (i.e. the normal force reduces to zero at the tip of the blade) yields

$$N(r) = \frac{1}{2} \rho A \omega^2 (R_1^2 - r^2) \quad (2.51)$$

The normal force $N(r)$ thus varies parabolically with r and attains its maximum value at the blade root ($r = R_0$).

2.3 Thermal Loads

Thermal loads on a system are caused by internal or external heat generation, resulting in an increase or decrease in the temperature. The externally generated heat can enter the body by convection or radiation. Combined with the internally generated heat, it is then distributed over the body by conduction.

The thermal load is expressed as the amount of heat q (W/m²) that is entering or leaving a certain area of the body per unit time. Also for this type of load, several sources exist. In the next subsections, the mechanisms of conduction, convection and radiation are treated and the different sources of thermal loads are discussed.

2.3.1 Conduction

Heat conduction is the mechanism that enables the redistribution of heat within a body. Heat can also be transferred to another body by conduction, but only when the two bodies are in thermal contact. In all cases, the magnitude and direction of the heat flow will depend on the temperature difference between (different parts of) the bodies. Heat will always flow from the higher to the lower temperature, and the magnitude of the heat flow will be larger when the temperature difference per unit length, that is, the temperature gradient dT/dx , is larger:

$$q = k \frac{dT}{dx} \quad (2.52)$$

where k is the heat conduction coefficient (W/mK). This coefficient is a material property with high values (~ 100 – 400 W/mK) for well conducting materials like metals and much lower values for materials like glass (~ 1 W/mK). The higher the conduction coefficient, the larger the heat flow will be for a given temperature gradient.

2.3.2 Convection

A second way in which heat can be transferred between two media is by convection. This process takes place at the interface of two media, for example, at the interface between the combustion gas and the metal parts of an engine. Also in this case, the magnitude and the direction of the heat flow depend on the temperature difference between the two media:

$$q = h (T_2 - T_1) \quad (2.53)$$

where h is the heat transfer coefficient ($\text{W/m}^2\text{K}$), and T_1 and T_2 are the temperatures of both media. The value of h depends on the two materials, but also on the flow conditions at the interface where the heat transfer takes place. For example, the heat transfer from a gas to a metal surface is much higher for a turbulent flow ($\sim 1,500 \text{ W/m}^2\text{K}$) than for a laminar flow ($\sim 150 \text{ W/m}^2\text{K}$).

2.3.3 Radiation

Finally, heat can also be transferred by radiation. According to the Stefan–Boltzmann radiation law, the amount of heat radiated by a black body is proportional to the fourth power of the (absolute) temperature T (K):

$$q = \sigma T^4 \quad (2.54)$$

In this radiation law, the constant $\sigma = 5.67 \cdot 10^{-8} \text{ W/m}^2\text{K}^4$ is the Stefan–Boltzmann constant.

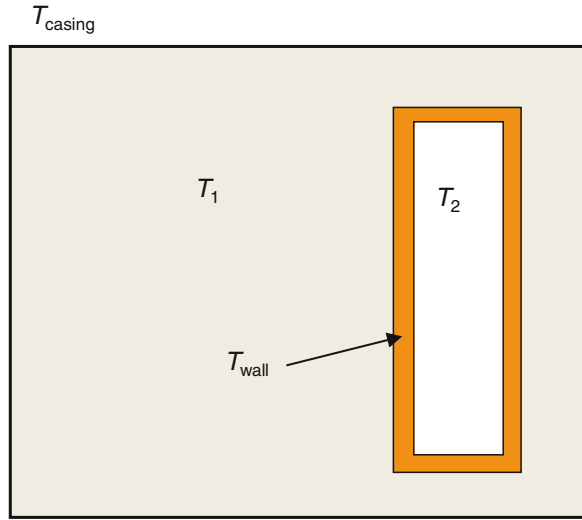
A non-black body will only radiate a certain fraction of the heat that a black body provides. This fraction depends on the emissivity ε of the material, which attains a value between 0 and 1. Further, in real conditions, a body will not only radiate, but will also receive radiation from other bodies and its environment. The net amount of heat that a body radiates in an environment with temperature T_{env} is therefore given by

$$q = \sigma \varepsilon (T^4 - T_{\text{env}}^4) \quad (2.55)$$

A typical value for the emissivity of a metal surface is $\varepsilon = 0.75$, while application of a ceramic coating to the metal reduces the emissivity to $\varepsilon = 0.35$.

Example 2.10 (Thermal Loading of a Gas Turbine Blade) Gas turbine blades face a severe thermal loading, since they operate in a very high temperature gas flow. A schematic representation of a turbine blade and its surrounding is shown in Fig. 2.23. To ensure that the metal temperature (T_{wall}) stays within acceptable limits, the blade is internally cooled by gas with a temperature $T_2 = 800 \text{ }^\circ\text{C}$.

Fig. 2.23 Metal and gas temperatures in the surrounding of a turbine blade



The temperature of the hot gas in the gas path of the engine is $T_1 = 1,500\text{ °C}$, and the temperature of the metal casing is $T_{\text{casing}} = 500\text{ °C}$.

The thermal load on the turbine blade consists of several contributions:

1. Convection from the hot gas to the blade wall: $q_{c1} = h_1(T_1 - T_{\text{wall}})$.
2. Convection from the wall to the cooling gas: $q_{c2} = h_2(T_{\text{wall}} - T_2)$.
3. Radiation from the blade to the external surrounding: $q_{r1} = \sigma \varepsilon T_{\text{wall}}^4$.
4. Radiation from the casing to the blade: $q_{r2} = \sigma \varepsilon T_{\text{casing}}^4$.
5. Radiation inside the blade (from one side to other side): $q_{r3} = \sigma \varepsilon T_{\text{wall}}^4$.

Assuming that the momentary wall temperature is $T_{\text{wall}} = 950\text{ °C}$, the heat transfer coefficients are $h_1 = 1,500\text{ W/m}^2\text{K}$ and $h_2 = 150\text{ W/m}^2\text{K}$ and the emissivity of the blade material $\varepsilon = 0.75$, the total thermal load on the turbine blade can be calculated. Taking the heat flows into the blade in a positive sense and the outgoing heat flows negative, this yields

$$\begin{aligned}
 q_{\text{tot}} &= q_{c1} - q_{c2} - q_{r1} + q_{r2} + q_{r3} - q_{r3} \\
 &= 1500(1500 - 950) - 150(950 - 800) \\
 &\quad + 0.75 \cdot 5.67 \cdot 10^{-8} \left[(950 + 273)^4 - (500 + 273)^4 \right] \\
 &= 7.23 \cdot 10^5 \text{ W/m}^2
 \end{aligned}$$

Note that the incoming radiative heat contribution q_{r3} on one wall at the inside of the blade is completely balanced by an equally large outgoing heat flow.

In the situation used in this example, the calculated heat flow is positive, which means that there is a nett heat flow *into* the turbine blade. This means that the wall temperature will increase and a new situation will arise: the incoming contribution

q_{c1} decreases, whereas the out flowing contributions q_{c2} and q_{r1} increase, resulting in a much lower thermal load. This process will continue until a steady-state situation is reached in which the nett heat flow $q_{\text{tot}} = 0$.

2.3.4 External Heat Generation

Different sources of heat generation exist. The most relevant sources are discussed in this subsection. External heat generation generally leads to an increase in temperature of the gas or fluid that surrounds a system. By convection or radiation, the heat is transferred from the environment to the system, resulting in a thermal loading of the system.

Compression

When a gas is compressed, the temperature will increase. The relation between gas pressure (p), volume (V) and temperature (T) in an ideal gas is given by the Boyle–Gay Lussac’s gas law:

$$\frac{pV}{T} = \text{constant} \quad (2.56)$$

This shows that increasing the pressure of a constant volume of gas will yield a proportional increase in the (absolute) temperature. In practical cases, the increased gas temperature generally yields a large heat input to the surrounding structure (e.g. cylinder wall in a piston engine) by convection or radiation.

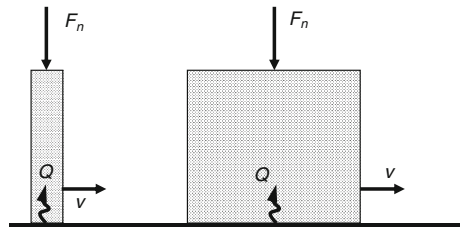
Combustion

The combustion process of fuels is a complex process that generates a considerable amount of heat. To quantify the amount of heat, measurements are required or a combustion model must be developed and applied. This process also elevates the temperature of the gas, providing a large thermal loading of the surrounding structures.

2.3.5 Internal Heat Generation

In addition to the external sources of heat generation, also a number of sources for internal heat generation can be identified. Opposed to the external sources, for which the heat must be transferred to the body under consideration by convection, conduction or radiation, the internal sources deliver a direct heat flow q in the body. The most common sources, mechanical friction and electrical losses, are discussed next.

Fig. 2.24 Heat generation in two similar bodies with different contact areas



Friction

When two parts are moving along each other, friction will occur at the interface. Friction is a force (F_f) that opposes the motion and its magnitude is determined by the friction coefficient μ and the (normal) force F_n applied to both parts

$$F_f = \mu F_n \quad (2.57)$$

The magnitude of the friction coefficient depends on the materials of both parts and the surface roughness at the interface, as will be discussed in more detail in [Sect. 4.6.1](#). By opposing the motion, friction also causes dissipation of energy, resulting in heat generation in one or both parts. The heat generation Q (W) is proportional to the relative speed v of the two bodies

$$Q = F_f v \quad (2.58)$$

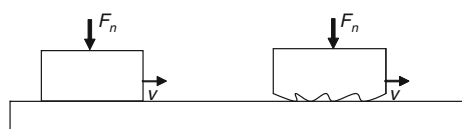
Note that this equation yields the amount of generated heat per unit of time, but the amount of heat is independent of the contact area. This means that two similar bodies sliding along a flat surface with the same speed and normal loads, but with contact areas A and $5A$, respectively (see [Fig. 2.24](#)), generate the same amount of heat Q . However, the heat flow q (W/m²) is a factor 5 higher in the body with the smaller contact area.

Electric Losses

When an electric current flows in a conductor, losses will occur due to the resistance. These electrical losses are converted into heat. The amount of heat P (W) generated per unit of time in a conductor (that satisfies the Ohm's law) is determined by the resistance R of the conductor and either the potential difference (or voltage) V or the current I :

$$P = VI = \frac{V^2}{R} = I^2 R \quad (2.59)$$

Fig. 2.25 Heat generation in two similar bodies with different surface roughness



Example 2.11 (Flash Temperature) As was mentioned above, the local heat flow due to friction largely depends on the contact area. An extreme case of high heat flows (and associated high temperatures) occurs when the contact between a part and the underlying surface is only provided by a few small roughness peaks. This is schematically shown in Fig. 2.25, where two parts with the same nominal contact area are presented.

However, whereas the left-hand part has a perfectly smooth surface, the right-hand side part has quite a rough surface profile. The real contact area of the smooth part is equal to the nominal contact area, while for the rough part it is only a fraction of the nominal area. Both parts move with the same speed and are loaded with the same normal force, so the total amount of heat generated in the contact is equal. However, the local thermal load q per unit contact area is much higher in the rough part. This means that temperature increase at the roughness peaks is much higher than the average temperature increase in the smooth part. This high local temperature is called the flash temperature and in some cases even leads to melting of the material at the roughness peaks.

2.4 Electric Loads

The external electric loads on a system are generally quantified in terms of the voltage or current that are applied to the system. The magnitude of voltage (ΔV) is expressed in Volt (V), while the unit of current (I) is Ampere (A). On an engineering level, electrical systems are generally analysed in terms of these quantities, but to understand the internal loading and failure of electric systems, the origin of these quantities is treated first.

Electric loading of a system can only occur when at some place in or near a system electric charge is present. The symbol generally used for electric charge is Q , while its magnitude is expressed in terms of Coulomb (C). It then depends on the property or the function of the system (i.e. conductor or insulator) whether the absolute amount of charge or its distribution in space and/or time is governing the electric load on the system.

The collection of all point charges in a body generates an electric field. As the electric field is characterized by both its magnitude and direction, it is mathematically described by the vector field \vec{E} . Further, for an electrostatic situation, where no time variation of the electric field occurs, at any location in the field the electric potential V can be calculated. This potential defines the amount of potential energy that a test charge would have when it is present at that specific location in the electric field. The potential V at some point can therefore be calculated as the energy that is required to move a small electric unit charge along an arbitrary path from a (remote) location with zero potential to the specified point. In mathematical terms, this is expressed as the line integral along a path C with length l

$$V = - \int_C \vec{E} \cdot d\vec{l} \quad (2.60)$$

The unit of potential is Volt (V), which is equivalent to Joules per Coulomb (J/C). The potential energy of a charge Q in a point with potential V is therefore

$$U_p = VQ \quad (2.61)$$

The other way around, each individual point charge contributes to the electric field and thus to the potential in each location. The contribution of the point charge Q to the potential at a distance r from the charge is

$$V = \frac{1}{4\pi\epsilon_0} \frac{Q}{r} \quad (2.62)$$

where ϵ_0 is the dielectric constant or permittivity (equal to $8.854 \times 10^{-12} \text{ Fm}^{-1}$). Finally, the magnitude and direction of the electric field can then be obtained by calculating the gradient of the potential

$$\vec{E} = -\vec{\nabla}V = - \begin{pmatrix} \frac{dv}{dx} \\ \frac{dv}{dy} \\ \frac{dv}{dz} \end{pmatrix} \quad (2.63)$$

This implies that the unit of electric field strength must be V/m. The foregoing discussion demonstrates that any distribution of electric charge in a body yields an electric field and an associated distribution of electric potential. The engineering quantities voltage and current are closely related to these definitions, as will be shown next.

The voltage between two locations is defined as the potential difference between these points. This means that the voltage represents the energy that is required to move a small electric unit charge along a certain path from one to the other location. Again, in a static electric field, voltage is independent of the path followed. In general, the voltage is thus the ratio of the amount of work (W) and the magnitude of the charge

$$\Delta V = V_1 - V_2 = \frac{W}{Q} \quad (2.64)$$

The unit of voltage is equal to the unit of potential, that is, Volt (V) or Joules per Coulomb (J/C).

Whereas the voltage is related to a static situation with a certain distribution of charge yielding potential differences, electric current is related to moving charges. The point charges in a body not only cause the electric field, but are also affected by the existing electric field. More specifically, the electric field exerts a force on each charged particle, resulting in a motion of that particle either in the direction (positive charge) or opposite (negative charge) to the direction of the field;

especially in solid materials, the charge carriers (mostly electrons) cannot travel in a straight line, but are bouncing from atom to atom. However, the net motion will be opposite to the direction of the electric field. The net velocity associated with this motion is called the drift velocity of the charge carriers and is proportional to the magnitude of the electric field (E)

$$v_{\text{drift}} = \mu E \quad (2.65)$$

The proportionality constant μ represents the mobility of the charge carriers (m^2/Vs), which largely depends on the type of material and especially the aggregation state of the material (gas, fluid or solid).

When the drift velocity of the charge carriers is known, the amount of charge moving in a material and thus the current I can be assessed as

$$I = nA v_{\text{drift}} Q \quad (2.66)$$

In addition to the drift velocity, the current is proportional to the cross-sectional area A and the number n (per unit volume) and charge Q of the moving particles.

Example 2.12 (Electron Drift Velocity) A typical material used for conductors is copper, with a mass density $\rho = 8.94 \text{ g/cm}^3$ and an atomic weight of 63.546 g/mol . If a copper wire with a 2 mm diameter is carrying a current $I = 2 \text{ A}$, the drift velocity of the electrons can be calculated. Firstly, the number and magnitude of charge carriers must be determined. In a metal, electrons will be the charge carriers, and in copper each atom has one free electron. One cubic centimetre of copper has a mass of 8.94 g and thus contains $8.94/63.546 = 0.1407 \text{ mol Cu atoms}$. By multiplying with Avogadro's number (6.02×10^{23}), the number of atoms per cm^3 is obtained. The charge of an electron equals $1.6 \times 10^{-19} \text{ C}$. Finally, the cross-sectional area of the wire is given by $A = \pi r^2 = \pi(0.1)^2 = 0.0314 \text{ cm}^2$. Using Eq. (2.66), the drift velocity can be calculated

$$v_{\text{drift}} = \frac{I}{nAQ} = \frac{2}{(0.1407 \cdot 6.02 \cdot 10^{23})(0.0314)(1.6 \cdot 10^{-19})} = 4.7 \times 10^{-3} \text{ cm/s}$$

This example shows that even a considerable electric current only yields a very low drift velocity of the electrons in the metal conductor.

Finally, the relation between voltage and current is defined by Ohm's law

$$I = \frac{\Delta V}{R} \quad (2.67)$$

showing that the component's resistance R determines the magnitude of the current at a certain applied voltage. Combining Ohm's law with Eqs. (2.65)–(2.66) and assuming that the voltage ΔV applied to a resistor with length l yields an uniform electric field $E = \Delta V/l$, the resistance R can be obtained from

$$R = \frac{1}{nQ\mu} \frac{l}{A} = \rho \frac{l}{A} \quad (2.68)$$

This demonstrates that the resistance in a material depends on the dimensions (A and l) and the resistivity ρ of the material. The conductivity, being the reciprocal of the resistivity, is proportional to the amount of free charge carriers per unit volume (nQ) and their mobility μ .

2.4.1 Sources

Similar to the mechanical loads, also electric loads can arise from different sources. The generic load in this case is the specific distribution of charge over a body, resulting in a potential difference or electric current. Specific sources for this type of load are the different methods to transfer or generate electric charge. The most widely applied principle is electromagnetic induction, where a changing magnetic field moves the charge carriers (i.e. electrons) and thus generates potential differences or electric currents. This principle is applied in, for example, generators. Alternative sources are the photovoltaic effect, as applied in solar cells, electrochemical reactions (e.g. fuel cells) and electrostatic sources. These different ways of generating electric loads are discussed next.

Electromagnetic Induction

Induction is caused by the interaction between electric and magnetic fields. Charge carriers that move in a magnetic field experience a force that is proportional to the magnitude of the magnetic field B and the velocity v . The direction of the force is perpendicular to the plane spanned by the vectors \vec{B} and \vec{v} , as defined by the following expression

$$\vec{F} = q\vec{v} \times \vec{B} \quad (2.69)$$

Due to the experienced force, the charge carriers (e.g. electrons in a conducting winding) start to move, yielding a potential difference or electric current. Since the relative orientations of the magnetic field and direction of motion are important, the concept of magnetic flux is used. The magnetic flux through a loop (winding) is the surface integral of the magnetic field over the surface of that loop. This means that the flux is maximum when the loop is perpendicular to the magnetic field and zero when both are aligned. The resulting electromotive force or voltage in a loop with surface S (and contour C) moving in a magnetic field with magnitude B is obtained from the gradient of the magnetic flux Φ according to

$$\Delta V = -\frac{d\Phi}{dt} = \frac{d}{dt} \left(\int_S \vec{B} \cdot d\vec{a} \right) = \int_C (\vec{v} \cdot \vec{B}) \times d\vec{s} \quad (2.70)$$

and thus also appears to be proportional to the speed of the loop.

This principle of induction is applied in a generator to move charge and create a potential difference or electric current by rotating a set of windings in a stationary magnetic field. All present generators are derived from the dynamo, which was the first electrical machine capable of converting mechanical rotation into electrical power. In a dynamo, a commutator or collector is applied, which reverses the direction of the electric field (and current) each half revolution. This is accomplished by sliding carbon brushes connected to the housing along different segments of the commutator. The result is a (slightly pulsed) direct current (DC).

Without a commutator, the dynamo becomes an alternator, which delivers an alternating current (AC). If such a generator is used to power an electric grid, the rotational speed must be constant and synchronized with the electrical frequency of the grid. In most generators, no permanent magnet is applied, but a rotating field winding, fed by direct current, moves relative to a stationary winding that produces the alternating current. The direct current for the field winding is obtained from the generated power, for example, through brushes contacting the rotor or by applying rectifiers.

Photovoltaic Effect

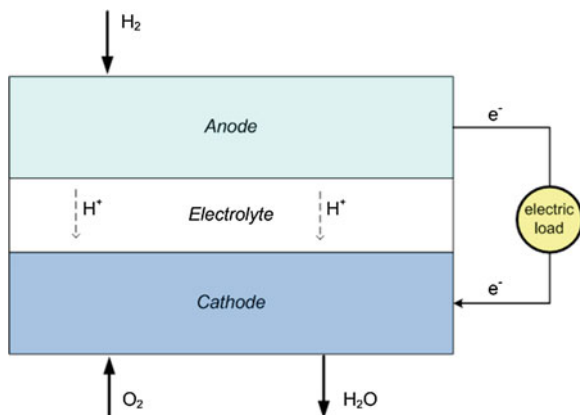
Another principle to move charge carriers and create a potential difference or electric current is the photovoltaic effect. This effect is observed in materials where energy from incident light (photons) is used to excite charge carriers into the conduction band (see [Sect. 3.4](#)). In a semiconducting material, a so-called p - n junction can be constructed, which makes that electrons are excited in the n side of the junction and holes are created on the p side [1]. Due to the built-in electric field, the negatively charged electrons are forced to the external electrical circuit, while the positively charged holes do the same in opposite direction, thus creating the electric current.

This principle is applied in a solar cell ([Fig. 2.26](#)), where incident sunlight is utilized to generate electricity. A solar cell is made of silicon, depending on the

Fig. 2.26 Solar cell (*Source* Wikimedia Commons)



Fig. 2.27 Schematic representation of a fuel cell



type of cell in either polycrystalline, monocrystalline or amorphous form that has been fabricated to produce a p - n junction. Since a typical single solar cell produces a voltage of only around 0.5 V, several cells are usually combined into a solar panel to increase the delivered voltage and/or current.

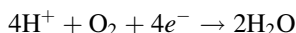
Electrochemical Reactions

Free moving electric charge carriers can also be generated by chemical reactions. This principle is, for example, applied in fuel cells, which generate electricity through a chemical reaction. A cell consists of an anode, an electrolyte and a cathode (see Fig. 2.27), and two chemical reactions occur at the two interfaces between the three sections. The typical fuel used in these cells is hydrogen gas (H_2), which is oxidized at the anode using a catalyst (e.g. fine platinum powder). The oxidation of hydrogen yields positively charged ions and electrons:



The ions travel through the electrolyte to the cathode, but the electrons cannot and are thus forced to the electrical connection with the cathode, where they create the required current.

At the cathode, the hydrogen ions react with oxygen and the electrons to form water, which is drained as waste product. The cathode reaction is



Also at the cathode, a catalyst is applied, which is often nickel. Depending on the design of the cell, the electrolyte material can be one of several options, for example, a H^+ -conducting polymer membrane, the ceramic yttrium-stabilized zirconia or an aqueous alkaline solution.

A typical single fuel cell generates a voltage of 0.6–0.7 V, and the delivered current depends on the surface areas of anode and cathode. If higher voltages or currents are required, several cells can be combined in a fuel cell stack, where

parallel connections deliver higher current and series connections yield higher voltages.

Electrostatic Sources

The final source of electric loads discussed here is the electrostatic source. Contrary to the previous sources, which typically generate motion of charge carriers in conductors (thus resulting in electric current), electrostatic electricity is generally related to a static surface charge imbalance. This means that the amount of charge varies across the surface of a body, which therefore only occurs in insulating materials. In a conducting material, all differences in surface charge will immediately be balanced since the charge carriers can move freely.

However, in practice, the unbalance in surface charge will generally be quite small, unless processes occur that accumulate charge at some location. An example of such a process is the triboelectric effect. Certain materials become electrically charged when they are rubbed against each other. One of the materials then gets a negative charge, while the other material obtains an equally large positive charge. Examples of material combinations exhibiting this effect are amber rubbed with wool and glass rubbed with silk. Although very high charges and associated voltages can be attained in this way, the discharge will generally not generate a large current. But still electrostatic discharge is a major problem for many sensitive electronic devices failing due to this load (see [Sect. 4.9.4](#)).

Piezoelectric and Thermoelectric Sources

Finally, also piezoelectric and thermoelectric sources exist. In the former case, the mechanical deformation of specific solids produces a certain amount of electric charge. As an example, piezoelectric materials are commonly applied as the ignition source for cigarette lighters. A thermoelectric source produces a voltage when a temperature difference exists between two ends of a conductor. This effect is widely applied for temperature measurements, for example, in thermocouples.

2.5 Chemical Loads

Chemical loading of a system occurs when certain substances, for example, acids or certain gasses that cause degradation of the system, are in contact with the system. The degradation can be either due to a direct chemical reaction, as is the case for aggressive materials attacking metal or plastic parts in which they are contained, or by an electrochemical reaction where the chemical reaction only occurs when also an electric current can be established. Most common corrosion processes are based on electrochemical reactions.

The concentration of the concerning substance generally determines the magnitude of this type of load, although for some reactions a small amount of material is sufficient to start the reaction and a higher concentration does not affect the

degradation rate anymore. On the other hand, external parameters like temperature and the presence of other materials (catalysts) may considerably affect the reaction rate. For acids, the concentration of hydrogen ions is governing the load, which is generally expressed as a pH value.

For electrochemical corrosion reactions, the presence of an electrolyte and an electric connection between anode and cathode (see Sect. 4.10 for details on corrosion) are required in addition to the presence of a galvanic couple (two metals). Each of these three constituents may act as the rate-limiting factor in the corrosion reaction. Together they govern the resulting electric current that determines how many corrosion reactions can take place and thus determines the degradation rate.

In some cases, the chemical loads originate from a biological source. An example of this type of load is microbiologically induced corrosion (MIC), where micro-organisms create the environment that enhance certain corrosion processes.

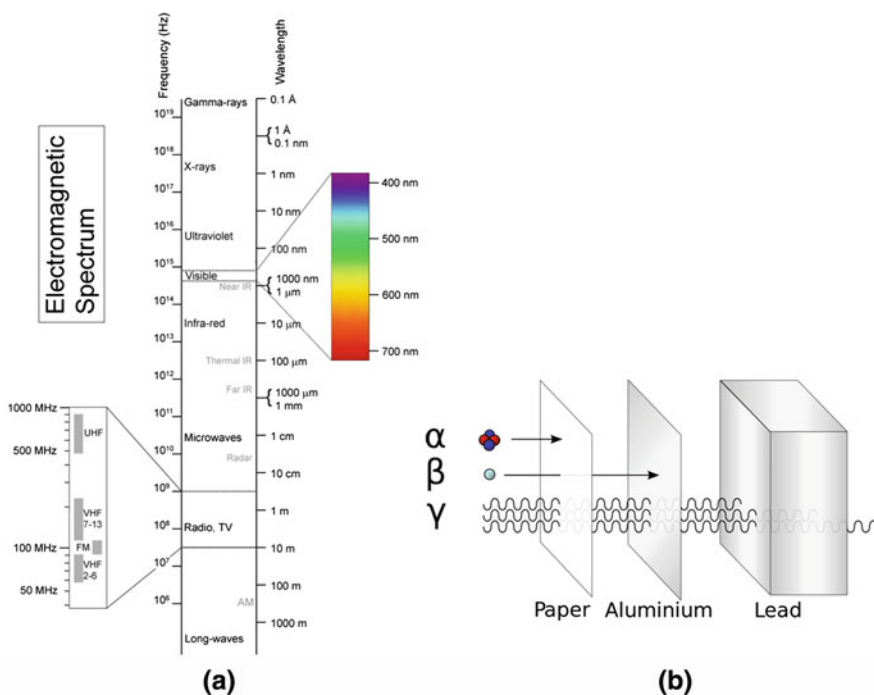


Fig. 2.28 **a** Electromagnetic spectrum. **b** Different types of radiation and their abilities to penetrate solid materials (Wikipedia)

2.6 Radiative Loads

Radiation can also cause degradation of a material, which ultimately could lead to failure of a system. In most cases, this is a secondary load: the material properties and thus the load-carrying capacity decrease over time. Two different types of radiation exist: radiation consisting of particles and electromagnetic radiation consisting of photons. The damage caused by the different types of radiation, both in structural materials and biological tissues (e.g. the human body) depends on the energy of the particles or photons. Particles like alpha particles, beta particles and neutrons generally have considerable energies and are therefore able to ionize atoms. Electromagnetic radiation is also able to ionize atoms, provided that the energy is sufficiently high. This is the case for radiation with very high frequencies (and thus small wavelengths) like X-rays and γ -rays, see Fig. 2.28a.

In addition to the energy, the damaging effect of the radiative load also depends on the penetration depth. The relatively large α -particles heavily interact with other materials, so they generally only travel a few centimetres in air or a few millimetres in low density materials. On the other hand, gamma rays consisting of photons with neither mass nor electric charge are very difficult to stop and therefore deeply penetrate into materials (Fig. 2.28b).

Finally, the magnitude of a radiative load is determined by the duration of the exposure and (for lower frequency electromagnetic radiation) the reflectivity of the surface, which determines the fraction of the incoming radiation to be absorbed.

2.7 Summary

In this chapter, an overview has been given of all relevant load types. For each type, the generic load was described and a number of specific sources for that generic load were discussed. In most cases, also quantitative relations were given that enable the calculation of the magnitude of the load.

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Further Reading

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