2. Limit states

In the chapter 6. Loads of the body, transition and limit states are defined as those of the operational states of the body (real system of bodies, structure) in which the ability of the body to fulfil the required functions is disabled either fully or partially, either temporarily or permanently. In those states the staff has to decide whether the equipment will continue its operation (either partially or after a repair by replacement of the failured component) or it will be put out of operation. This decision is substantially influenced by non-mechanical factors (economy, environment, ergonomy etc.), so that knowledge of mechanical factors **cannot** be enough to distinguish between transitional and limit states; therefore all these states will be further denoted as limit states. In this general sense, the following definition can be formulated: loads

> Limit state is such one of the possible operational states of the body (system) which brings either a qualitative change in the ability of the body (system, structure) to perform some of its intended functions or an absolute loss of its functionality.

We can present some examples of limit states using an example of turbine rotor:

a) a crack occurred in the rotor during its pressing on the shaft or during operation – limit state of crack initiation,
b) an excessive rotor deformation occurred during operation and the displacement of the vane end reaches the value of clearance between stator and turbine casing –limit state of deformation,
c) fractures of some vanes occurred – limit state of fracture ,
d) the pressed coupling between the rotor and the shaft has loosened during rotation – limit state of deformation..

limit state of failure

limit state of deformation

An assessment of limit states of the system must take into account that the system consists of many subsystems and component parts. We can define a certain amount of possible limit states, substantial for the system in question. If any of these limit states is reached, the system is set out of operation.

The factors influencing the occurrence of limit states can be divided into external and internal ones.

a) External factors can be for example:
   - mechanical load (steady - changing in time; static or dynamic or impact load; the value as well as time dependence of the load is important), loads
   - temperature load,
   - milieu – inert or aggressive, influencing the surface or the whole volume of the material,
   - energetic fields (electric field, magnetic field etc.),
   - violation of production or operation instructions,
   - wrong manipulation,
   - wildfire or high flood etc.

b) Internal factors can be for example:
   - incompetent choice of material (chemical composition, heat, chemical or mechanical treatment),
   - material or weld imperfections,
   - incompetent design or technology,
   - infringement of production quality regulations, etc.

It is very difficult to describe all the possible limit states of a system; they can be systemised from various viewpoints. Therefore we present the following brief overview of the most frequent of them which must be never neglected by designers:

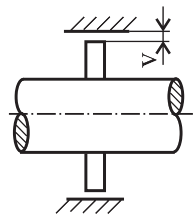
– limit state of deformation,
– limit state of elasticity,
– limit state of buckling,
– limit state of fracture.

2.1. Limit state of deformation

All component parts deform under any load, i.e. they change their shape, dimensions, tolerances between them (clearance or interference). If these changes do not disturb the function of the equipment, as defined in specifications and technical standards valid for the equipment (concerning the accuracy of production, mobility of the components etc.), we call them admissible deformations.

Example 404

For example, there is a clearance v between turbine casing and its rotor. From the thermodynamical viewpoint (to achieve high efficiency of the turbine), this clearance is required to be as low as possible. However, it is important for the function of the turbine that this radial clearance v be greater than the sum of radial displacement on the external rotor surface u_r and of the elongation Δl of the vane. The following relation can then occur:



$u_r + \Delta l < v \quad \rightarrow$ deformation is admissible for the turbine function,

$u_r + \Delta l > v \quad \rightarrow$ deformation is inadmissible for the turbine function,

$u_r + \Delta l = v \quad \rightarrow$ **limit state of deformation**; in practice, the equality cannot be ensured because of the stochastic character of all quantities.

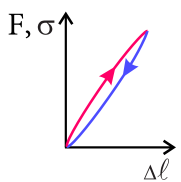
Limit state of deformation is such a state among the operational states of the body when admissible deformations change into inadmissible from the viewpoint of the functionality of the body.

Note: inadmissible deformation can be elastic as well as permanent (plastic).

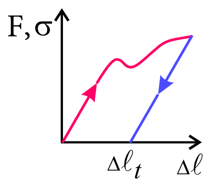
2.2. Limit state of elasticity

If a body is loaded from the initial (unloaded) state and then unloaded from a certain load level, this process is called **load cycle**. After this load cycle, two different situations can come into being:

a) the deformation after unloading to zero load is as small that it cannot be measured in the way usual in the technical practice; all the deformation during the load cycle was **elastic** (reversible),



b) the deformation after unloading to zero load is non-zero and it can be measured in the way usual in the technical practice; in addition to the elastic deformation, a **plastic** (irreversible) deformation occurred during the load cycle.

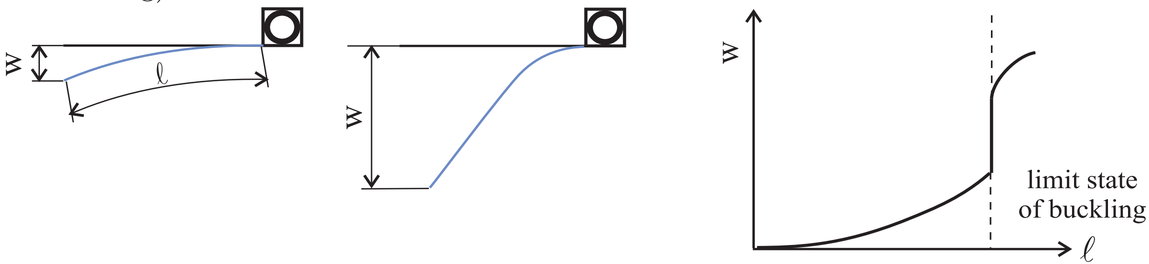


Limit state of elasticity is such a state among the operational states of the body when the first measurable plastic (irreversible) deformation occur.

The stress value corresponding to this limit state is called yield stress. This limit state is the most common computational limit state in technical practice. It is not because of its importance (often a permanently deformed component can continue operation) but it is easy to be solved (all the computation is only elastic) and it is conservative for all ductile materials (there is a reserve of loadbearing capacity in plastic region, i.e. the load can be higher in practice than in computation). safety factor

2.3. Limit state of buckling

If a body (beam, shell, plate or another thin-walled body) is loaded, the equilibrium state of the acting external and internal forces can become unstable; then a sudden change in the body shape can occur (e.g. a stepwise increase of deflection of the beam in the figure under bending).



Limit state of buckling is such a state among the operational states of the body when the equilibrium shape of the body becomes unstable and a stepwise shape change to another stable geometrical configuration can occur.

This limit state is typical for components (structures) with at least one dimension substantially lower than another (thin walled components, slender bars). It can occur any time when there are negativ normal (compression) stresses in a part of the body in question. Then a loss of loadbearing capacity of all the structure can come into being. As this limit state is accompanied by large strain and large displacements, its computational solution is extremely difficult. The critical quantity which can be used **to decide when this type of failure occurs at a body** depends on its shape; in the case of columns (i.e. bars **loaded only** by compression) it is the **critical force** or **critical load**.

normal stress

buckling

2.4. Limit state of fracture

continuity of body

If a continuous body is loaded, its continuity (in the sense of mechanics, i.e. macroscopically) remains well-preserved in a certain loading range. Even under load the body remains continuous in all its volume. Outside of this range, some continuity defects (cracks) can occur; in this process some new surfaces of the body are created and this process can continue until the body **disintegrates into pieces** - a fracture of the body occurs. Fracture is a catastrophic consummation of the stage of crack growing when the body changes from an integral entity to several (two or more) new bodies (pieces). In accordance to the material behaviour and to the character of loading and influencing factors, the following types of fractures can be distinguished:

a) **Ductile fracture**
From the mechanical viewpoint, ductile fracture can be defined as a high-energy plastic breakdown induced by a plastic instability in the critical part (cross-section) of the body. From the viewpoint of physics or metallurgy it is a process consisting of nucleation, growth and interlinking of microcavities or microcracks. In practice this process often occurs in microdimensions at the tip of a propagating crack [6]. It must be avoided during technological operation which exploit large plastic deformations (deep drawing of sheets, cold drawing of wires, cold forming etc.).

b) **Brittle fracture**
This type of fracture occurs without any significant previous plastic deformation, under stresses lower than the macroscopic yield stress. The quantity decisive for the occurrence of brittle fracture is the *critical normal stress* (in the case of a body without any pre-existing macrocracks) or the *critical value of crack driving force* or

fracture toughness (in the case of bodies with pre-existing macroscopic cracks).

c) **Fatigue fracture** Fracture of the ductile body can occur under loads inducing stresses lower than yield stress of the material in question, especially if the load is changing in time. Varying load induces a process of successive nucleation and interlinking of microdefects called fatigue of material. The fatigue fracture is the most frequent limit state in technical practice. The fatigue strength is **determined** by a characteristic stress value called **fatigue (endurance) limit**, the fatigue life is evaluated using Wöhler or Manson-Coffin curves and their mathematical descriptions.

d) **Corrosion fatigue** fracture
The surroundings can substantially accelerate the processes of crack initiation and growth. Corrosion denotes chemical or electrochemical reaction among various types of materials and surrounding fluids. The **corrosion** process, as well as radiation, can reduce the **fracture toughness** substantially. While corrosion occurs more or less at all technical equipments, **radiation** is important e.g. for the bodies in active zones of nuclear power stations.

e) **Creep** fracture
Creep means time dependency of deformation under constant load. After a sufficiently long time fracture can occur under loads corresponding to stresses lower than the yield stress of the material in question. The most frequent critical value used in technical practice is **creep strength**.

Limit state of fracture Limit state of fracture is such a state among the operational states of the body when the ability of the body to fulfil the required functions is violated by crack initiation or growth induced by some of the above mentioned fracture mechanisms.

The body or structure can be disqualified from the operation because of the following reasons:

– because of safety in the case of occurrence of any crack in very important component parts (e.g. **X-ray tested weld** joints of pressure vessels),
– if the crack length grows near the **critical length** at which an unstable crack propagation occurs,
– if there is no risk of fracture but the crack disables the proper function of the equipment (e.g. leakage of a pressure vessel),
– because of fracture of some component part.