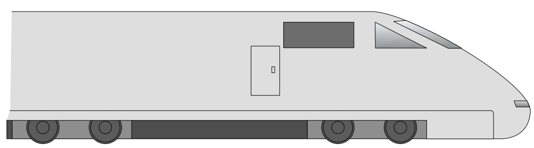
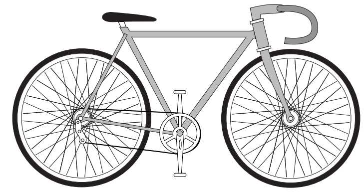
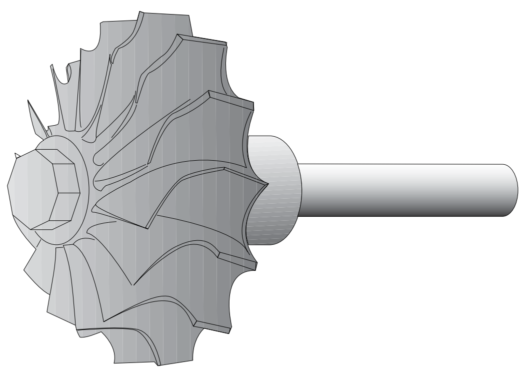
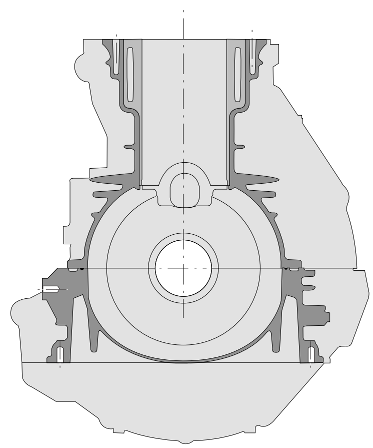
3. From Machine Engineering to Lightweight Design.

Lightweight design has many aspects, it can be found in the whole modern machine engineering.









Designs which target a **minimizing of its structure weight**, can be overall assigned the term lightweight design. The trend to lightweight design has now intensified to the **entire machine engineering**. So this gets increasing lightweight design. In the literature (Lit. 3-4) the lightweight principles are distinguished by the terms concept, shape and composite or condition and material (Lit. 3-5, Ill. 3-2). With this not only for sheet metal structures certain design features get more and more into the foreground (Lit. 3-3).

- As possible uniform **high load/stress of the whole design** respectively the volume.
- Widely **utilization of the strength**, i.e. a stress niveau as high as possible.
- Exploitation of the room available for high **load capacity and stiffness**.

The **strength utilization** presumes as possible an exact and comprehensive knowledge of all relevant operation loads/conditions. Above that lightweight designs demand the especial consideration of the distribution of forces/power flow, materials properties, connections/bonds, surrounding/environment conditions, safety and reliability. These demands are by far not only applied to sheet metal designs but meanwhile for wide ranges of the mechanical engineering. The realization demands a suitable production, function and properties. Light weight designs can be assigned three main types: Differential, integral (in combination as integrated structures, Ill. 3-7) and composites/assemblies. Without doubt, the **trend goes to the integral design** (Ill. 3-14 and Ill. 3-15) **and to composites** (Ill. 3-2).

Ill. 3-1 *(Lit. 3-3 up to Lit. 3-19): The significance of the* ***lightweight design*** *shall be illustrated here with help of* ***typical examples****. It can be seen, that technologies are concerned, which are often already known since years from the aerotechnics (aircraft structures, turbo engines) and are successful proved (Ill. 3-2 and Ill. 3-11). From the examples a trend to the combinations of different materials types (e.g., metals with ffibre reinforced plastics - FRP) can be identified. This demands application adapted designs, necessary for the not seldom extensive pioneer work. Also the operarational risk must be minimized with practice relevant experiences to an acceptable degree of the conventional constructions.*

Traffic systems*: Here the energy efficiency by low weight as possible with high safety requirements stands in the foreground. This aspect may even intensify with the introduction of alternative (electric) drives.*
Motor vehicles*: Lightweight design in the car body (Ill. 3-7, Lit. 3-20), motor (Ill. 3-15, Lit. 3-7) and undercarriage (Ill. 3-14). In the car body materials with higher specific strength (Ill. 3-4) are applied. Typical are high strength steel sheets, lighter materials like aluminium and magnesium in the bearing structure as well as fiber reinforced plastics (FRP). This demands* ***adapted design principles*** *e.g., 'Spaceframe'® , Ill. 3-4) to meet the technology specific advantages and also the weaknesses (Lit. 3-21). The very low stiffness compared with steel (modulus of elasticity 1/3 of steel, Ill. 3-5) must be compensated. This demands the crash behaviour and the torsional stiffness needed for the driving characteristics. These requirements can be achieved with casting gussets, which connect extruded hollow profiles. If planar structures are used thicker walls are applied. So the weight of a body shell can be lowered about 40%. For the realization, adapted connection technologies like laser welding, punch rivets, self cutting bolts, glueing/bonding, and clinching are used.*

Trains*: The same trend like at cars can be observed also here. Expecially demanding is the longevity and the reliability.*
Ships*: For the high speed application in the passenger traffic (e.g., air cushion crafts, multi hull boats) low weight is required. Additionally it must be reckoned wit a very intense corrosion influence, which further aggravates the materials selection.*

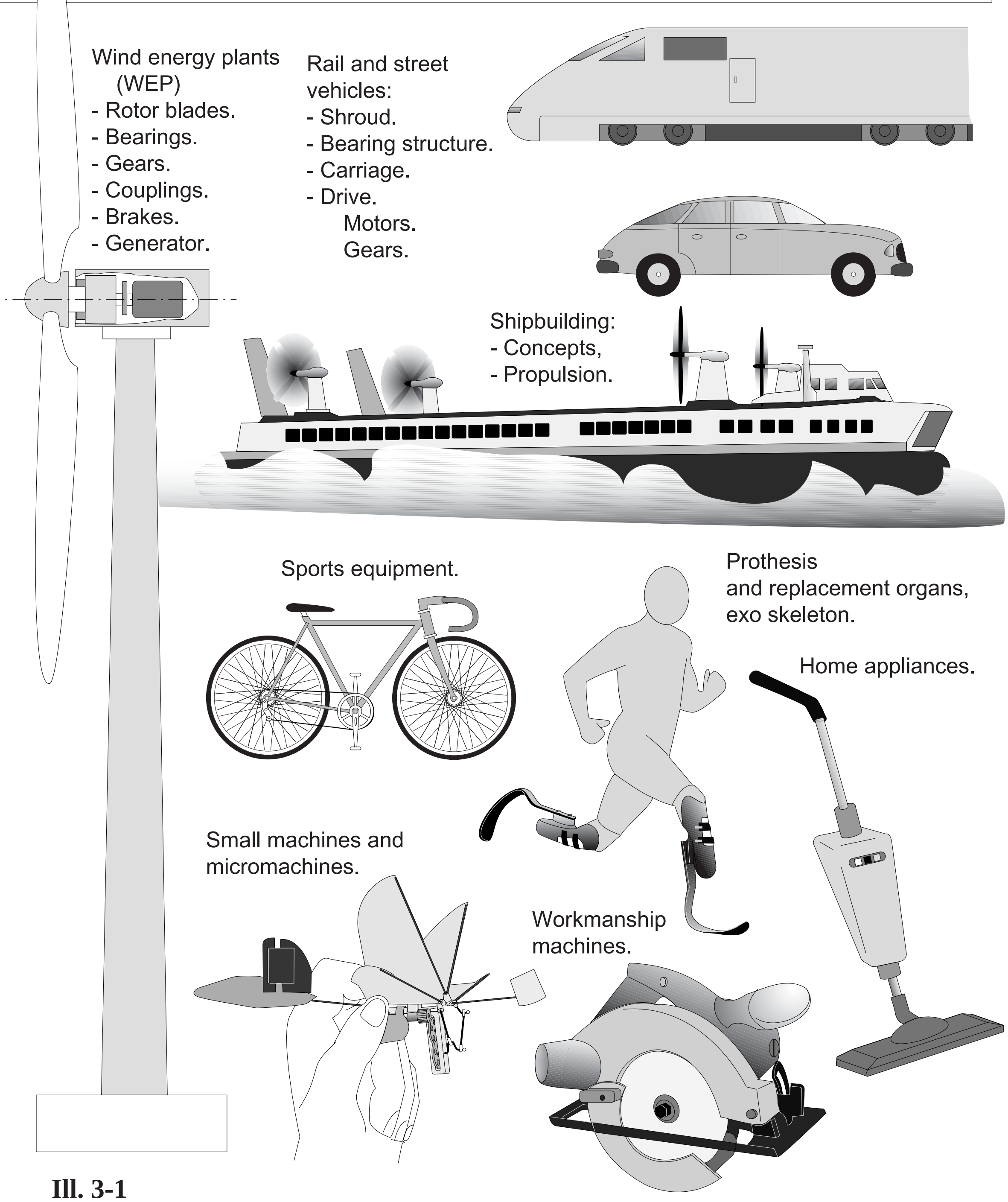
Sports equipment *is since long a domain of the lightweight design. To these count as well race cars and sports cars as just also devices, driven/moved by muscle strength like racing bicycles, tennis rackets and ski equipment. In this field expensive composite designs can be found. These not only utilise the low weight, but also the special advantages of the technologies like a 'structured' elasticity (Lit. 3-22).*

Home appliances*: Here the reduction of costs may positioned before weight saving, although it is for the handling quite of importance. This also is true for the do-it-yourself market. Additionally advantgages like corrosion resistance, damping of vibrations and noise as well as electric insulation can be utilized.*

Alternative energy production*: A typical example are wind enery plants (WEP). Concerned are static and dynamic highly loaded machines which are intensely exposed to environmental influences (e.g., corrosion, lightning strike). The weight or the rotor head from gondola/nacelle, hub and blades must be as low as possible to minimize the load of the pylon.*

Small machines und micro machines*: These are often conventional devices like drones (e.g., helicopters) or turbomaschines (Ill. 3-3) where a miniaturisation enables the handling by a single person or in small facilities (e.g., heating/energy production in houses).*

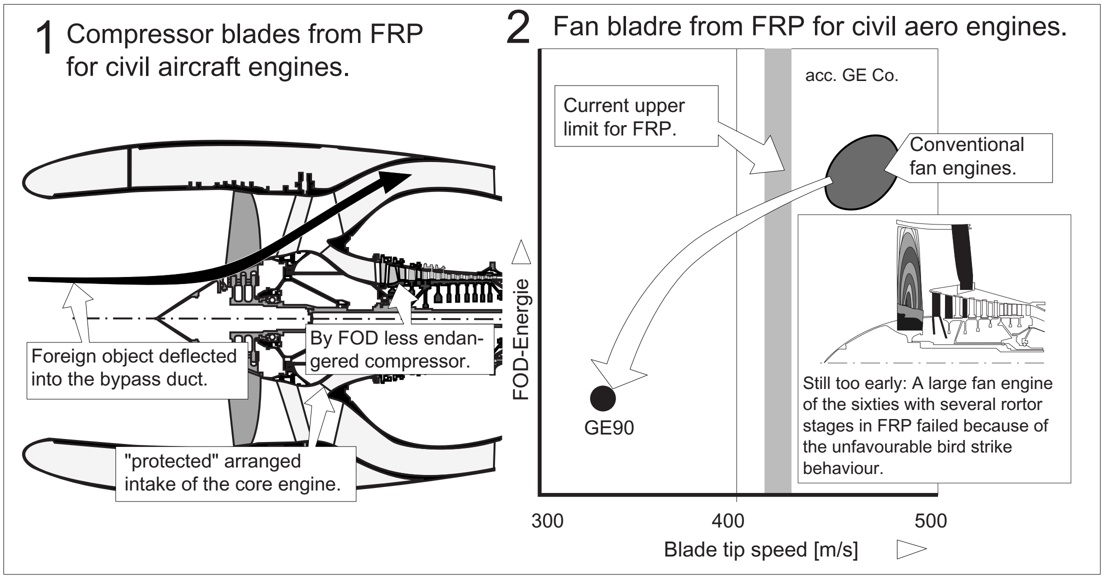
The lightweight design has captured besides the application in the aviation, many fields of the mechine engineering. To these belong also unusual:



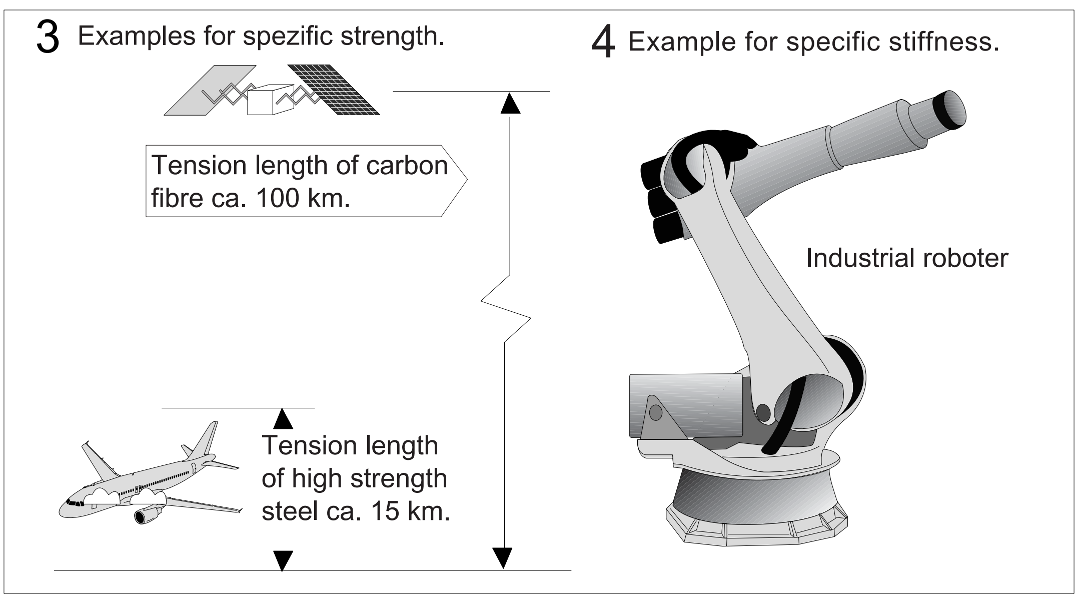
Ill. 3-1

Principles of the lightweight design can be assigned different terms. Often they can be found all together in a single design.

Condition light weight design: Optimization/adaption for the task.



Materials leight weight design: Material oriented optimization according to special data (density related) of strenghtt (tension length), stiffness (elastic deformation) and volume.



Ill. 3-2

Ill. 3-2*: In the literature 3-5 we find a conceptual* ***systematization*** *of the light weight engineering.*

Condition light weight design*: Minimization of the acting* ***forces****. In spite of higher utilized capcity of the components there is an accceptable safety due to* ***fail-safe behaviour****.*

***Materials light weight design**: For this serve **materials** with higher specific strength and stiffness (Ill. 3-4). Precondition for the success of a **technology** is, that it comes to series application. However here special requirements like a favourable production and acceptance of the costs must be met.*

***Shape light weight design**: Configuration with optimal force flow/distribution. Takes place with a geometric optimization of the structure under consideration of the f**orce application and force leading**. To these the bearing cross sections will be adapted. This occurs especially also under the aspect of dynamic loads.*

*As can be seen from examples given later, often not only one of these features alone meets a light weight design. To fulfill high demands it is necessary to use all approaches/ philosophies. The realization needs the following **requirements**:*

*- The specific **advantages and disadventages of a technology must be identified and understood**. Only so it is possible to define the necessary development steps for a successful application.*

*- All **dimensioning and shaping specifications and guidelines** are prepared and must be assured. The quality as basis of the dimensioning must be guaranteed.*

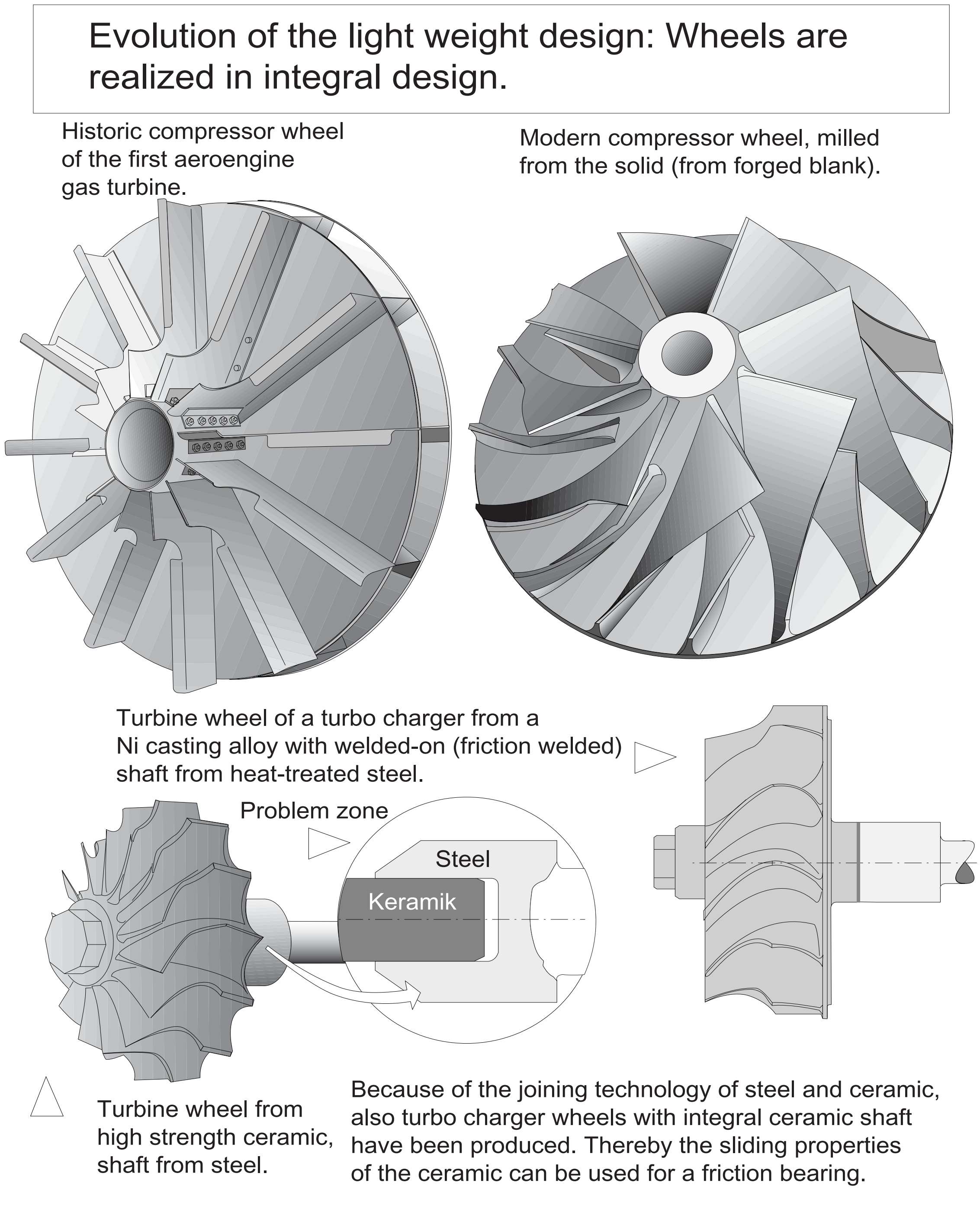
*- Already the phase of project and draft must consider the optimal **utilization of the advantages of the technologies to be applied**. This means, the development of technologies are laid out long-term (Lit. 3-2). They must **exist before a project phase**. In the beginning phase the technology development must be embedded in a **strategy**, independent from a certain project. The following examples (Lit. 3-2) show the necessity of these requirements:*

***Example 1:** To utilize **FRP compressor blades and other FRP** (fiber reinforced plastics) **components** (casings/boxes, rotating nose cone) **in an aero engine**, first the bird strike risk must be minimized (Ill. 5.2.2-12, Lit. 3-1). With a suitable **contour of the bypass duct** a direct impact of the bird inside the core engine can be avoided. At fighter engines the **intake duct** can be suitable shaped. Hits the bird first its wall, it „splashes“ and load at the blade will be minimized by the small particles. Precondition for the success is, that the particles can no more collect again.*

***Example 2**: Extensive investigations have shown, that **FRP fan rotor blades** can be realized with sufficent low mass. For this the circumferential speed must ly below a threshold. So the impact velocity of a bird with a specified minimum mass stays controllable (diagram above right, Lit. 3-2). This is considered during dimensioning and shaping.*

***Example 3**: Extremely materials light weight design could always be found in the aviation and astronautics. Here the specific strength (tension length, Ill. 3-5) plays an important role.
It gets as important as the components load itself. This is the case due to the high accelerations of missiles and through the centrifugal forces in rotors of turbomachines. Dream of the future is the imagination of a lift to the orbit at a continuous rope.*

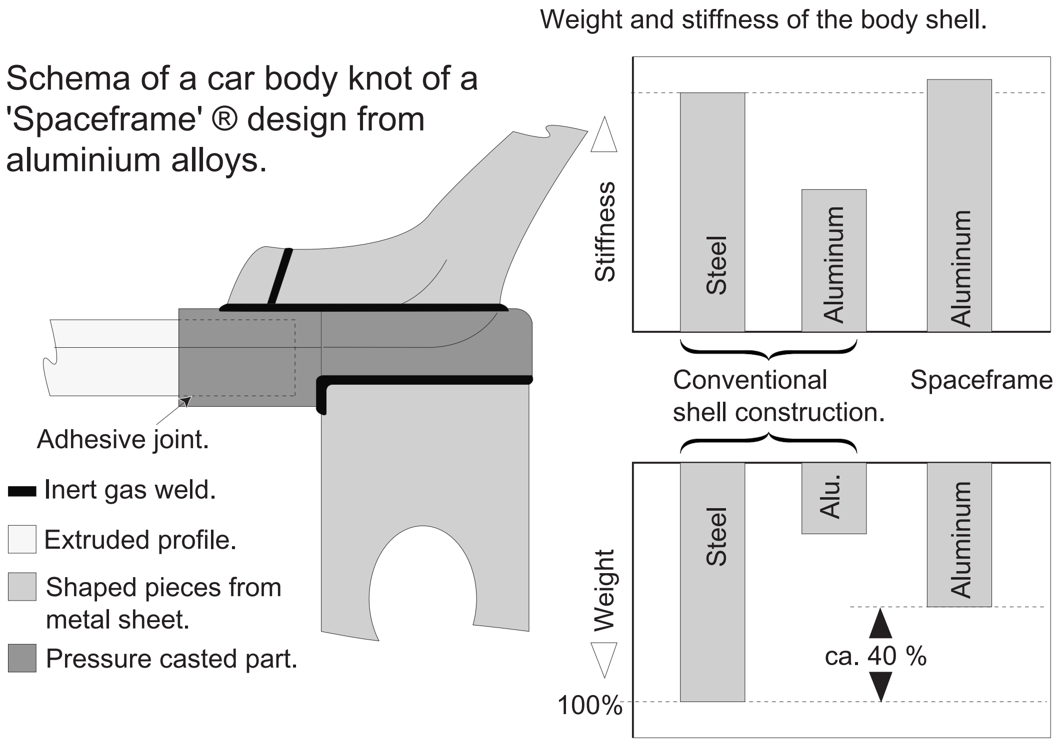
***Example 4**: To execute fast movements with production roboters, high mass/inertia forces must be overcome. For this offer itself structure materials with high **tension length** (Ill. 3-5). Above this the accuracy of the position requires also a high **spezific stiffness** (Ill. 3-5) to master the elastic deformations.*



Ill. 3-3

Ill. 3-3 *(Lit. 3-19): Compact parts are realized if possible in light weight design* ***integral****. This trend can be well recognized at* ***rotors of turbomachines*** *(Ill. 3-16). Early radial compressors of former turbo engines ave already joined from sheet metal shaped pieces (sketch above left). Such designs can be also found even today at relatively low loaded* ***blower wheels*** *in industry devices and household equipent (vacuum cleaner). The joining consists of* ***rivets, form fit*** *or* ***welds****.*
Highly loaded rotors of turbo machines today consist of single piece ***castings or weded parts*** *(sketch above right). To these belong* ***turbo chargers****. The steel shaft is joined with the cast wheel body from a Ni alloy by brazing or friction*

Improvements through consequent application of a light weight design principle.



Ill. 3-4

welding (sketch below right). Also wheels of turbo chargers from ***high strength ceramic*** *(e.g., hot pressed silicon nitride, Ill. 3-22) have already been produced in large series during the eighties.A motivation was the low polar moment of inertia and with this a* ***good acceleration behaviour*** *(avoiding the 'turbo gap'). Motivation was also the danger of shortage of raw materials (nickel and cobalt). If this gets again acute, it is absolutely once more to be reckoned with an intensified application of such a design. The* ***joining between ceramic and a steel shaft*** *is a highly demanding task for the designer.* ***Different thermal expansions and stiffness must be safely controled in spite of the brittleness of the ceramic****. A solution are* ***shrink joints****. Its* ***shaping must be adjusted to the different elasticity*** *of shaft and wheel. So local overloads can be avoided.*

Ill. 3-4 *(Lit. 3-21): The motorcar industry stands because the energy efficiecy under the the especial constraint to realize a light design./ construction. The transition from conventional* ***steel sheets to aluminium allloys*** *demanded more than only a materials change. Besides the* ***weight*** *stands the* ***stiffness*** *of the design in the foreground (Ill. 3-5). It influences the driving behaviour with the twisting of the autobody. Because the* ***modulus of elasticity of the aliminium alloys*** *only reaches ca. 1/3 of steels, increased hollow profiles and/or ca. 40 % thicker walls came to application. These designs are called 'spaceframe'®. They must be realized with new or* ***unconventional joining techniques****. To these belong also* ***adhesions of hollow profiles*** *with complex shaped* ***'knots' made as pressure castings****. It should also noted, that in spite of a comparable static strength, the fatigue strength of aluminum alloys is lower, because in contrast to steels, a real fatigue endurance limit does not existis and the corrosion behaviour (Ill. 3-6) must be handled.*

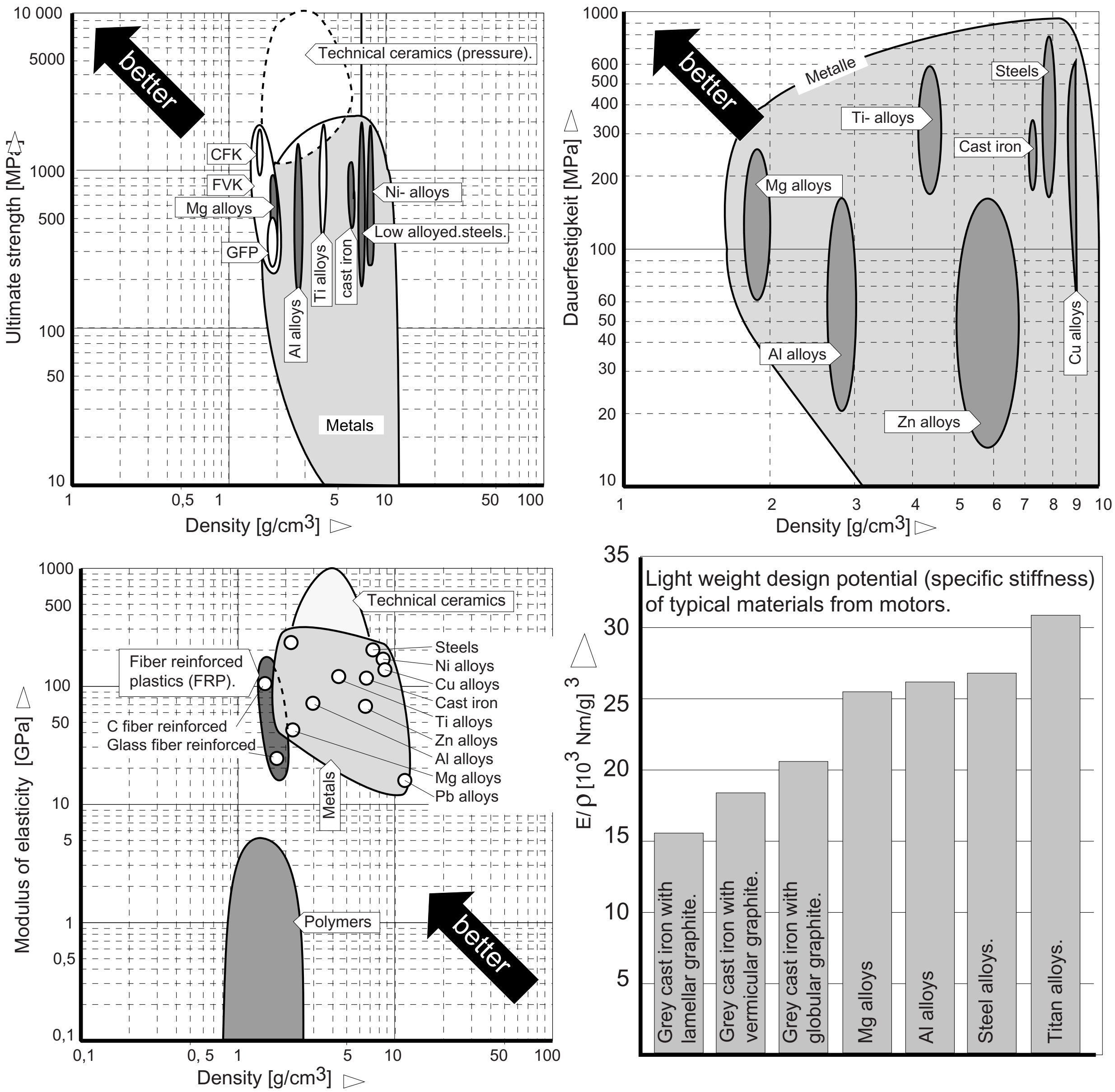
Ill. 3-5 *(Lit. 3-6): If we take as indication the strength properties of* ***low alloyed steels*** *as preferred materials of the 'conventional machine engineering', potential light weight design materials can be assessed as follows:*

Aluminium alloys*:*
The ***ultimate strength*** *of the steels lays about double as high as this of high strength aluminium alloys. Anyway its* ***specific*** *(tensile)* ***strength*** *(tension length) because of the markedly lower density (diagram above left) is at least comparable.*
The ***fatigue endurance limit*** *(a real one does not exist for many nonferrous metals and austenitic alloys) however is located a multiple lower (factor ca. 5) as for steels (diagram abov e right). Interestingly in this field Mg alloys can behave better. If the specific (dynamic) fatigue behaviour is concidered, the disadvantage is reduced but a deficit remains. Are deteriorations by corrosion added, the notch effect of these pittings can dangerously downgrade the fatigue strength. This may especially apply to corrosion susceptible magnesium alloys (Ill. 5.6.1-2).*
The ***stiffness****, shown by the modulus of elasticity (E module) is for aluminium alloys only about 1/3 of this from steels. Even more unfavourable behave magnesium alloys (diagramm below left). Here also the low density can not compensate this deficit (diagramm below right) and must be adjusted with suitable design principles (Ill. 3-4).*

Titanium alloys*: These prevailed so far in spite of the high price in the applications of light weight design like the aircraft industry, especially in aeroengines or high performance motors of the motorsports, . Here a rich treasure trove of experience about the disadvantages and the advantages which can be utilized by the mechanical engineering.*
The ***ultimate strength*** *of high strength titanium alloys correspondents with strong steels and outperforms these if the density is considered (specific strength) markedly (diagramm above left).*
Fatigue endurance limit*: For high strength titanium alloys this is in the range of heat-treated steels. Is the 40% lower density considered, the use especially in dynamically high loaded components (i.g., connecting rod, compressor rotors), does not surprise. However problematic is an especially large materials specific drop of fatigue strength during fretting (Ill. 5.9.3-4). This demands special design measures like strain hardening or intermediate layers. An advantage is the high corrosion resistance of the titanium alloys.*
Its ***stiffness*** *respectively the modulus of elasticity are markedly lower than for steels. But the low density does more than compensate this disadvantage (diagram below right).*

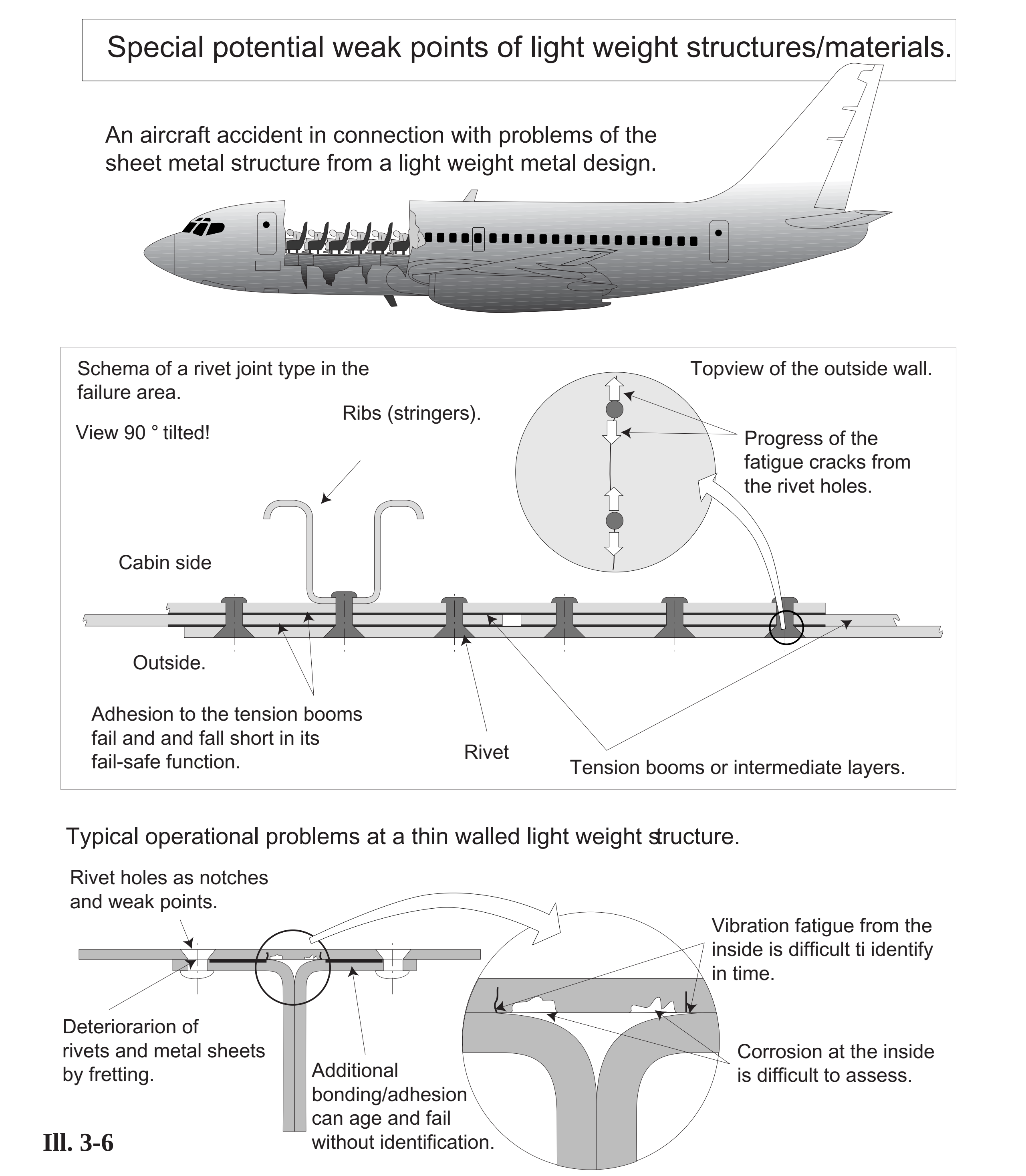
Fiber reinforced plastics *(FRP): The buildup sequence of layers and the orientation of fibers prevent a direction depending strength and stiffness (anisotropy). This property must be adapted to the special requirements of the application. The tensile strength of FRP, especially if a* ***damage by delamination*** *exists, is markedly higher as the* ***usable compressive strength*** *(Ill. 3-12).*
Ultimate strength*: Because of the anisotropy of the FRP materials a direction independent strength correspondent to the metals ,can not be specified. Therefore values from diagrams concerning the realiability in the part must be considered with care. Also the temperature resistance because of the plastic/resin matrix is very limited (long-term about 100 °C). In spite of this, carbon fiber composites (CFC) are because of the low density superior to metals if orientated strength is used (diagramm above left).*
Fatigue endurance limit*: A (dynamic) fatigue strength with crack formation as failure criterion like for metals does not exist for FRP materials. These* ***fail in the fatugue phase by delamination*** *(desintegration of the composite layers). This can*

Dependency of the strength and stiffness from the density of a material is an important criteria for the application in light weight design.



Ill. 3-5

be used as fail safe behaviour. It leads to increased inner ***damping*** *and can so minimize high frequency vibrations respectively resonances. Because a perpendicular crack does not occur in spite of the fatigue* ***remains a high tensile strength.***



Ill. 3-6

***Ill. 3-6** (Lit. 3-23): This accident is an impressive **example for design caused problems of a light weight design from high strength aluminium materials in maintenance and overhaul**. It was the impulse for increased activities concerning the influence of the „human factor“.*

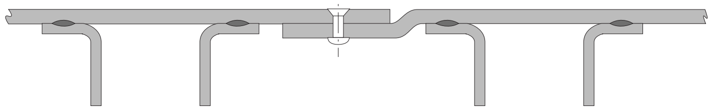
*The failing sequence started in the region of a **rivet joint**. Along the rowe of holes lengthwise the cabin wall at several points **fatigue cracks** developed, after the additional **adhesive joint** of the riveted tension boom failed. It was intended for a **fail safe behaviour of the connection**, but*

showed faults, probably because of the not easy production. After the failing of the connection it came to the displayed failure.
*From the **conclusions in the investigation report** of the responsible authority in exerpts can be said summarized:*
*- Before the loosening of the adhesian joint with following corrosion and fatigue cracks, already about **14 years before in a bulletin of the aircraft producer was warned** and repeated inspections have been demanded. **The potential failure dimension however was not realised**.*
*- There have been **sufficient informations** at the operator to link (indirectly) the loosening of the adhesion joints and the crack formation in the metal.*
This should have been enough for the execution of the maintenence program to identify the crack formation and a repair in time.
*- The **inspecting authority** should have expanded the inspections from a (obviously especial critical) overlap joint at all joints.*
*- It could not be figured out, if the operator actually carried out the one year before edited **airworthiness directive** (AD) in which an **eddy current test** was demanded, or if the test was insufficient. This **test would have also shown additional fatigue cracks in the metal**.*
*The instructions of the **AD** tolerated, because of a **inaccuracy**, that the maintenance personnel did not carry out the exchange of a critical rivet version.*
*- From the inspecting authority **no sufficient knowledge was demanded from the mechanics approved by it**. This was however necessary to maintain and test modern airplanes. Reason for this knowledge deficit has been t**raining material which was no more contemporary** for the state of the art.*
*- There have been **work conditions** (**human factors**), which acted adverse at a **visual and non destructive testing**. This could lead to the effect, that identifiable failures could not be found (Lit. 3-27).*
*- The **managemt of the operator ignored human factors**, needed to motivate for a successful test. To this belonged the concentration at corrosion and crack formation in critical joints. Later informations showed, that this **deficit obviously existed at many operators** of the concerned aircraft type.*
*- A national inspection/review program (NASIP) of the operators fleet, carried out one year before **did not find the weak points/faults**.*
*Additionally the inspection authority was **not especially familiar** with the problem of the joints and **informations** about safeguarding programs of the authority with the aircraft producer lacked.*
*The conclusion of the investigation for the **main failure cause** can be summarized as follows:*
*The aircraft accident can be traced back to the **failing of the maintenance program** from the operator. Dangerous separations of the **adhesive joints and fatigue failures**, which triggered the failing of the cabin have **not been identified**.*

***Comment**: Also if the main cause is seen by the authorities in deficits of the maintenance process, it must be stated that the following l**ight weight specific influences finally created the requirement for the problem**:*
- Combination of adhesive and riveting joint.
- Fail safe behaviour is not garanteed.
- Difficult/uncertain tests during operation, obviously especially of the adhesive joint in the early stage of the deterioration.
- Very endangered by corrosion in sea atmosphere .
- Dynamic fatigue fractures have not been realized.
- No adequate training of maintenance and repair.

Proven light weight designs.

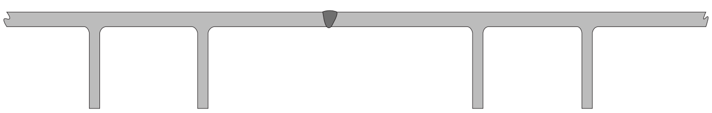
Light weight design at the example of a **plane structure**.



Advantages:
- Fail safe behaviour.
- Easy recycling,.
- Repair friendly.
- Universal joint.
- Vibration damping.

Disadvantagese:
-Weight of the joint.
- Notch effect.
- Corrosion
- Non destructive testing.
- Work effort.

Differential design
(structural design technology)
- Punctual joints with rivets, adhesive bonding and spot welding.



Advantages:
- Optimal weight reducing.
- Producible by casting.
- Power flow can be optimized.
- Better automatable production.
- High strength complex parts.
- Non destructive testing.

Disadvantages:
- Weight of the joint.
- Notch effect.
- Undamped/vibrations.
- Corrosion.
- Crack detection.
- Repair can be problematic.
- Material inventory for the production by chipping.

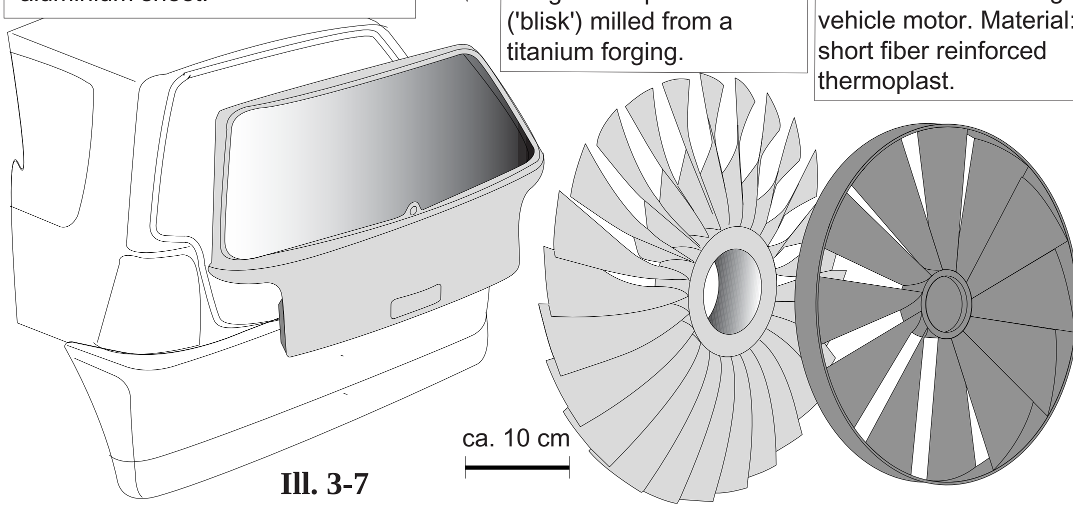
Integral design
(in one piece)
- Casting, forging, chipping/milling.
welding, adhesive bonding, powder metallurgy, electrochemical machining, rapid prototyping/3D laser printing, electroforming.

Examples for integral designs of c**omplex geometries**.

Hatch door with inner struktur from magnesium pressur casting and a adhesive bonded planking from aluminium sheet.

Integral compressor wheel ('blisk') milled from a titanium forging.

Blower wheel of a large vehicle motor. Material: short fiber reinforced thermoplast.



Ill. 3-7

Ill. 3-7 *(Lit. 3-3 and Lit. 3-4): Besides load related terms (Ill. 3-2)* ***light weight strategies can als be assigned designs****. Thereby the* ***differential design can differ from the integral design*** *(upper frame, Ill. 3-3). Every design has its specific advantages and disadvantages.*
At the conventional differential design the component is joint from several elements. If

In leight weight designs, because of the elastic flexibility, thin cross sections and high strength utilized capacity as possible, all operation influences must be determined.
To these belong also such, which at conventional designs must not be considered.

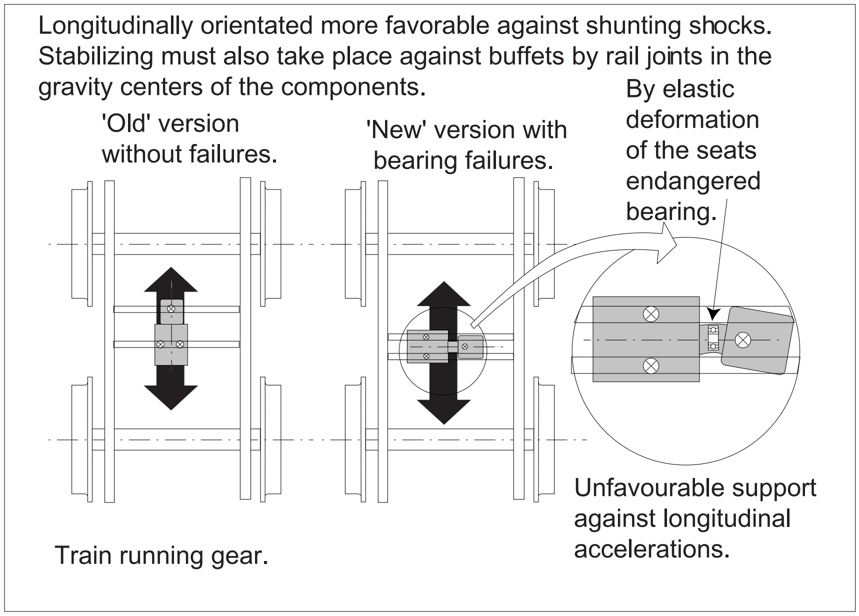
Examples (no claim for completeness):

Inner forces:
- Acceleration.
- Gyroscopic forces.
- Unbalances.

Inner stresses:
- Internal stresses from production
- Thermal stresses.

External forces:
Impact forces.
Inertia forces.

Corrosion:
- Material, combinations.
- Shaping (cavity).
- Operation atmosphere.
- Storage/down times.
- Equipment/auxiliaries.



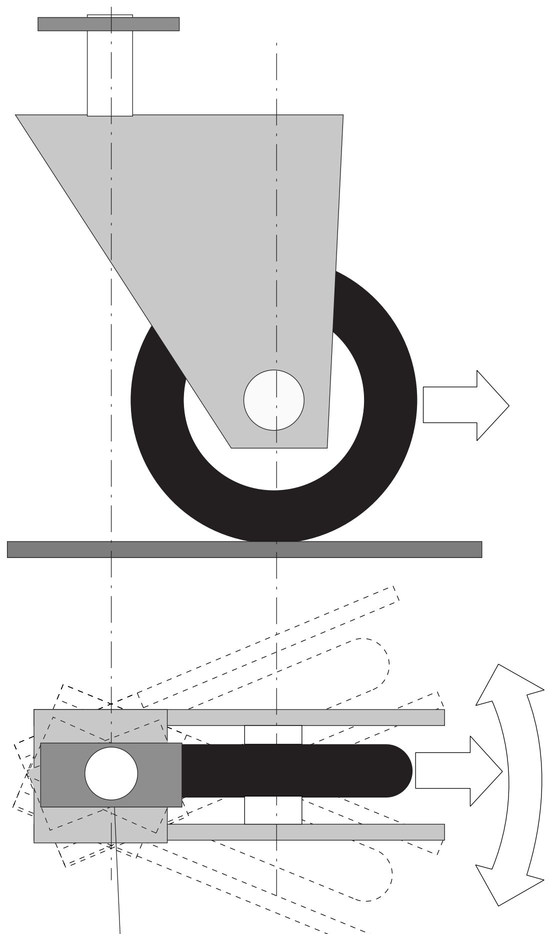
Ill. 3-8

possible, these are produced from standardized semi-finished products in a simple manner. This design was especially applied at airplanes and ships.

The ***integral design*** *tries to produce a component with as little as possible substance-to-substance bonds/joints. For this casted and/or chipped elements of complex geometry are used. In the aircraft construction this approach is used since long time. It was adopted by the vehicle construction. Typical example are doors with a complex structured light metal pressure cast frame (Al and Mg alloys). This is combined to a 'hybrid design' with planar parts from other metals (sketch below left). For this it can be necessary to optimize bonding/joining processes partspecific (adhesive bonding, riveting, bolting). However different materials can demand special measures against corrosion (corrosion cell forming). The sketch below right shows a so called 'blisk' (bladed disk, Ill. 3-16). It concerns a milled and/or by friction welding joined compressor wheel of the front stages (fan). Such components can be found today in military and civil aeroengines. As blower wheels (Ill. 2.2.2.1-7), e.g., for coolers, these are since long usual in the the machine/vehicle industry.*

Ill. 3-8: Conventional designs whose weight is not first priority, *distinguish with relatively massive design, especially thicker walls. With this they have besides* ***high strength reserves a high stiffness****. Passing to light weight design, just its* ***elastic flexibility can lead to unexpected problems****. An example are* ***vibrations and overloads*** *of the bearings from rotation components. In such a case the unfavourable* ***load transmission*** *triggered the early failing* *of bearings during operation. An example is the displayed air pressure aggregation for wagon brakes. At a new model, different until now, a orientation of the aggregation longitudinal axis was choosen transverse to the direction of travel. This allowed shunting and rail shocks to act as a bending load transverse at the casing. Thereby its 'wasp waist' cross section between compressor and electric motor, which contained an anti friction bearing, was heavily elastic deformed. This lead to an* ***overload of the bearing*** *and its failing. These failures have been for a longer time misinterpreted as corrosion, because of the fretting (elastic micromovements, Ill. 5.9.3-2) at the outer bearing seat. Also the effect of the stiffness problems obviously was not aware. This shows the importance of basic knowledge about technical problem analysis.*

Flutter of a wheel.



Elastic deviation of the setting and swiveling axis.

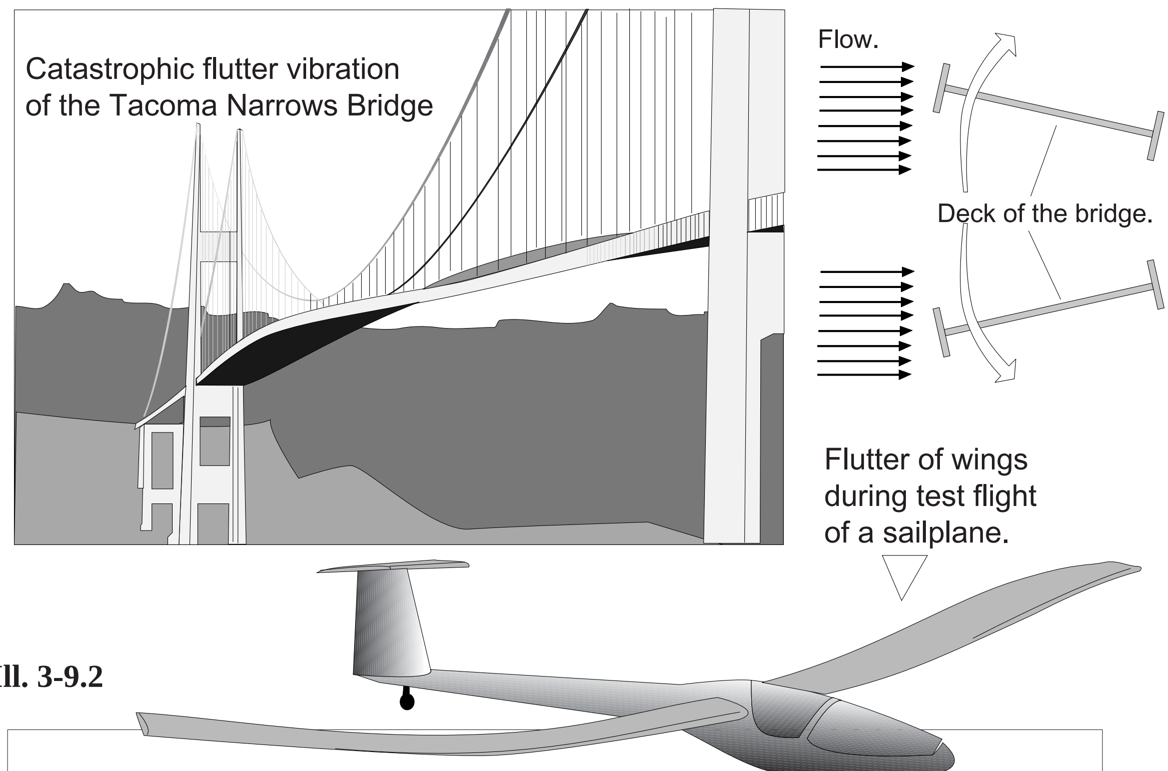
Ill. 3-9.1

Ill. 3-9.1 and Ill. 3-9.2 *(Lit 3-2): A* ***flutter vibration*** *is a* ***self exciting, self intensifying process****. Tis can be of different nature. Examples are* ***aerodynamic and mechanic excitations****. Mechanical excited* ***flutter occurs at wheels*** *(shimmy, wobble, Lit. 3-53). This is the case, if the contact ares in movement direction is unfavourable to the piercing point of the swiveling axis of the wheel. A play in the guidance acts triggering. Elastic deformations arrange the retraction. The forward moving feeds the necessary energy.*

Interplay with a partial or fully separated flow can excite components and machines (e.g., flown planes like at blades of turbo engines, Lit. 3-2) to ***dangerous vibrations*** *(flutter). Thereby a periodically separating* ***vortex formation*** *can play a role (Kármán vortex street, Ill. 3-9.3). In such cases in very short tome a catastrophic failing must be expected (sketch above). The danger increases with slender,* ***aerodynamic highly loaded cross sections*** *how they are typical for modern light weight design.*

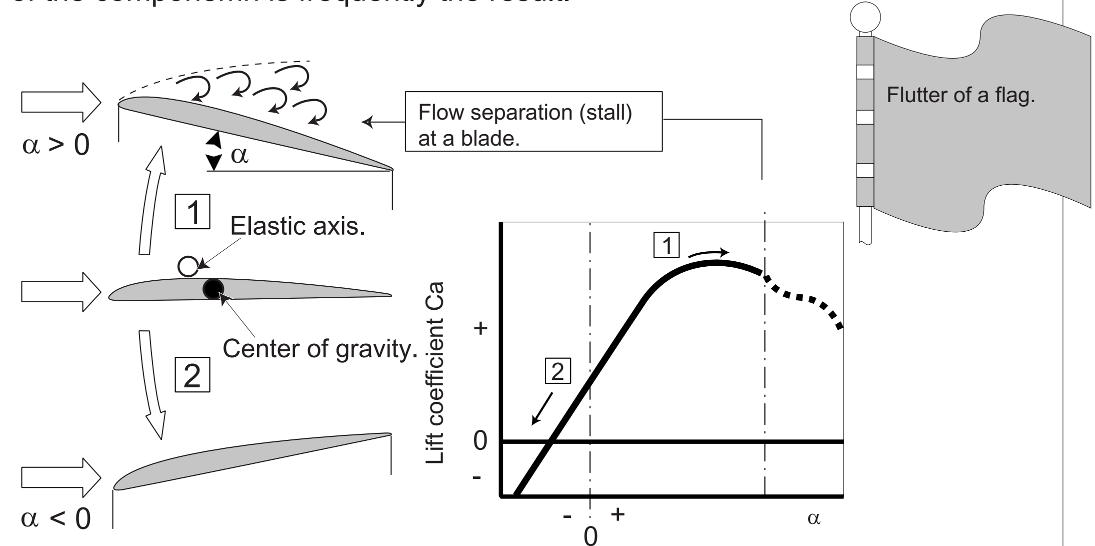
Triggering act ***little vibrations*** *of the blade like it is excited in manifold manners, e.g., by flow distortions before and behind the flown part. The blade vibrations influence the flow in a manner, that pulsating gas forces develop. These act at the blade self intensifying. The excitation mechanism shows the sketch below. To get into the flutter condition,* ***first of all a sufficient large vibration deflection of the blade is necessary****. Such a vibration can be excited in different ways. Typical excitations are flow disturbances or in turbo compressors changes of the tip clearance at the circumference. The blade profile does not only twist during a* ***torsion vibration*** *(especially dangerous) but, because of the change of the angle of the blade chord, also during a* ***flexural mode****. With this changes the angle of attack. Is the deflection not enough a stall occurs („1“). As*

Flutter vibrations are not only a problem of aiplane wings. Flowed light weight designs are potential endangered.



Ill. 3-9.2

Flutter is a self exciting process from which is hardly to escape. A failing of the componemn is frequently the result.

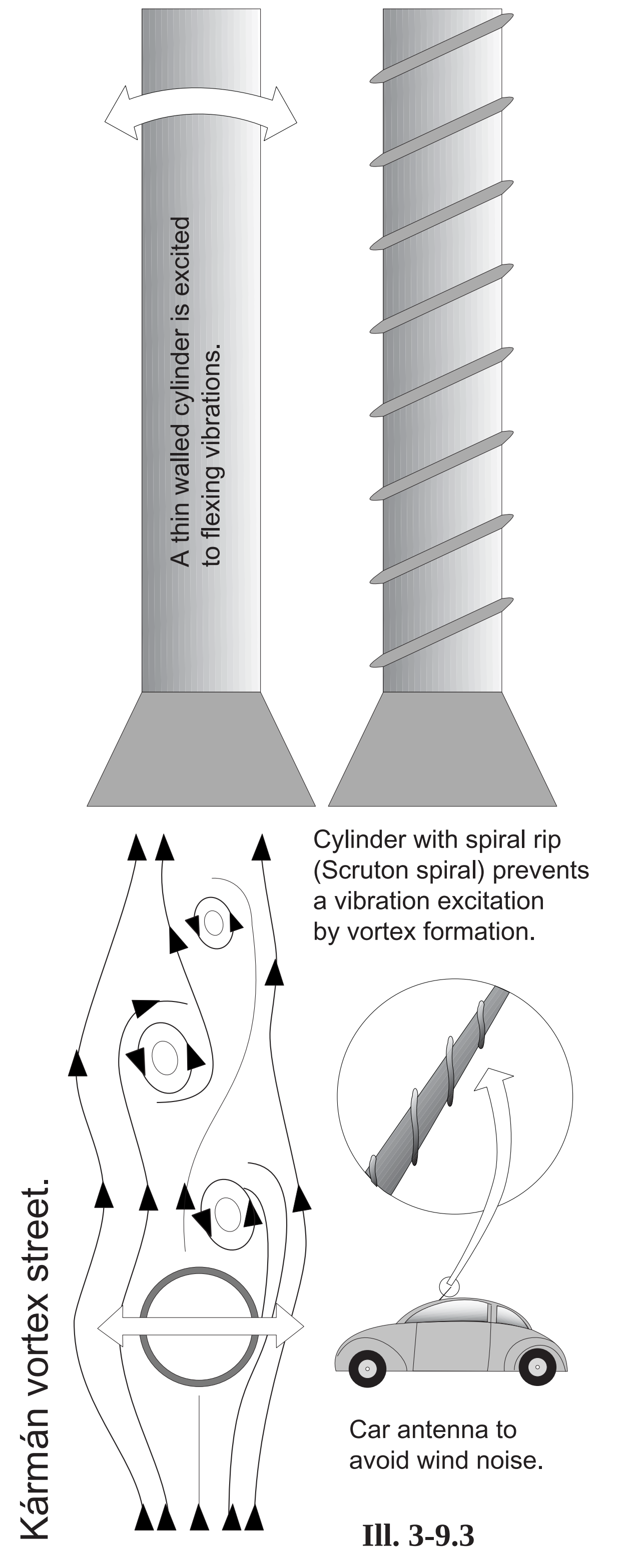


Flutter of a compressor/fan blade in the region of the separation.

consequence the deflected gasload drops. The part swings back elastically. So the angle of attack decreases, the flow fits again („2“). The gasload (lift) builds up again.

So an interaction of mechanical and aerodynamic forces is concerned. It is difficult to get out of the flutter condition. A pressure drop is in fluid flow engines usually not sufficient. In contrast a change of the inflow is necessary.
The deflection depends from the ***stiffness of the whole vibration system****, whose element is the actual excited component.*
Flutter occurs, if the ***flutter speed*** *(there are several flutter types, corresponding the type of excitation) will be exceeded. This vibration process is in* ***turboengines*** *not limited at blades of axial compressors. Also blades of* ***radial compressors*** *and* ***turbines*** *can be excited to flutter. As examples show, flutter can occur in very different machines and even at* ***buildings*** *(flutter of a light weight suspension bridge 1940). In the displayed case a double T-profile of the deck from a suspension bridge is concerned.*
At ***airplane wings and control surfaces*** *(sketch in the middle) an extreme dangerous condition exists, which must be absolutely avoided. Appropriate proofs must be carried out during the dimensioning and the development phase.*

Note
The ***flutter of a flag*** *is merely based on a rhythmic separation from flow vortices. A lift, comparable with a stiff profile does not exist. Therefore a comparison is markedly 'limping' .*

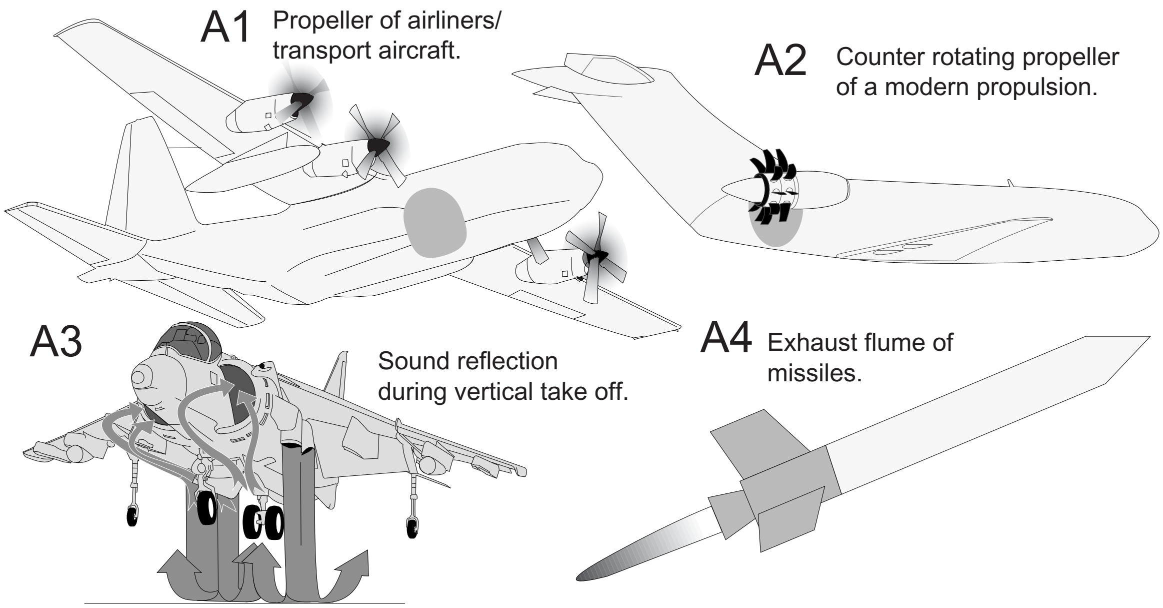


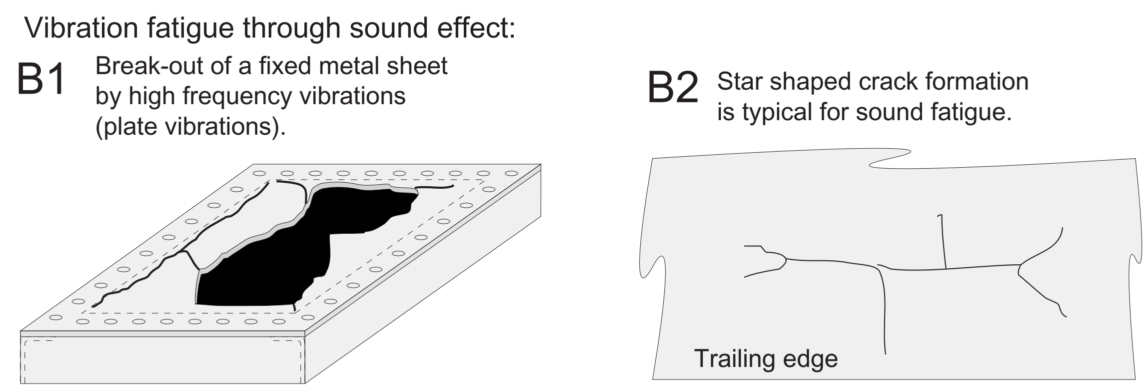
Ill. 3-9.3

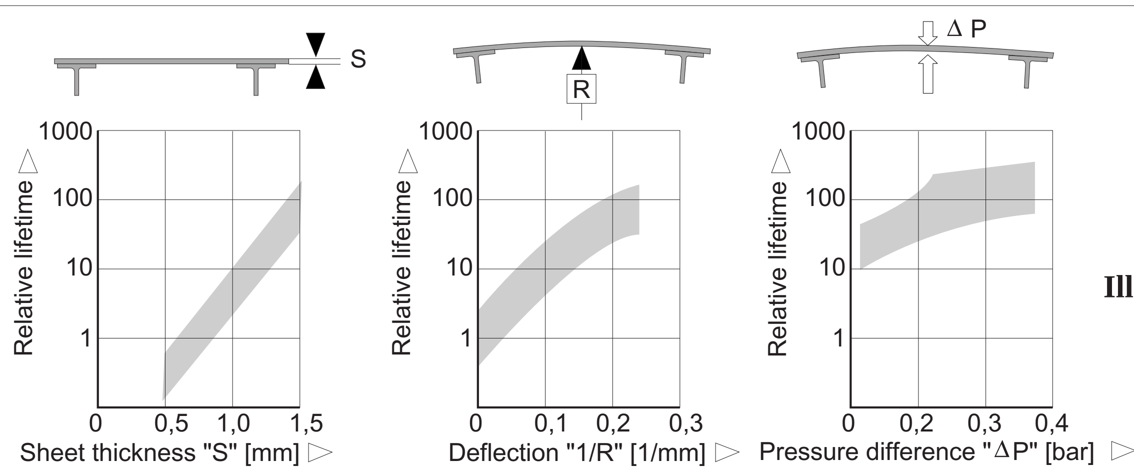
Ill. 3-9.3 *(Lit. 3-39 and Lit. 3-40): Under certain flow conditions (Re number) a* ***Kármán vortex street*** *develops. Thereby at the* ***lee side of a body****, here a cylinder,* ***two counter-rotating, periodic separating vortex bubbles*** *develop. Its separation frequency is determined by the Strouhal number. The vortex formation creates* ***lateral forces*** *at the body/cylinder which deflect it. In* ***the case of resonance*** *it comes to dangerous* ***flexural vibrations****, the aerodynamic* ***flutter****. This effect is held responsible for the vibration excitation, which finally collapsed the Tacoma-Brücke (Ill. 3-9.2). Here the vortex street developed behind the side plates of the bridge.*
At cylinders a dangerous vortex excitation can be prevented with a ***spiral circular rip*** *(vortex breaker, Scruton spiral). This design is uset at light elastic buildings like cooling towers and chimneys. At* ***roof antenna*** *of cars so the irritating* ***whistling noises*** *are prevented.*

Ill. 3-10 *(Lit 3-13 and 3-41): Light weight parts are sensitive for high frequency* ***vibration fatigue*** *because of its high elasticity and low structure weight. To this counts the* ***fatigue by sound****. It causes crack formation up to fracture. Concerned are especially plankings/****panelings of aircraft fuselages****. As exitation serve sound vibrations, i.e. high frequency pressure oscillations of the air. The upper sketches show some typical examples at which sound fatigue is of especial practical importance (Lit. 3-24). It must be considered by the designer. To this also belongs the rear area of* ***fighters with afterburner*** *(Ill. 5.2.5-2). This was often only* ***indicated by the operation experience****. Especially loaded are surfaces, orientated* ***transverse to the propeller plane*** *(„****A1****“). New developments of high-speed, multi blade propellers, especially also counter-rotating, may intensify the problem (Lit. 3-14). This is the cause, why at the displayed test aircraft the* ***propellers are located at the tail*** *of the fuselage („****A2****“). Also* ***vertical take-off aircraft*** *(„****A3****“) have shown as especially endangered by sound fatigue. The hot* ***exhaust gas plume*** *in connection with reflections at the ground, represents an especially intense noise source. Similar dangerous are the exhaust gas plumes of missiles/****rocket engines*** *(„****A4****“) for its rear part. Because of the high sound frequency even short firing periods can be sufficient for a failure.*
With little luck and expert knowledge it can be suggested at sound fatigue as cause from cracks and break-outs in the ***failure mode****. Typical are branched cracks („****B2****“) and plane out-breaks („****B1****“) in thin metal sheets (plate vibrations). The proneness for sound fatigue can be minimized at the* ***stiffeners*** *(arrangement, thickness). In extreme cases even aircraft fuselages with extensive elements as sound absorption and active arrangements (‘counter sound’) have been taken into account and tested.*

Light weight structures can react sensitive at high frequency loads which are not considered in the 'normall mechanical engineering'.

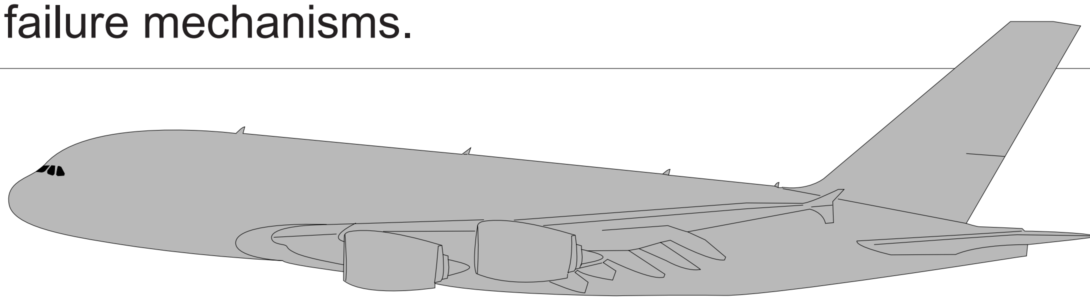






Ill. 3-10

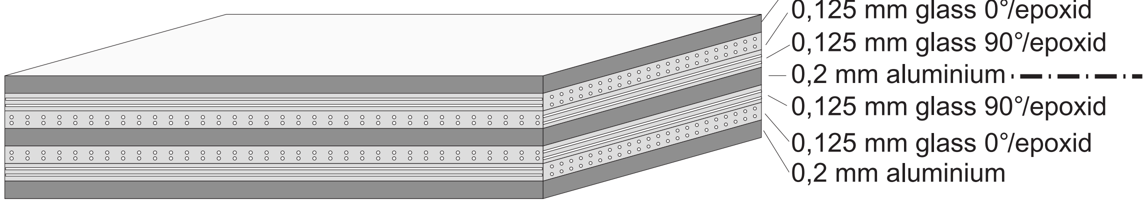
In the light weight design increasingly materials and material compounds are implemented which are till now unusual. Requirement is the knowledge of the failure mechanisms.



Laminates of fiber layers (aramid, glass), metal (aluminium alloy)

Aramid **R**einforced **Al**uminium **L**aminate (ARALL)
Glass **A**luminium **Re**inforced Laminate (GLARE)

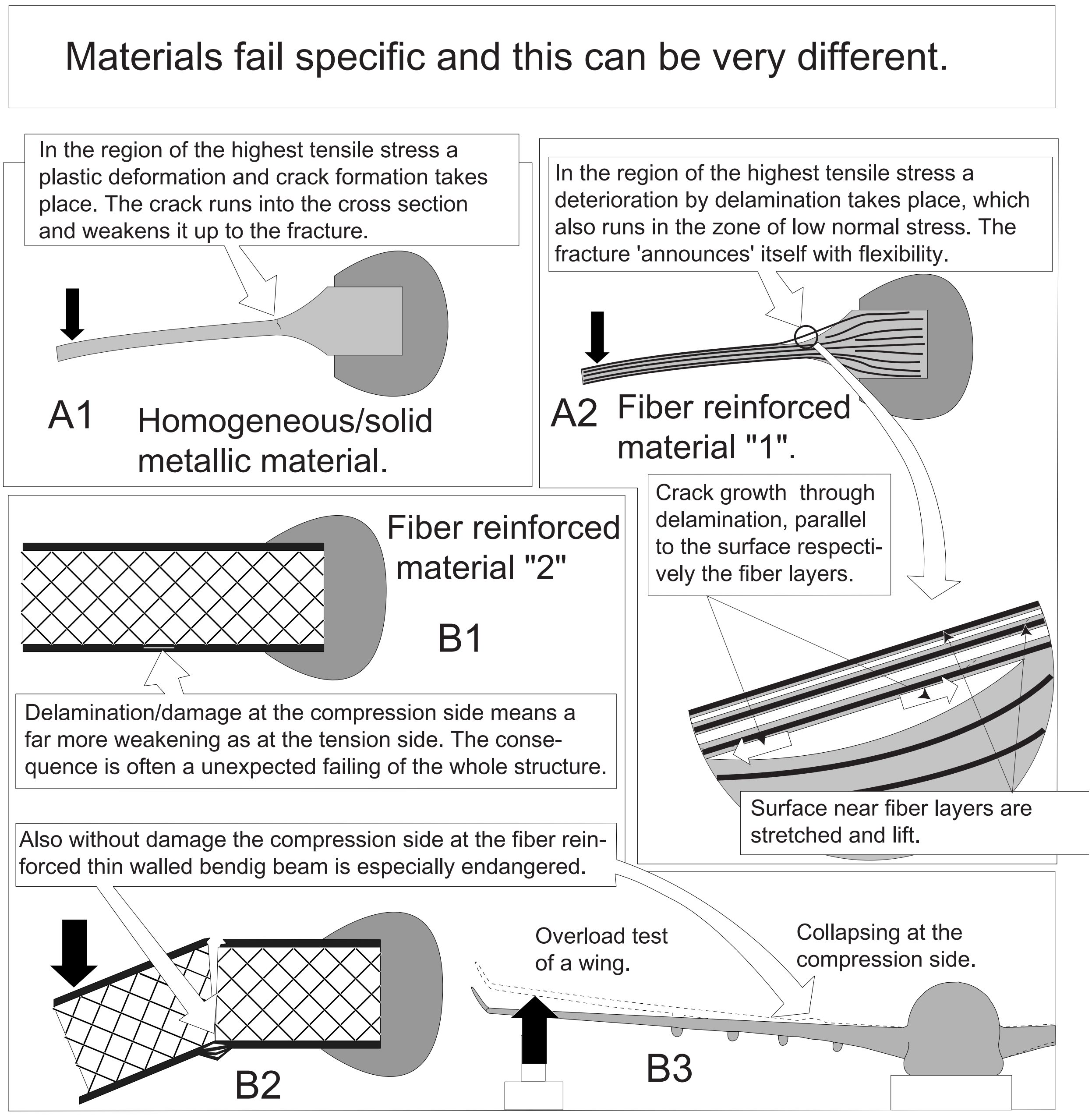
Buildup sequence (symmetrical) of a Glare material.



Ill. 3-11

Ill. 3-11 *(Lit. 3-26): For the* ***planking of the fuselage*** *from a modern wide-body airliner a* ***laminate*** *(layer material), GLARE) from several GRP layers and aluminium sheets was choosen. The layer build up with fiber orientation shows the luwer sketch. The* ***symmetry*** *is necessary to prevent distortion. The stiffness (low modulus of elasticity= E-module) of this laminate lays below solid aluminium. However for high frequency vibrations corresponding sound fatigue (Ill. 3-10) is the* ***inner damping*** *of especial importance. At this vibration fatigue practice comparable operation influences like temperature cycles obviously had no noteworthx influence. It is astonishing, at least for sound fatigue, that the laminate sequence showed a minor importance. Thereby adhesion bonds proved superior to rivetings. The* ***fail save behaviour*** *(Ill. 3-19) of such layer structures should not be overestimated. Still is a fast propagating fatigue crack, because of the fiber reinforcement and damping delaminations surely not so dangerous like in a homogeneous sheet metal (see also Ill. 4.3-24). A special potential problem is corrosion sensitivity, especially at contact of FRP/fibres with light metals. This must be considered by the designer.*

Ill. 3-12 *(Lit. 3-2):* ***Different materials specific failing*** *must be considered during design.*
For example, if at a one side fixed ***metallic beam*** *with thickened clamped cross section („****A1****“) static bending loaded (sketch above left), plastic deformation and* ***crack formation occurs, transverse to the tensile stress loaded surface****. A crack leads to accelerated loss of strength and fracture.*
A beam in bending from ***fiber reinforced plastic*** *(FRP, „****A2****“)* ***with a reinforcement at the clamping*** *may indeed fail at the same zone like*

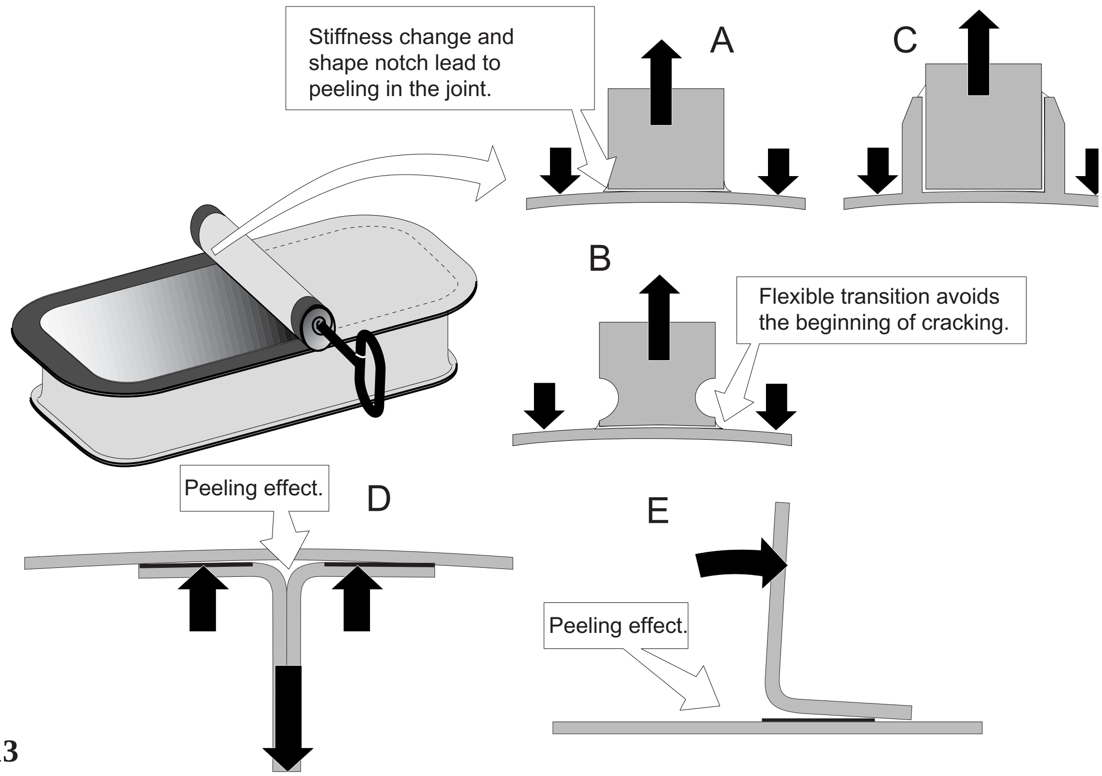


Ill. 3-12

*the solid metallic version. However the **failing mode** takes place with the **lifting of surface near layers(delamination)**, thus with a **crack formation along** (parallel) **the surface**. The special failing modes of fiber tecnical structures can also observed in **wood** (Lit. 3-50). Here the **bionics** (Ill. 3-24) can serve the understanding and offers **approachs and orientation for bearing fiber layers**. Thereby the drop in tensile strength is relatively moderate, because the delaminated fiber layers can take tensile loads. So **the fracture signalises itself in time and so can be intercepted**.*

*Especially endangered ahre **hollow bumper brackets** (bended beams, „**B1**“) like sandwich struktures or tubes (e.g., masts, ski sticks) from FRP. These are susceptible for a **collapsing of the compression side** (Lit. 3-38, „**B2**“). This is especially true if a **local damage** exists and must be considered during **repairs**.*

The worst which can be done to a joint of fiber layers respectively an adhesive bonding is the peeling effect ("fish can effect").



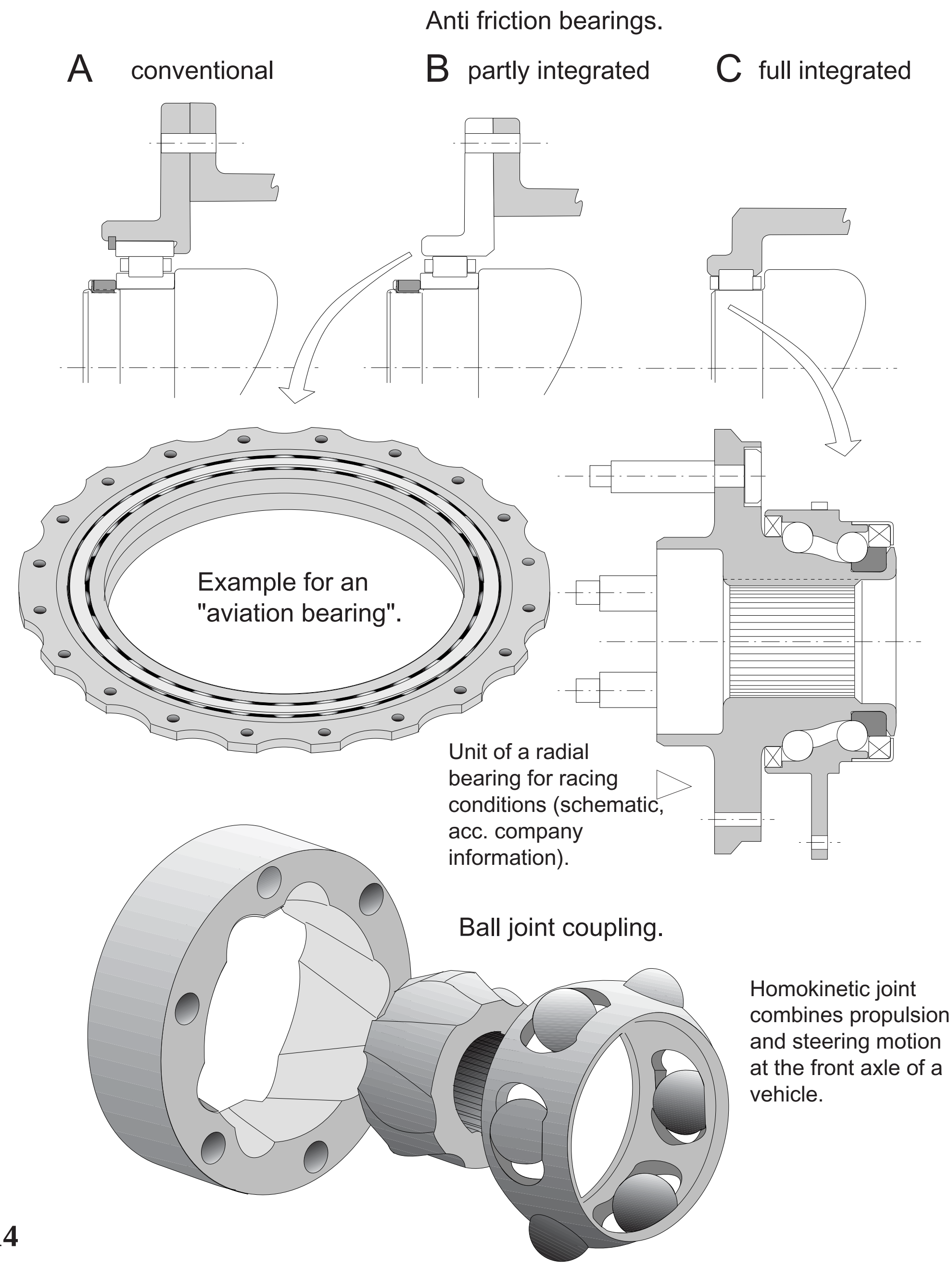
Ill. 3-13

*„**B3**" shows the fracture of an **aircraft wing** with a plankung from fiber reinforced plastic during an overload test. Thereby the compression stressed upper side failed with typical collapsing (Lit. 3-38).*

***Ill. 3-13** (Lit. 3-27): The **specific strength behaviour of a braze joint must be considered by the designer**.*
*Thereby especially a **peel stress** ('fish can effect') must be considered. Concerned is a combination of bending and shear (upper sketch). This load is not alwas to identify at the first glance. It can develop only through markedly elastic and/or plastic **deformations**. For this, light weigtht structures are sensitive („**D**" and „**E**"). At the other hand these can also use an elasticity, by avoiding stiffness jumps in the region of the joint.*

***Design examples for brazing and adhesive joints:** Aspired should be **brazing surfaces** which are **loaded by shear** („**C**") **as large as possible**. Must brazings be tension loaded, the brazing surface has to be enlarged and attention payed, that no stress increases act through **changes of stiffness** („**B**"). Also **elastic deformations** during a stress load may **not trigger a peeling effect** („**E**").*
*If not avoideble, the peeling effect can not be prevented, it must be minimized with an **elastic design** („**B**").*

Constructions of the light weight design, advantages and problems at the example of anti friction bearings and universal couplings.



Ill. 3-14

Ill. 3-14 *(Lit.3-27): Also* ***anti friction bearings*** *become light weight design. At wheel suspensions a demand for little as possible undamped masses can be satisfied. In aeroengine design the minimizing of weight is traditional. Must the bearing fulfill satisfy several tasks like transmitting forces from drive, brake and steering, this will be fulfilled in complex systems (sketch below and middle right). Such bearing rings have complicated geometries to meet the additional* *tasks. With this, the highest* ***materials quality*** *is necessary for anti friction bearings and the guarantee for close-fitting bearing typical dimensional tolerances is a challenge. The* ***repair*** *of such parts is usually excluded. Often these are exposed to a whole load spectrum. To this belong besides the bearing loads also corrosion and wear. This demands for the design correspondent experiences and/or an application specific proof of serviceability.*

Ill. 3-15 *(Lit. 3-3, Lit. 3-4 , Lit. 3-14 and Lit. 3-15): Light weight design uses the advantages of* ***composite design****. Almost all thinkable combinations can be found.*

- ***Different metals****: The sketch above left shows the engine block of a motor vehicle. The* ***cylinder liner consists of coated aluminium casting****. It is casted integral into the casing from a* ***magnesium alloy*** *(Lit. 3-4).* ***Boltings*** *between both light metal alloys consist* ***of a high strength aluminium alloy*** *(Lit.3-7). With this an* ***usable strength*** *of the connection can be realized, which is with steel bolts even superior. Reason is the better adjusted thermal expansions and stiffnesses (modulus of elasticity, Ill. 3-4). These guarantee the safe prestressing of the bolts.*

- ***Metals in combination with ceramic materials*** *for example can be found in* ***protective panels against penetration*** *(containment, Lit 3-28) by high-energy parts like fragments of high speed cutting tools (sketch above right, Lit. 3-3).*

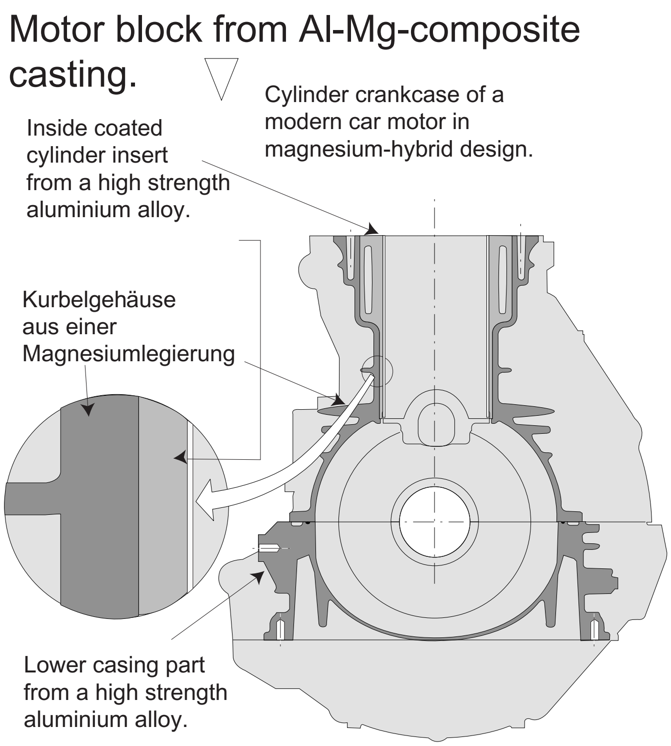
A further application is tested respectively applied in hot parts of internal combustion engines and turbines. To these belong ceramic turbocharger wheels which are joint with a shaft from heat-treated steel (Ill. 3-3). The sketch below left shows a ceramic turbine vane in a detachable hybrid design with a metallic supporting structure.

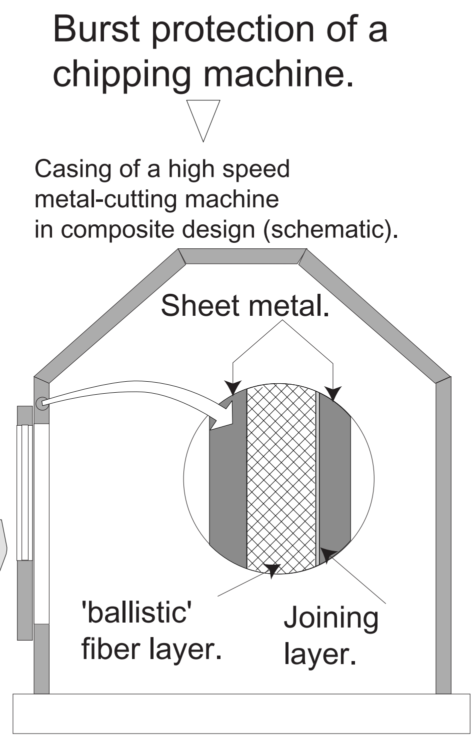
- Plastics with and without fiber reinforcement *together with* ***metals,*** *for example can be found in aircrafts and car bodies. Typical are* ***plankings*** *at a supporting metal skeleton. The joining will be realized for example as riveting or inseparable by injection molding (e.g.,* ***bumpers****).*

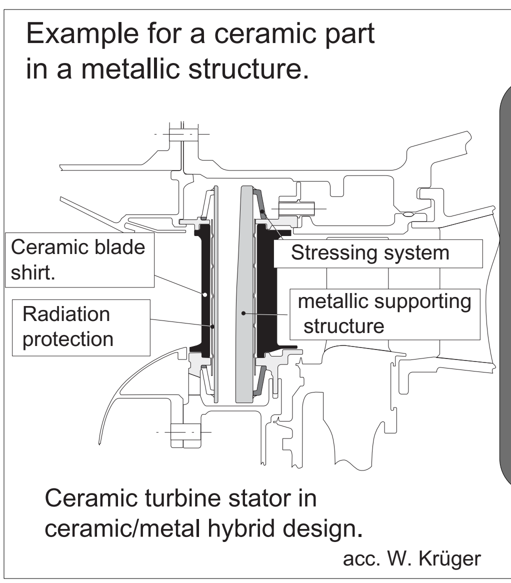
- Fiber structures *(e.g., textures)* ***with monolithic ceramics.*** *This technology is used as* ***ballistic protection****, e.g., in* ***bulletproof vests****. Thereby ceramic tiles take on-site the energy absorption by splintering. In contrast, in the fiber layers (aramid - 'Kevlar'®) friction and elongation acts. It can still highly load supporting and or protecting structures beneath.*

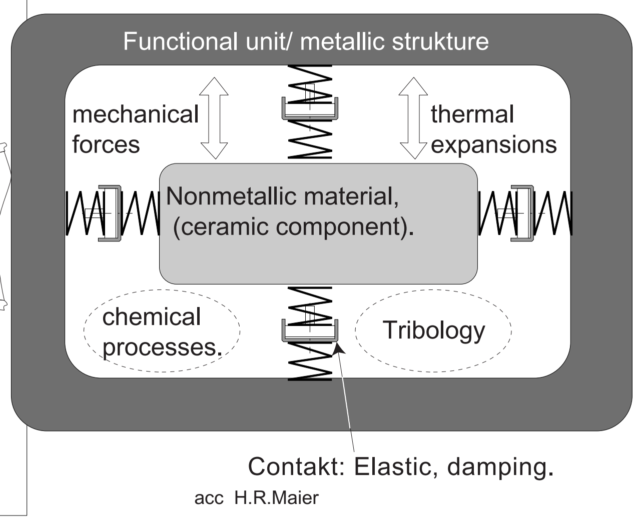
An especiel ***problem uf the hybrid design*** *from* ***metallic and nonmetallic materials****, especially ceramics, is displayed in the sketch below right (Lit. 3-15). Concerned is the* ***contact region of the components****. Different thermal expansion and stiffness must be disarmed and surely controlled with suitable design principles.* ***Load transmission*** *may not locally overload brittle materials, because the danger of fracture. This must be guaranteed by a suitable* ***shaping*** *of the contact surface,* ***adapted stiffnesses*** *of loaded cross sections (Ill. 3-3) and/or* ***compliant interlayers****. Also chemical processes like* ***corrosion*** *or* ***reactions*** *(e.g., silicon carbide with nickel alloys at high temperatures) must be avoided. Sliding and* ***friction properties*** *for example influence the* ***stresses*** *(shear)* ***in contact surfaces*** *(Lit. 3-28).*

The modern light weight design frequently uses composite designs. The integration of nonmetallic materials into a metallic construktion is an especially challenge.









Ill. 3-15

Description of the Ill. see previous page.

Ill. 3-16 *(Lit. 3-2): With the example of a compressor rotor disk from an aeroengine an* ***evolution of the light weight design can be shown****. This trend is supported, because especially in military applications a low weight has a higher priority as minimized costs. It can be easy seen, that every design has advantages and disadvantages.*

„A“ Conventional design*: The blades are fixed in slots of the disk rim. The material of blades and disk can be different and so optimal adapted to the operation requirements. For example blades from FRP combined with a disk from a titanium alloy. So exists the possibility of an exchange of blades and/or disks. For this at a suitable casing design (axial split), a half shell can be opened on-site. Friction damping at the contact surfaces offers a certain protection against vibration overload. Potential disadvantage is a deterioration of highly loaded supporting zones by fretting (Ill. 5.9.3-4). On the other hand the blade slots weaken the rim. Therefore it is thicker, to take tangential stresses in the slot regions. So higher centrifugal forces load the disk, which now also, especially in the hub region, must be thickened.*

„B“ Integral *(blisk)* ***design****: Advantage is low weight, because the rim, bearing the blades is nit weakened by slots. This minimizes the weight in the hub area. The hollow shaft, formed by the ring lands to the neighbored disks, has a larger diameter whicht increases the stiffness. So the dynamic behaviour of the whole rotor improves. Disadvantage is the lacking friction damping at the blade roots. This increases the risk of dangerous resonance vibrations. An exchange of damaged blades is only limited and in spezial shops with highly adapted processes possible. With this also the logistics get more complicated.*

„C“ Hybrid design *with attached fiber rings: Concerned is an intermediate step from „B“ to „D“. It is not yet in opperation. The problems to expect for the integral ring design seem be markedly decreased. Especially a more simple and reliable quality control of the bearing fiber rings can be expected in production and during overhaul.*

„D“ Integral ring design *(bling) is in the development stadium. To realize potential advantages, especial minimum weight, a hybrid design is necessary. Thereby integral (with unidirectional fibers) or attached (here not shown) fiber rings are used. This promises additional high rotor stiffness and inner damping, to prevent dangerous vibrations. In contrast there is a very cost intense complex production. Additionally the quality assurance and with this the safety in production and operation (overhaul) is not sufficient clear.*

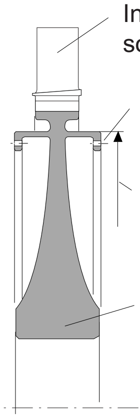
Ill. 3-17 *(Lit. 3-23): Designs with a* ***multitude of fibers or wires*** *as bearing element offer the possibility of a* ***fail save behaviour****. This is the case, if the load transferring* ***matrix*** *has no sufficient* ***strength*** *and* ***adhesion*** *at the fibers. However the single bearing filaments can break without already acute endanger the safety of the whole composite. So the chance exists, to identify in time this weakening and to exchange the part. In contrast a crack development in a homogeneous (solid) material (metal) can not be sufficient safe intercepted during fast* ***crack growth****, especially shortly before and during the residual fracture.*

The trend to "light weight design" captures the mechanical engineering more and more. With this, experiences from the aviation get more important.

The evolution of the light weight design at the example of a rotor disk from a turbo compressor.

Conventional design.

"A"



Inserted blades, solid rim.

Rotor connection, bolted flanges. Small shaft diameter.

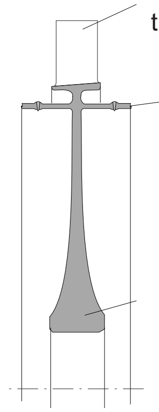
Load (centrifugal forces) caused massive disk membrane, especially the hub.

Advantages:
- Repair friendly (blade exchange, disk exchange)
- Vibration damped.
- Material of the blade and disk optimal adaptable.

Disadvantages:
- Heavy design.
- Assembly effort (bolting of the rotor).
- Problem of the blade root (fretting).

Integral design (blisk).

"B"



Integral blades, thin rim.

Rotor connection, welded.

Bigger shaft diameter.

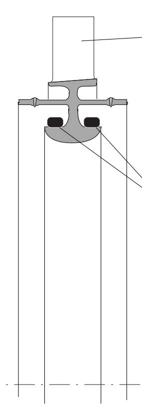
Load (centrifugal force) caused thin disk membrane and hub.

Advantages:
- Low weight.,
- Large diameter (increased stiffness).

Disadvantages:
- Undamped
- Exchange of blades or disk extensive.
- Repair demanding and limited.
- Logistics complicated.

Hybrid designs with attached bearing unidirectional fiber rings.

"C"

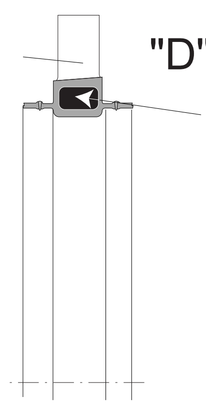


Integral blades, Thin rim.

Bearing form-fit fiber winding.

Integral ring design with integrated fiber reinforcement (bling).

"D"



Bearing material bonded fiber winding.

Ill. 3-16

Advantages:
- Extremely light.
- High rotor stiffness.
- Large hub diameter.

Disadvantages *):
- Complex production with high costs.
- Difficult quality assurance
- Bad monitoring of a deterioration during operation.
- No blade exchange.
- Repair problems.

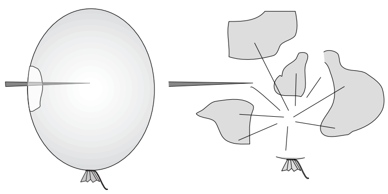
*) Disadvantages count less for the design with attached fiber rings.

Description of the Ill. see previous page.

Problems of components from a homogeneous material at uniform high stressed volume.

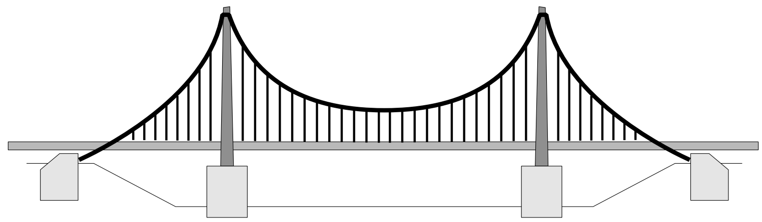
- A crack propagation acclerates and is fast, with this not controllable.

- The usable strength drops respectively the risk of failing increases with the stressed volume respectively the loaded surface.

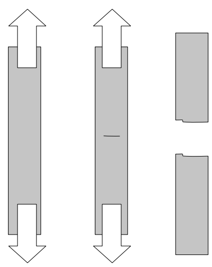


Light weight design should have "fail safe" behaviour. This demands know how. Here a spot 'super glue' prevents catastrophic failing.

Leight weight design has specific problems, because of the persued as high as possible loaded whole cross section.

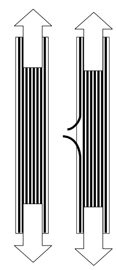


Tension bar.



A problem of the homogenuous/ solid cross section: Unfavourable fail safe behaviour.
- Fast crack propagation.
- Hardly to intrecept.
- Catastrophic failing.

Rope.



Ill. 3-17

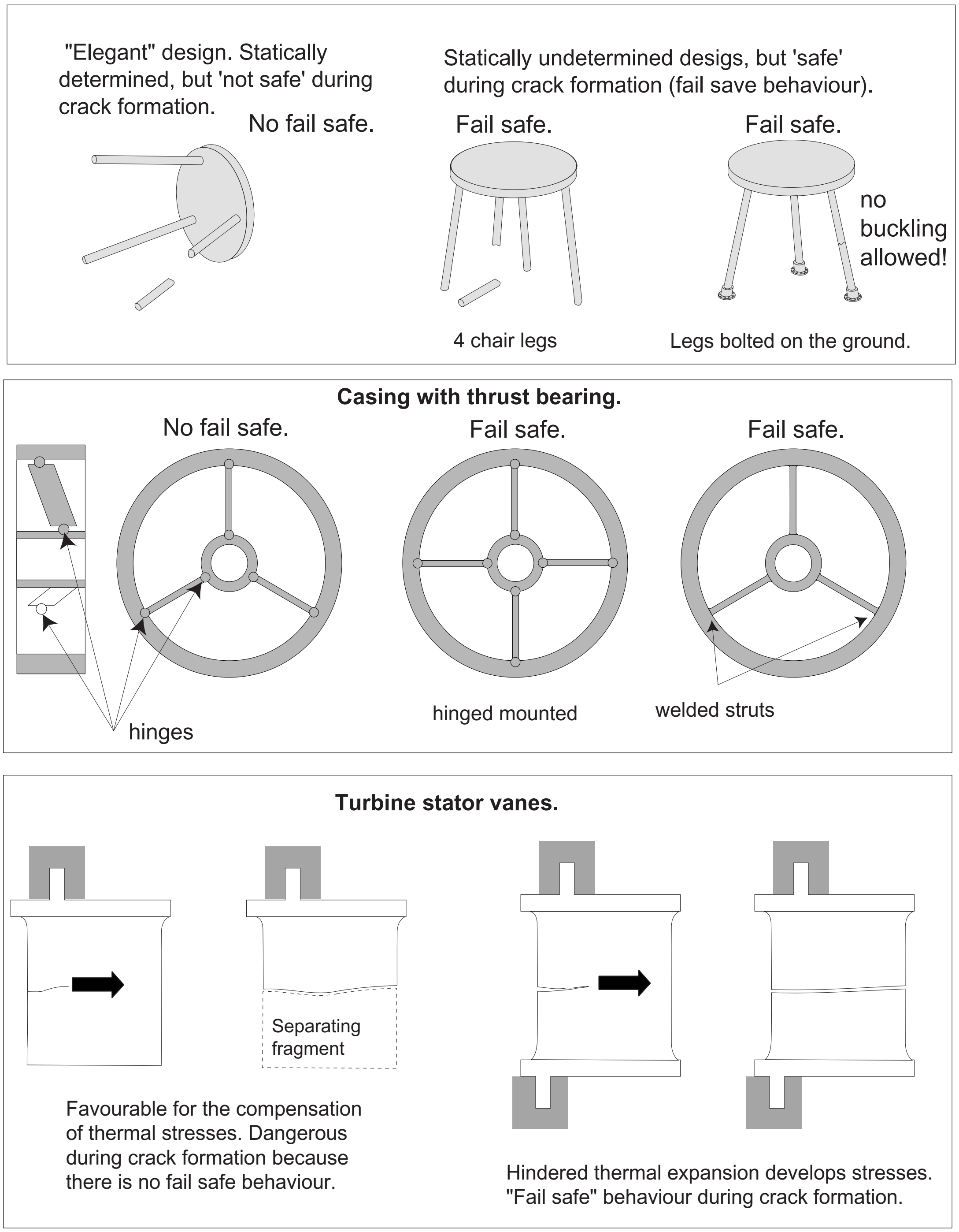
Ill. 3-18 *(Lit 3-2): The* ***design philosophy*** *plays an important role for the* ***crack behaviour and failing sequence****.*

*-**Statically determined designs**, especially such, where a single element transfers the operation loads, seem in fact 'elegant' and are well accessible for the calculation. But mostly, because the danger of a spontaneous failing, they allow no cracks. Such designs have no **fail safe behaviour** (see also Ill. 3-19). The fracture of one single bearing element causes at once the failing of the whole system. Crack growth leads to a fast load increase in the remaining cross section. This addtionally accelerates the crack. After a relatively short operation time, which leaves an identification rather the chance, it comes to the fracture with catastrophic failing. Here the dimensioning for life time must be limited at the incubation phase (Ill. 4.3-1). A typical example from our surrounding are tripod versions of tables and chairs (sketch above). A wobbling as long as three legs bear,can be ruled out. However, if it comes to the fracture of a leg, the 'system' fails inevitably by toppling.*

*- **Multiple statically indetermined designs** behave more failure trolerant as determined ones. Because several elements bear, during crack formation and fracture the loads relocate. So the deteriorated element will be relieved. Static indetermination develops e.g., if more than the absolutely for the loas transfer necessary elements are involved and/or a hinge effect at the knots is eliminated by firm connections e.g., welds.*

With four supports/struts the chair stands absolutely still if a leg breaks. A similar effect can also be achieved with three legs, if these are fixed at the ground. Also here a static undetermined version is concerned. Does a leg break, the intact legs take the load if the bending strength is sufficient.

Influence of design philpsophies at the failing of components during crack formation.



Ill. 3-18

In the figurative sense, bearing struts in casings can be compared with the example of a chair. Here a strut fracture at the statically undetermined versions may attract attention before a catastrophic failing with vibrations and rubbing processes.

The sketch below shows at the example of a turbine stator vane the ***influences of the fixing at the failure sequence****. A one-sided fixing relieves indeed the part from thermal stresses. However during a crack it comes to the breaking of a blade piece and extensive secondary failures. The version at the right leads to a confusing load. However if the blade fractures, it must not be reckoned at once with a failure malfunction and secondary failures. In this case a borescope inspecction has the* ***chance, to identify the failure in time****.*

Ill. 3-19 *(Lit. 3-1): In the adjacent illustration are typical examples assigned to the terms, which describe the safety relevant behaviour of the components.*

Example to „failsafety“:

*At high speed production machines/machine tools exists the danger, that parts of the rotating clamping device or of the workpiece will be centrifuged. Such a situation can also occur at tools like millers or grinding wheels (Lit. 3-14). The term for the absorbing/catching of such high-energy bodies is „****containing****“. Mostly the so called „****containment****“ is achieved with constructive arrangements, providing a sufficient strengthening of the casing/box against penetration.*

Example for fail safe „1“:

Typical are faults which are acceptable in an exact specified region. With this they don't influence the operation safety through the scheduled time period unacceptable. Such faults are thermal fatigue cracks in turbine stator vanes, when the crack growth typically decelerates (Ill. 5.4.2.1-2) and so gets surely controllable.

Example to fail safe „2“:

For this case the wheel of a bicycle is a nice example. The fracture of a single spoke attracts attention because of the sufficient remaining strength by vibrations and a rubbing of the tire at the frame. Also the location of the failure can be at once identified. With this it is guaranteed, that it does not come to the fracture of the wheel rim and with this to a catastrophic failing.

Example to fail safe „3“:

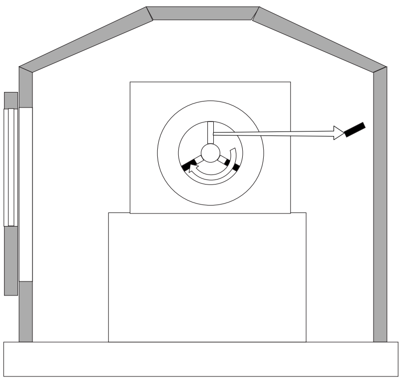
To this can also count the behaviour of parts, which in spite of an identified deterioration/ damage still allow a safe operation. If for example single wires of a tensioning rope fail (Ill. 3-17) suitable dimensioning it must not be reckoned with a spontaneous failing of the whole rope. Thereby it becomes beneficial, that the fracture of a single wire does not endanger the remaining structure uncontrollable like the crack in a homogeneous/solid cross section (Ill. 3-17).

Example to „fail safe „4“:

With the fracture of the shaft, the turbine delivers no more power to the compressor. Thus the turbine rotor can accelerate to dangerous overspeed in fractions of seconds („runaway“). In such a case it must not come to the burst of the rotor (this process would be uncontained) or an unacceptable axial offset. Therefore different constructive measures are used, to suspend such dangers. It is important to limit overspeeds controllable. To this belongs a suitable aerodynamic layout together with a suitable safety of the disks against bursting. A slow down of the rotor during purposeful contact with the stator ('Intermesh' principle, Lit 3-1) can also limit the speed effective.

"Fail safe", an important term with different interpretations and possibilities of realization.

Related terms: Failsafety, failure tolerance, damage tolerance, redundancy.



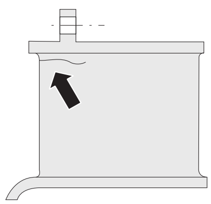
What is failsafety respectively fail safe behaviour?

Failsafety is a design principle, if considered, developing partly or total faults and failures at a component can not lead to a catestrophic failing of the whole device.

Example: Protection against impact of fragments (containment).

Failsafety respectively fail- safe behaviour can be achieved in different ways:

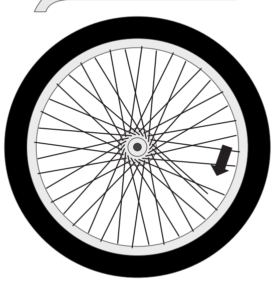
1



Fail safe (1):
Means, that a damaged structure further satisfies its function and triggers no catastrophic or secondary failures, whatever condition in the normal operation range of the device.

Example: Turbine stator vane.

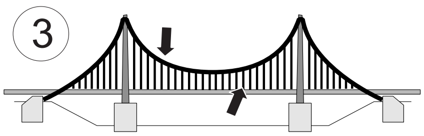
2



Fail safe (2):
Is a design even then, if faults can be certain identified, before they can develop failures/damages.

Example: Bicycle spokes.

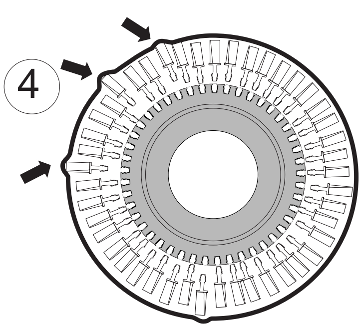
3



Fail safe (3):
Is a design acc. MIL-Spec's of the USA, if a system is able, to withstand 80% of the original dimensioning loads without failure, if a single main element of the system is damaged.

Example: Supporting cable.

4



Fail save (4):
Is a design according considerations of the FAA, if through calculation, test or both is proven, that a catastrophic failure or an excessive deformation of the structure, which could significant influence the whole characteristic of the device, after a fatigue failure or a simple failure at a single main structure is not probable.

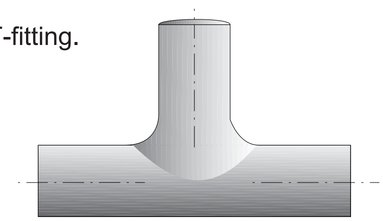
Example: Fracture of a turbine rotorblade.

Ill. 3-19

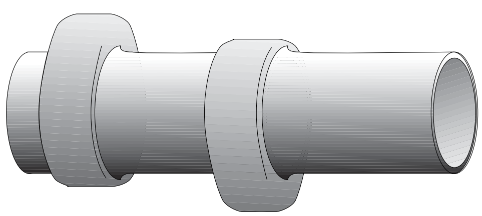
Description of the Ill. see previous page.

Light weight design demands shape and materials adapted production processes. To these belong 'new' forming processes, especially for hollow pieces.

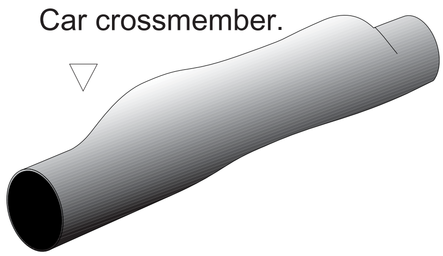
T-fitting.



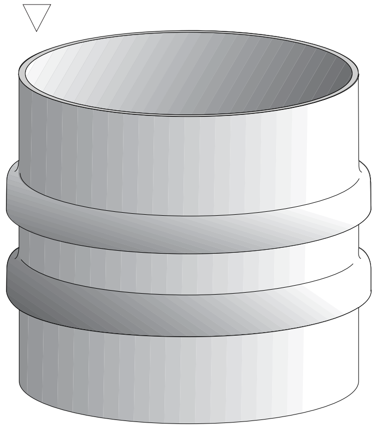
Part of a built cramshaft.



Car crossmember.

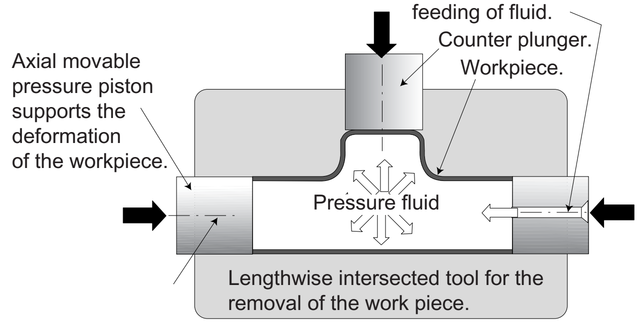


Hollow body with corrugations.



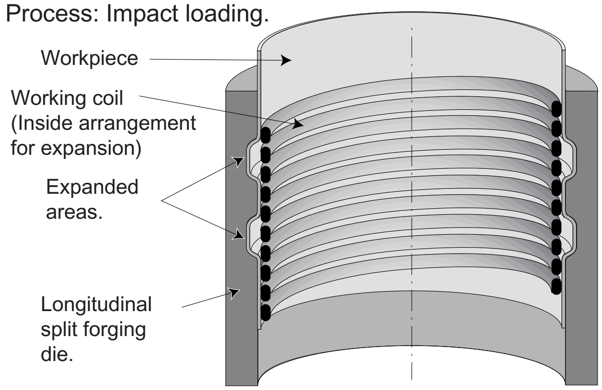
Metal forming with inner high pressure (hydroforming).

Process: Slow.



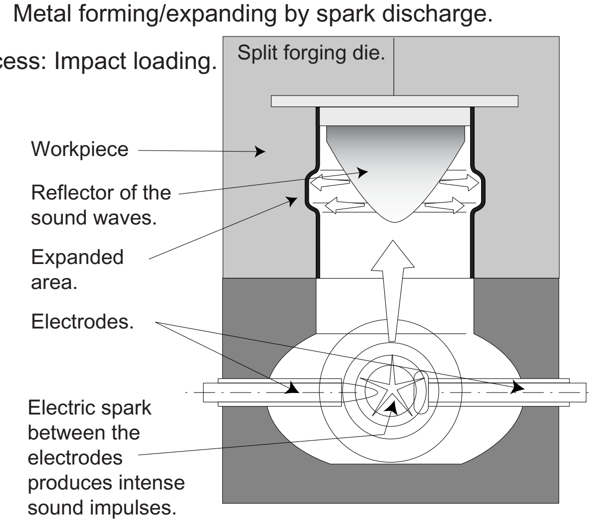
Magnetic metal forming (electromagnetic forming)

Process: Impact loading.



Metal forming/expanding by spark discharge.

Process: Impact loading.



Ill. 3-20

Description of the Ill. see neyt page.

Ill. 3-20 *(Lit. 3-8 up to Lit. 3-13): Light weight design structures are more and more applied in the mechanical engineering. Freequently* ***solid cross sections become hollow structures for the necessary stiffness****. For this, adapted special processes or new production processes are necessary.*

- ***Metal forming****: Hydroforming (sketch above right), electromagnetic forming (sketch middle right), forming with power pressure pulses (expanding by spark discharge, sketch below right).*

During a cold forming also the materials strength can be eincreased (work hardening).

- ***Welding processes****: Electron beam welding (EB welding), laser welding, diffusion welding, friction welding (Lit. 3-27).*

Such processes often demand extensive part and materials specific adaptions//optimizations.

Ill. 3-21 *(Lit 3-30 up to 3-33 and Lit. 3-35): Ceramic, especially as high strength* ***structural ceramics*** *(Ill. 3-22) became an important design material with high future potential. The use in mass production opposes in some cases still the* ***high production costs*** *(raw part and post-processing), as well as the problematic* ***non destructive quality control****, compared with metallic components. But this becomes more convenient with the* ***raw material costs****/ availability and the demand for higher* ***thermal efficiencies of power machines****. A role play material specific properties, which can be benificial used with an* ***adopted design****.*

- Low thermal expansion.
- Corrosion/hot gas corrosion (HGC)and oxidation resistance.
- Sliding and dry running (emergency operation) properties like missing seizing tendency.
- Wear resistance.
- Low density, ca. 35 % of competing metals.
- Strength properties in the range of metals.
Hot strength, temperature stability,
high stiffness (modulus of elasticity).
high hardness.

However ceramics have ***disadvantages****. These must be well-known and understood, to protect a design from failures and problems. Generally counts:*

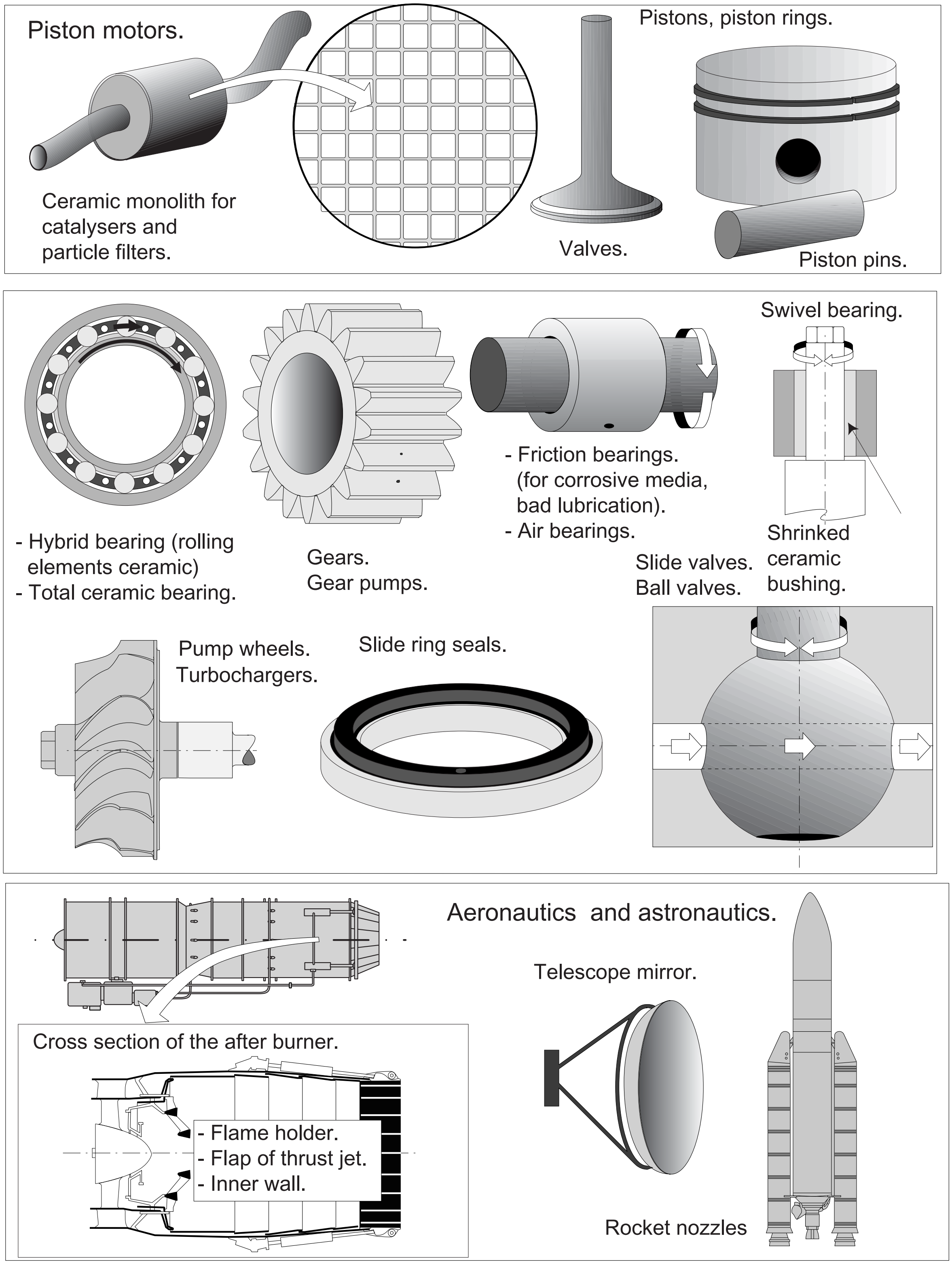
Production of the raw part *in contrast to the assumption (coffee cup, sanitary ware) is often very extensive. Processes must be developed part specific to guarantee the required quality (e.g., appropriate samples).*

Post-processing*: In many cases, ‘machining’ is only possible with diamond tools. Additionally exists the high danger of a unnoticed deterioration/damage of the machining surface. This can lead to a dangerous drop in strength.*

Quality assurance*: The higher the used strength the smaller are the critical faults (Ill. 5.2.1-9 and Ill. 5.2.1-10). This, certain to exclude failure size, usually lays markedly below the detection limit*

continued page 3-36

Ceramic components are also light weight design.



Ill. 3-21

continued from page 3-31

of series suitable non destructive tests (NDT, Lit. 3-30, Lit. 3-31 and Lit. 3-33). In such a case only remain so called ***proof-tests****. Thereby the part will be operation relevant loaded. This can be very demanding, e.g., for pump wheels and turbo chargers. A quality assurance by locking up the production parameters is thinkable. However the danger exists, that these change unrealized or important influences because of missing experience are not monitored.*

Strength*: Depends for brittle materials, especially ceramics, from the crack position, volume and surface (Ill. 5.2.1-10). This must be recognized during dimensioning and requires appropriate 3D calculations with realistic assumptions of the highest operation loads. Thereby also short-term processes (e.g., thermal shock, Ill. 5.4.2.1-3) must be considered.*

Stiffness*: Structure ceramics have in comparison with steels a high* ***modulus of elasticity****. Therefore ceramic parts can bad compensate already small elongation differences and will be overloaded. Especially attention is necessary during fast* ***thermal cycles*** *(steep thermal/****stress gradients*** *(Ill. 4.3-11).*

The ***density*** *of high strength pore free ceramics is about 3g/cm^3 and with this markedly lower as from steels. With this, its* ***spezific strength*** *(tension length) as relation of strength to density is absolutely comparable with metals. This is exspecially important for inertia forces (centrifugal forces, acceleratings) of self loading parts (rotors, pistons, valves).*

Failing mechanisms*: The higher the applied tension stress, the smaller the developing* ***fragments*** *(Ill. 4.4-9). Thereby energy is consumed. For example this advantage use* ***bulletproof vests*** *(Ill. 5.2.2-5) and* ***burst protection*** *(containment, Ill. 3-15 and Ill. 5.2.2-7).*

Examples of use*: Here only few examples can be given. Ceramics however are in series application in the most different fields. An example is the process technology (Lit. 3-32 and Lit. 3-37) and chemical facilities where corrosion resistance stands in the foreground.*

Motor components *(upper frame): Here offer itself especially components whose loads are considerably influenced by own* ***inertia forces****, i.e., the density. To these belong valves and pistons. Valves from SSN have been proven successful in* ***extensive long time tests*** *of motot vehicles. Also here obviously the costs opposed a series application. At piston pins the high stiffness, e,g., a little bending can act positive or negative. The challenge of such mass products is the* ***quality assurance under statistic aspects*** *(Ill. 3.3-3)****.*** *Challenging is the* ***integration in/with metallic structures****. Main problem are till now the production costs.*

Elementes/components *of the mechanical engineering (middle frame): Ceramics with appropriate beneficial, application specific properties are choosen. For* ***high speed anti friction bearings*** *are interresting the good emergency running propereties and wear resistance as well as low* ***centrifugal force of the rolling elements****. Hybrid bearings have conventional race rings and ceramic rolling elements. The* ***shaping of the contact surfaces*** *and the cinematics must be adopted at the differences of stiffness from steel and ceramics.*

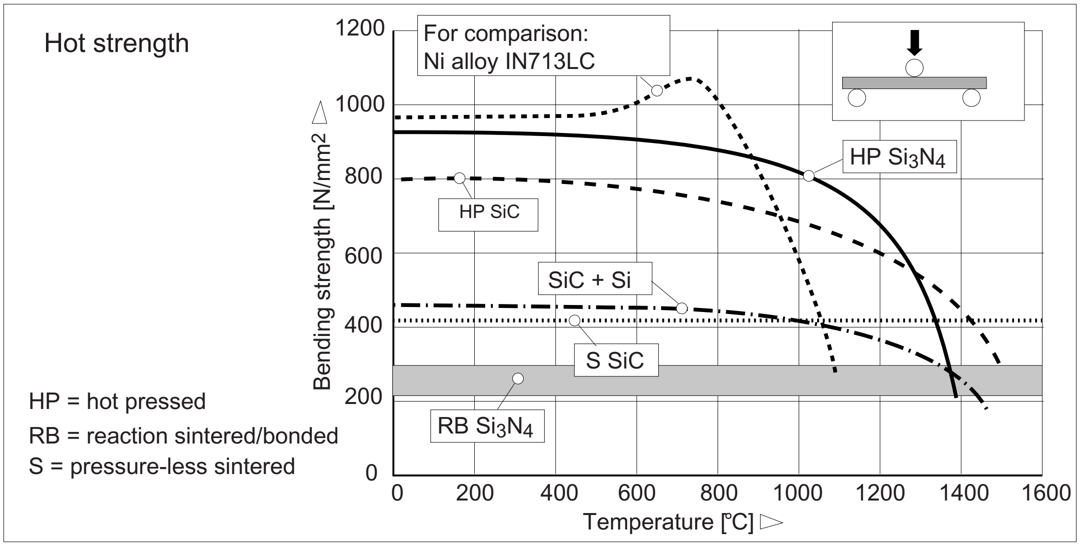
Gear wheels *offer itself for gears and gear pumps. Suitable selected* ***ceramics do not or only little*** *tend to* ***seize*** *(gall, cold welding, chapter 5.9.2) and so may tolerate* ***starved lubrication****. Problematic may be* ***shock like,*** *fracture endangering loads. In pumps, e.g., for the metering of drugs od cosmetics, lacking* ***toxic*** *alarming* ***metallic abrasion*** *can suggest the use of ceramics. At* ***pumps*** *and* ***valves*** *for aggressive media the high corrosion resistance of ceramics can be used.*

Katalyst carrier and particle/soot filter *in the exhaust gas stream of vehicle motors and power plants are predominant extrusion molded.*

Concerned are thin walled structures with lengthwise channels (honeycomb bodies/ 'monolith'). They consist of porous ceramics.
***Katalyst carriers**: Here the honeycomb body consists for example of sintered, prous cordierite ceramics. Concerned is a complicated structured silicate. It bears a prous, catalycing, ceramic coating (Al_2O_3 , 'washcoat') with embedded precious matals. This material has an **extreme low heat expansion.** This must be mastered against supporting metallic structures by sufficient elasticity/flexibility, harmonizing of the thermal expansions as well as compliant **itermediate layers**. At temperatures above 1200°C the danger of a melt sweating exists.*
***Particle filter/soot filter:** Are applied in diesel engines. Theis 'monolith' in exhaust systems of motor vehicles consists of meist aus porous (pore sizee ca. 10 µ) **silicon carbide**. Two deposit principles are distinguished. At the **wall stream filter** the gas flows through the wall pores, at the **flow-through filter** in lengthwise channels. The filter effect does not correlate a sieve. At the beginning it relies on a **surface filtration**. Then follows a **deep bed filtration by means of** adhesion. Thereby the diffusion of the particles in a filter wall is used. Is the flow resistance too high, a **regeneration** by oxidation of the soot takes place ('free burning'). Thereby arising **temperature peaks/**hot spots must be considered by the designer.*
***Friction bearings/swivel bearings** can besides the emergency operation/dry-running use its low friction up to high temperatures. This leads to a series application in control valves ('wastegate') of turbo chargers.*
*To make the bushings sufficient **thermal shock resistant** (Al oxide/alumina), they must be under **compression stresses**. For this they are **shrinked in** bores of the metalloc part.*
*Ceramic **shafts** of friction bearings can e.g., allow a materials specific lubrication with water instead oil. Besides the emergency operability (dry-run) the low thermal expandsion allows narrow lubrication gaps. With this it can be thought about the lubrication of a turbocharger with cooling fluid of the motor. Also for **air bearings** the mentioned properties offer itself.*
***Seals** have since long large-scale application **achieved**. Concerned are slide ring seals and seal disks in water taps with ceramical sealing surfaces.*
***Turbochargers** have been already, at least temporary produced in mass production and introduced. Here the low **moment of inretia** was used to minimize the so called 'power gap'. Problematic are the production costs.*

***Application in aviation and astronautics**: Here tests and appligations emerged. Obviously concerned are components with markedly **limited lifetime**. In all cases these are SiCSiC materials (Ill. 3-22) with **long fibers**. Because of the production technology this is primarily restricted to thin walled structures. Such are riveted in **hybrid design at supporting metal structures** (!). This shows the high usable failure tolerance of the fiber material. Emerged are thrust nozzle flaps at a fighter engine. Not throughout coated carbon fiber structures let expect at high temperatures with oxygen contact (combustion gases) **only short lifetimes**. Reason is a crack development during operation, which enables the 'burning' of insid C-fibres.*

'Design ceramics'.



Parameters for the estimetion of the potential capabilities.

Materials term	Acronym	Tempera-ture limit. °C	K_{1C} $MN/m^{3/2}$
„Nitride“			
· reaction bonded Si_3N_4	RBSN	1300	2 - 3
· hot pressed Si_3N_4	HPSN..................	1200...........	6 - 8
· pressure-less sintered Si_3N_4....	PSSN (SSN).......	1200...........	~ 5
„Carbide“			
· hot pressed SiC.........................	HPSC	1400	
· pressure-less sintered SiC ..	PSSC (SSiC)......	1400.........	3,5
· Si - infiltrated SiC	SiC - Si (Si SiC)...	1200.........	3,5
„Oxide“			
· Aluminium oxide $AlO_{2\,3}$	'Korund'.......	1800	
· Zirconium oxide ZrO_2	PSZ....................	1700	~ 8
· Glass SiO_2	(Quarz)	1300	
· Mixture ceramics from Si, Al, O, N	'Sialon'	1200	
· Aluminiumtitanat			
for comparison:			
Heat treated steel...			~ 100
Ball bearing steel..			~ 30

Ill. 3-22

Ill. 3-22 *(Lit 3-30 up to 3-33 and Lit. 3-35)* ***Selection of important structure ceramics:***

Silicon carbide *(SiC) develops in the as sintered form (SSiC) from SiC powder together with* ***sintering admixtures****. It distinguishes itself by a remarkable hot strength up to high temperatures. However problematic are thereby* ***glassy phases*** *at the grain boundaries, which are built by the* *sintering admixtures. They are the reason for a* ***time dependance of the hot strength*** *(creep effect, Ill. 5.3.2-3). During* ***access of humidity*** *(range of room temperature) under high tensile stress (bending) the danger of an* ***subcritical crack growth*** *due to the sintering glass phase, may exist (Ill. 5.6.3.1.1-8). The material has a high thermal conductivity and is electrical conductive. However above about 1400 °C it comes to a markedly oxidation (CO_2 formation). The part* ***dissolves gaseous****. A further problem already develops at relatively low temperatures (about 1000°C) through a* ***reaction with Ni alloys****. This complicates the* ***integration in metallic structures****. Additional comes a high modulus of elasticity. This* ***stiffness*** *increases this problem through a* ***low fracture toughness****, compared with other high strength ceramics.*

Silicon infiltrated SiC*: Several materials families are distinguished. These materials already come to operation or are imminent.*

Monolithic material *SiSiC by infiltration of a porous sintered SiC-C body is infiltrated in a Si melt. In the end product about 10% free silicon can be expected.*

Especially interesting properties have ***fiber reinforced versions*** *at which* ***SiC fiber preforms*** *are infiltrated with the Si melt. These are markedly more* ***failure tolerant*** *and* ***thermal fatigue resistant*** *as monolithic ceramics. Even with smaller damages no spontaneous fracture must be expected.*

SiC infiltrated SiC *(SiCSiC): The infiltration of a* ***SiC fiber preform*** *with SiC takes place in an extensive process by the* ***gas phase****. Such parts may only be suited for high price components. This depends from a relatively long process time inside demanding facilities and partspecific adaption of parameters. The high failure tolerance however leads to practical applications like in the astronautics (rocket nozzles) and military aviation (thrust nozzle flaps).*

Si infiltrated carbon fiber struktures *develop by submersing of carbon fiber preforms in a Si melt. Thereby the infiltration takes place and an, at least partly, reaction of the fibers with the melt to SiC. These materials show micro cracks and porosity, which in fact reduces the strength, but instead enables a* ***failure tolerance****. This leads to an application in the* ***brake disks of sports cars****. Thereby the high* ***coefficient of friction already at low temperatures*** *is used. This is an advantage, compared with the used carbon fiber brake disks in race cars and airplanes, which reach only at very high temperatures the desired brake effect.*

Silicon nitride *(Si_3N_4) is used in three different materials versions.*

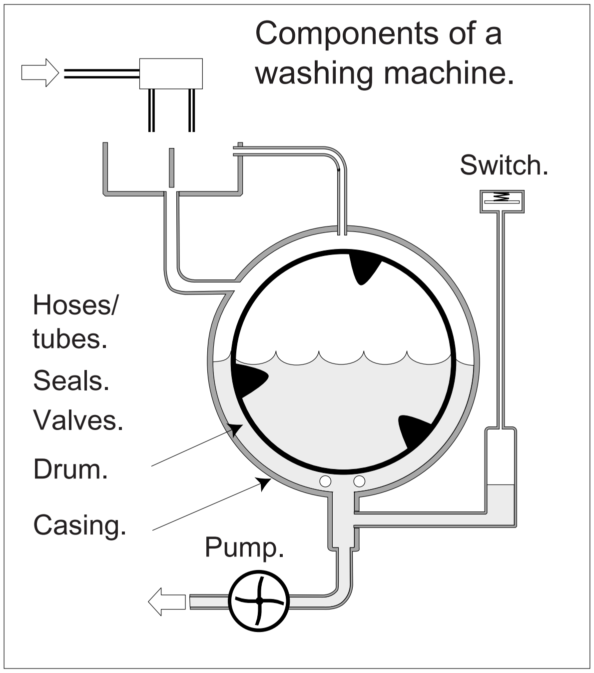
Sintered silicon nitride *(SSN) develops from fine Si_3N_4 powder and sinter aid. So also* ***complex parts*** *like turbocharger wheels can be realized. Concerned is a dense product with* ***ultimate strength****, quite comparable with steels. This material is tested in near-series applications at different components, e.g., of* ***piston engines****. To this belong (exhaust) valves, pistons and seal rings/ piston rings/sealing strips. Till now the still relatively high production price is hindering.*

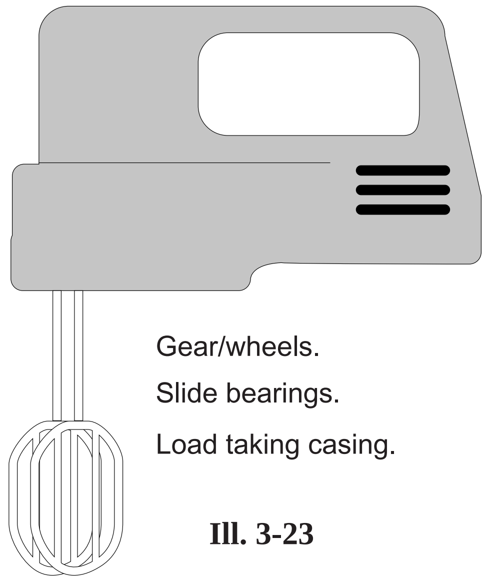
Reaction bonded silicon nitride *(RBSN) develops from a porous pre form which is nitrided in gaseous nitrogen. Therefore it is a porous material (15-30 Vol.%).*

The quite complex parts can have finite shape and are relatively cheap. In fact its hot strength is low, but does not drop also at high temperatures.

Further ceramics: *To these belong besides cubic boron nitride the „oxides“ aluminum oxide (alumina) and zirconium oxide (zirconia).*

Household aids as pioneers of the plastics application at different machine elements and light weight design.





Ill. 3-23

Ill. 3-23 *(Lit 3-29 and 3-34): In a multitude of* ***household aids*** *for kitchen, washing, room cleaning and do it yourself plastic components, fiber reinforced or short fiber filled* ***plastics*** *are since long unimaginable. Thereby concerned are besides in the mechanics integrated highly complex casings/boxes, are* ***machines/engines and its elements*** *like:*

- *Valves.*
- *Pumps.*
- *Tubes/pipes and hoses.*
- *Gears/gear wheels.*
- *friction bearings.*
- *Blower wheels.*

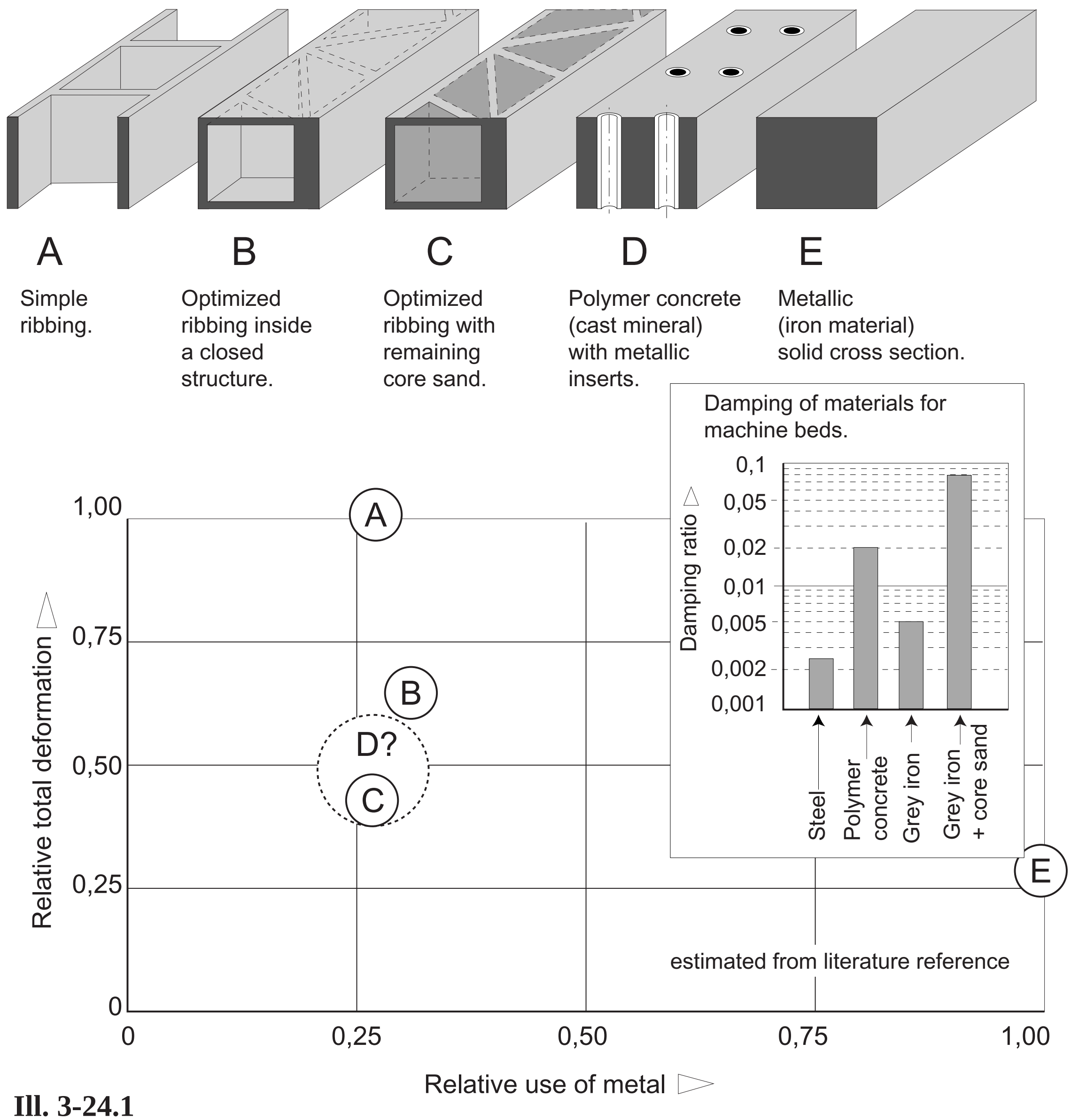
Beneficial usable properties*:*

- *Price: Forming/shaping, integrated colour.*
- *Low weight.*
- *Freedom of shape.*
- *Corrosion strength.*
- *Vibration damping, sound damping.*
- *Sliding properties.*
- *Electric and thermal insulation.*

Problematic properties *(Ill. 5.6.3.1.1-11 and Ill. 5.6.3.1.1-12)****:***

- ***Low strength****, depending from influencing* ***medium*** *and the* ***load period****. Distinct drop of strength during slightly higher operation temperature. Tends to plastic deformation by creep.*
- ***Low stiffness*** *(low modulus of elasticity).*
- *Plastic deformation already ar moderate surface/contact pressure (e.g., gear wheels).*
- ***Volume change****:* ***swelling, shrinking****. Can block/jam friction bearings.*
- ***Stress corrosion*** *during influence of material specific media (Ill. 5.6.3.1.1-12).*
- *Tendency for* ***embrittlement*** *during longtime operation under environmental influences (aging), light/UV-rays, thermial decomposition.*

Also the light weight design does not stop at machine tools/production machines. Important criteria are stiffness, damping, weight and material inventory.



Ill. 3-24.1

__Ill. 3-24.1__ and __Ill. 3-24.2__ (Lit 3-52): Light weight design seems at first unsuitable for __tool/production machines__ because its usual high weight rather. In spite since long, alternative materials/ technologies are tested and successful used for __machine beds__/frames. Thereby it is tried to utilize different characteristics as advantage. Unfortunately non of the different __materials and technologies__ offers advantages. To the unusual load-bearing materials belongs __polymer concrete__ (also called as cast mineral). This has, compared with 'normal' concrete, an especially high mechanical strength and good chemical properties. The binding of the aggregates 90%