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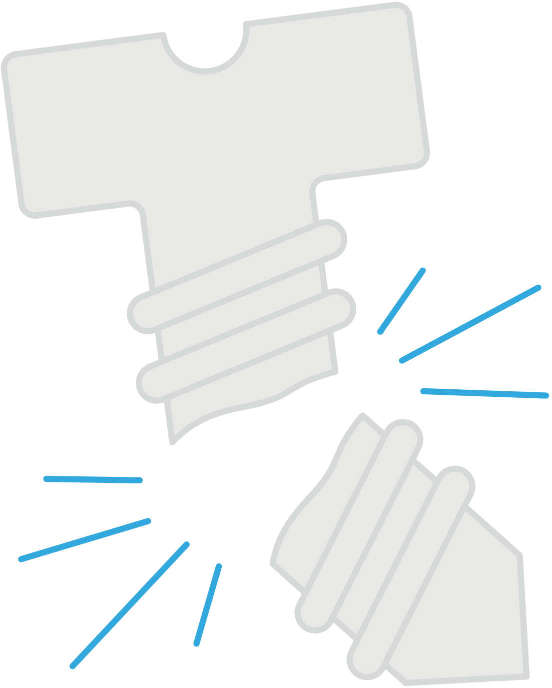

# Material fatigue – silent, sudden, deadly

White Paper

# Material fatigue – silent, sudden, deadly

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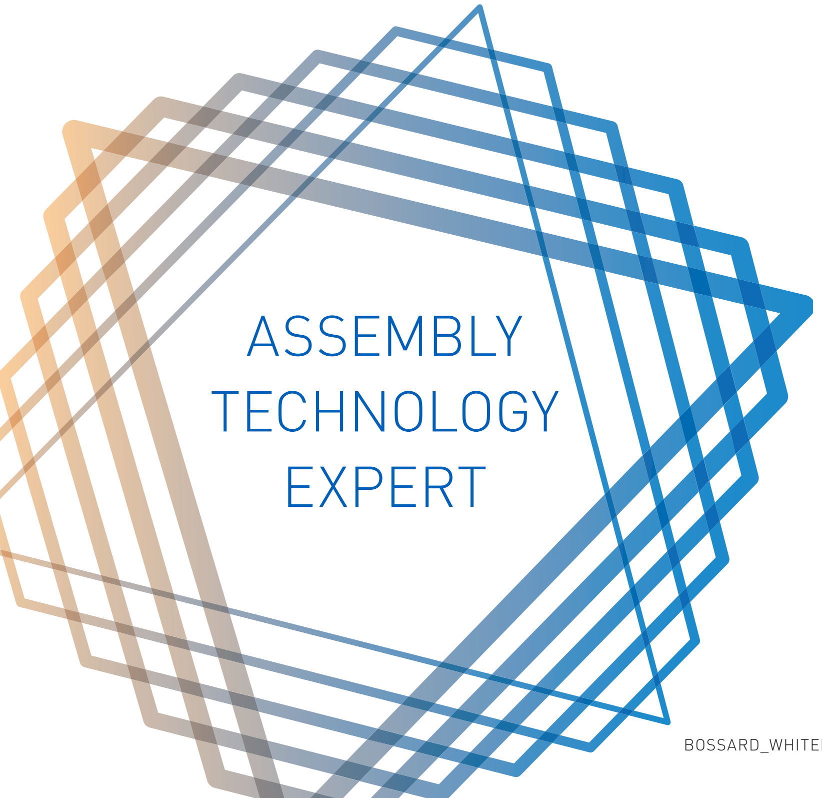

## MATERIAL FATIGUE – SILENT, SUDDEN, DEADLY

# History

Material fatigue was accompanying us since the beginning of the bronze age. A lot of tools and simple devices were damaged or broken under the load, way below the yield point, without paying much attention to this phenomenon. Reason? The smith is not going to study the case of the failure of his hammer. Simply, he changes for a new one. Nobody cares.

Situation begins to change with the development of industry and technology during the revolution started by James Watt´s invention of steam engine. Simple tools and mechanisms are being replaced by heavy machines in first factories build across western Europe. Public transport, e.g. trains, is being introduced, and that´s exactly the point, where it started.

It all happened during the calm afternoon of Sunday, May the 8th 1842. Celebrations of King Louis Philippe's at Versailles has just finished and about 700 people were looking forward to going home, to Paris. Shortly after their train left the Versailles station and accelerated to 40 km/h, it started to descend from the hill, which led to slight increase of its speed. There was a curve located right below the hill, which pressed on both sides of rails violently, leading to snap off the axle on the first locomotive. First locomotive derailed immediately and the second one, which was still set on a full throttle, rose easily over the first one as if it was a toy and pulled the rest of the train over it. Moreover, the second engine broke into thousands of pieces and caught on fire rapidly.

Figure 1: Painting of Disaster on the Railway between Versailles and Bellevue, 8th May 1842 - A. Provost

No technical problem was detected before, engine-driver didn´t make any fault, no external influence was observed. So what caused the death of up to 200 people and hundreds of injuries?

The issue of material fatigue was very poorly understood at that time. Lack of answers forced academic elite to investigate this crash and find out what really caused the worst train accident at those times. And it really didn´t take so long. Rankine solved the fatigue problem for axles and few years later, German mathematician August Wöhler created the first systematic description of fatigue behaviour. He is the author of so called Wöhler´s curve, which is being still used.

Despite the development of our knowledge and technology, material fatigue occurred as the cause of disasters other many times. In most cases, failure is caused by wrong design or maintenance. Design engineer should be always aware when dynamic load is expected to occur. And it´s also valid for fasteners.

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# Introduction

Material fatigue is defined as a cumulating degradation of material caused by dynamic stress with amplitude below the tensile strength limit. From the practical perspective we can divide the fatigue into two groups:

- low-cycle fatigue with number of cycles up to $10^4$ and amplitude of stress above the yield point, where plastic deformation predominates
- high-cycle fatigue with number of cycles more than $10^4$ and amplitude of stress, usually way below the yield point, where elastic deformation predominates

Low-cycle fatigue is not important for a design of the joint. During the low-cycle fatigue process, stress amplitudes usually exceed the yield point. Fasteners shouldn´t even reach this value of stress. On the other hand, we should be aware of the high-cycle fatigue! Designers of a fastened joint should always consider the influence of high-cycle fatigue when dynamic forces are expected!

On the Fig. 2 a typical example of dynamic loading cycle can be seen. The most important variable is not the maximal value of stress ($\sigma_{max}$), but the amplitude of applied stress $\sigma_a$. It´s the essential parameter determining the fatigue behaviour of the material.

There is a very specific danger in fastener branch. When the lower amplitude of the loading cycle crosses the zero line, all preload in the fastened joint is lost and the screw will rotate loose or even break after some time. This situation should be prevented by the designer of a joint.

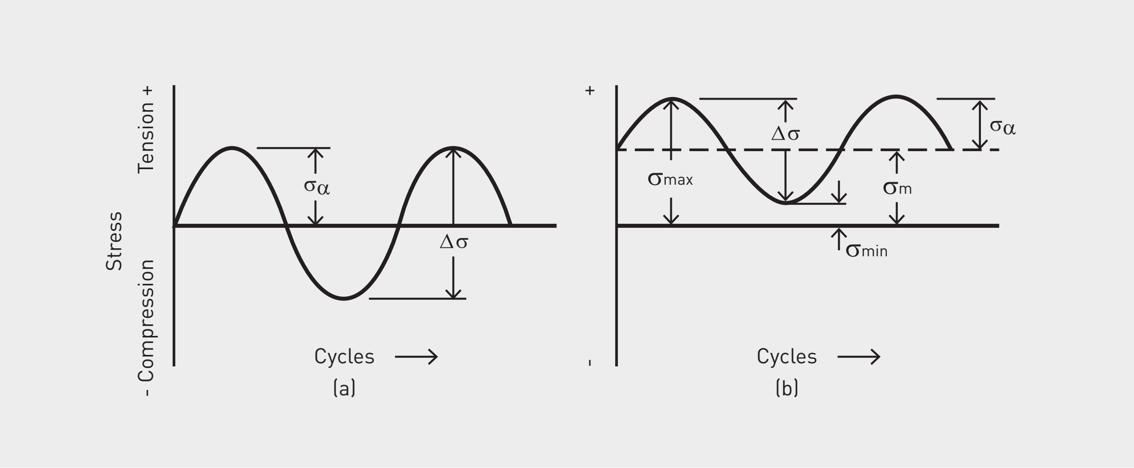

Figure 2: Examples of dynamic load regime: a) symmetric b) pulsing – typical cycle of tightened fastener

Wöhler´s curve is being widely used for calculation of the fatigue influence more than a century. It´s a diagram showing the dependency between the load amplitude of one cycle and the number of cycles without fracture. It can be seen on the Fig. 3. Diagram has four areas, which picture four periods of fatigue life.

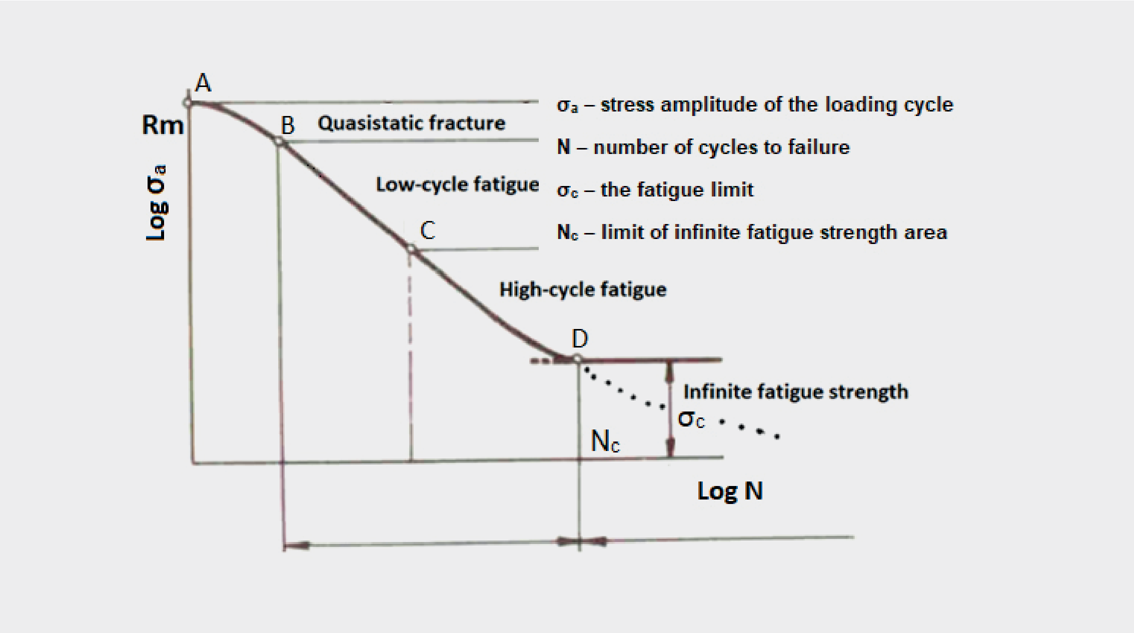

Figure 3: Wöhler´s curve – dependency between amplitude of one loading cycle and the number of cycles. Coordinates could be either linear or logarithmic. The shape of the curve is preserved in both cases.

As we can see on the Fig. 3, right from the point D, no further decrease in the amplitude dependence occurs. After reducing the stress amplitude below a certain value, no fatigue damage occurs. Area, right to the point D under the Wöhler´s curve is called the area of infinite fatigue strength. When an engineer is designing a fastened joint, he should do his best to operate in the area of infinite fatigue strength. But of course, values of $N_c$ and $\sigma_c$ are theoretical. In the ideal case, they are a function of the material. But reality is quite different. When we calculate the fatigue resistance of a fastener, aspects like geometry, surface conditions, temperature, material purity, loading conditions and surrounding environment must be considered. For general mechanical engineering purposes, the value of $N_c$ is standardised. For instance, steel alloys have $N_c = 10^8$ cycles, and the standard VDI 2230:2015 states $N_c = 2.10^6$ cycles for fasteners.

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# Mechanism

Fatigue life could be divided into four stages, visible on the picture below.

1. stage of mechanical properties change – unimportant for designing fasteners
2. stage of fatigue crack initiation
3. stage of propagation of fatigue crack/s
4. final rupture of reduced cross section of a fastener

The first stage is connected to a change of mechanical properties. Due to the influence of the cyclic loading, material might get slightly harder or softer, hysteresis behaviour occurs. The change of mechanical properties is rarely bigger more than 1 % and it is not important when engineers design a joint.

The fatigue crack appears during the second stage, yet micrometric. It is caused due to the extreme local accumulation of plastic deformation in the surface area with roughness and discontinuities. The stress amplitude could be greater than yield point of material in these areas. By the time, plastic deformation is concentrated here and could cause a crack initiation. Fatigue crack always starts from the surface.

The third stage is a stage of propagation. Freshly created crack grows due to the persistent dynamic load. Coalescence of small cracks occurs, leading to a creation of one dominant crack, with great potential of causing the final fatigue fracture. This stage is responsible for creating striations – equidistant curves visible on the fracture surface.

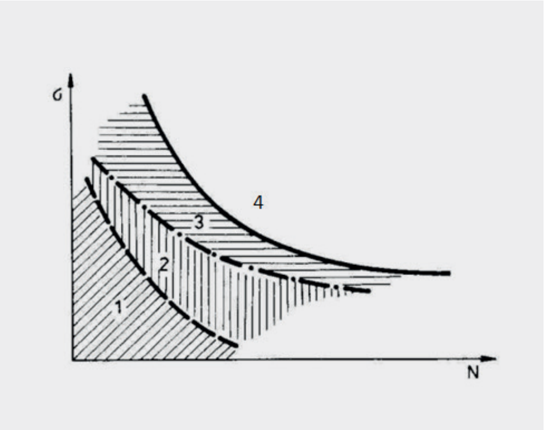


Figure 4: Schematic illustration of fatigue stages

Final rupture, caused by overload of reduced cross-section, is considered as the stage four. Character of the final rupture depends on the material and loading conditions. See the picture below.

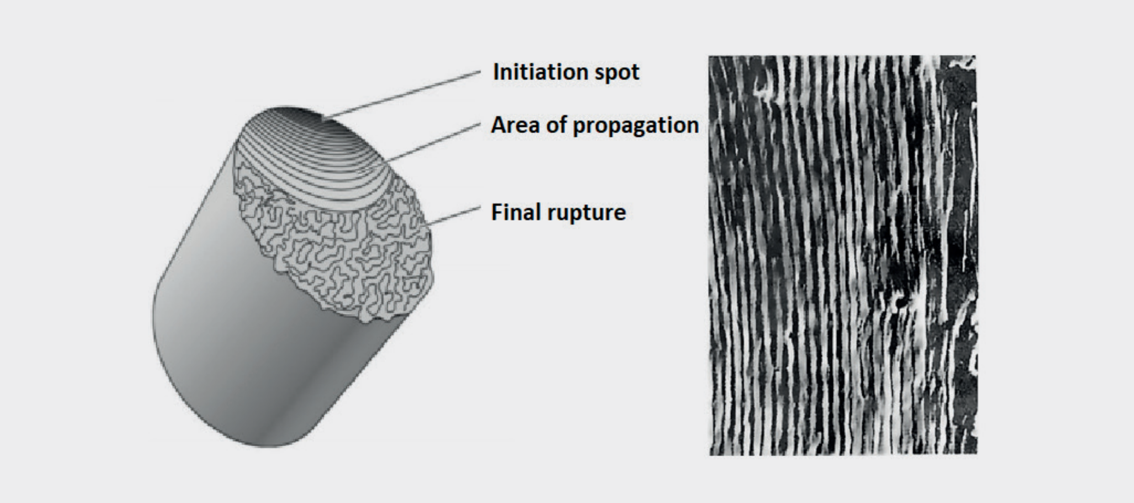


Figure 5: Fatigue fracture – striations present in the area of sequential growth of the fatigue crack and the detail on striations on the right

Striations are the best indicator of material fatigue. They are visible by eye in many cases, so they are very quick and easy tool for detecting a fatigue. However, one should be aware that absence of striations does not mean the absence of material fatigue.

In reality, we can hardly achieve situation when material is stressed by a cycle of constant amplitudes. That means consideration of changes of stress amplitude throughout the time should be undertaken. For this purpose we can use wing of a passenger plane. A lot of attention on safety is spent in aircraft industry, maintenance and traffic. That means a lot of calculation for fatigue resistance and fatigue lifespan are realised. A typical example of applied stress record on the wing during the flight is illustrated on the Figure 6.

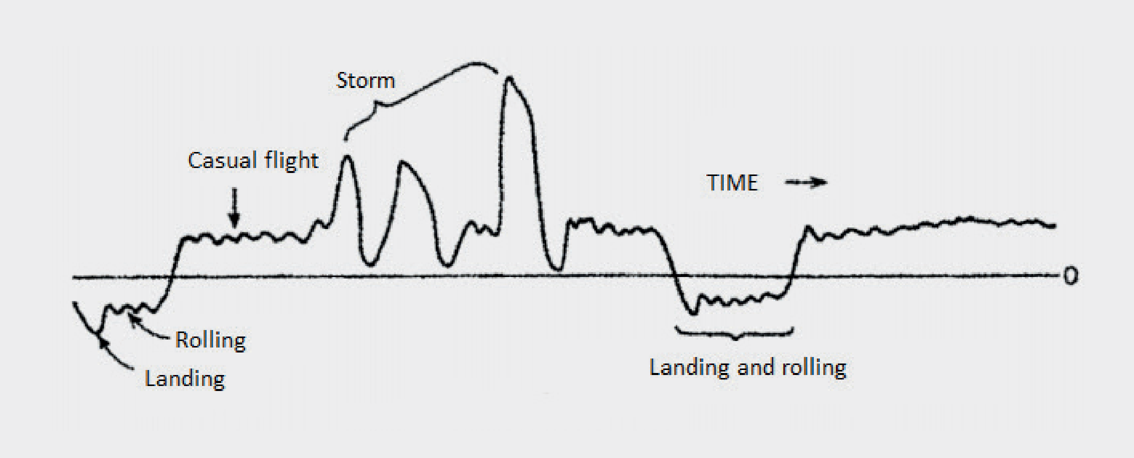


Figure 6: Record of stress acting on the hinge of the plane wing

As we can see on the Fig. 6 the stress amplitude is different while rolling, different while taking of, much more different when passing through the storm and when landing. Besides, conditions of different flights can be very variable. One must always remember diversity of flight conditions.

When an engineer is designing a fastened joint, he should be aware of changes of the stress amplitude. Even fasteners suffer from changing amplitude when exposed to dynamic loading. In order to provide basic understanding of how to calculate fatigue life or residual life of a fastener exposed to the variable dynamic loading, following section describes the simplest model of prediction.

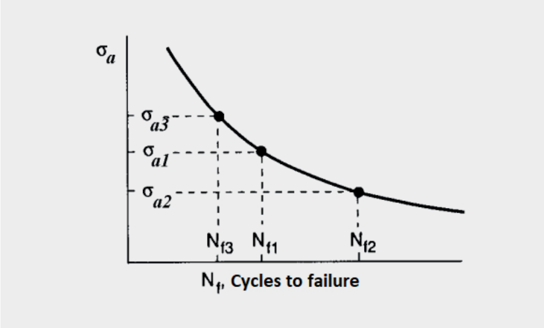


Figure 7: Different number of cycles to failure at different stress amplitudes

Any damage (even microscopical) caused by dynamic loading has cumulative character. And that is a very important information, which engineers should always remember. For illustrational purpose, let´s picture a blade of a wind turbine. This turbine was designed for 5 000 000 cycles at stress amplitude 150 MPa. But due to the hurricane passing around, turbine was exposed to stress amplitude 250 MPa for 100 000 cycles. How many cycles left? How long will the turbine work safely? Can we decrease the load to 100 MPa and believe it´s safe?

The oldest and simplest model allowing prediction of fatigue life is called Palgrem-Miner rule. It is a relatively simple equation on the Fig. 8, still widely used in practice.

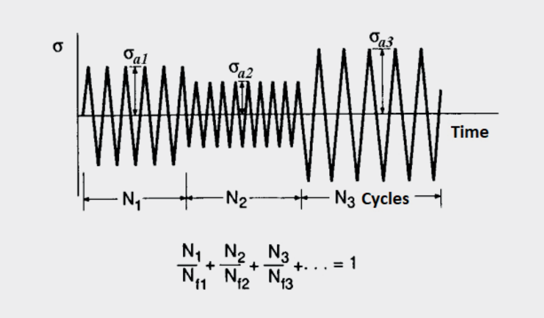
$N_i$ – number of cycles at amplitude $\sigma_{ai}$

$N_{fi}$ – number of cycles to failure under amplitude $\sigma_{ai}$

When the sum on the right side of the equation reaches 1, fastener will most likely fail due to the material fatigue. When we need to determine the residual life of fastener we must calculate all the influence of previous loading very carefully. The sum of all ratios $N_i/N_{fi}$ must be below 1.

Fracture occurs when:

$$\frac{n_1}{N_f^1} + \frac{n_2}{N_f^2} + \ldots\ldots = \sum_{j=1}^{k} \frac{n_j}{N_f^j} = 1$$



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# Detection

Detection of material fatigue before breaking the fastener is a very tricky task. Thanks to the development of defectoscopy, we are able to detect cracks in the bulk of material by using ultrasound, X-ray, capillary test or even by tomography. The output of these analysis can tell us whether material does contain a crack or not, but there is no tool which could clearly confirm its fatigue origin. That could be achieved only by metallographic analysis after breaking the fastener (or by damaging the part due to the analysis purpose).

The most significant symptom of material fatigue is the presence of striations, visible on the picture on the Fig. 5. With a certain dose of oversight, it could be said that every single striation represents one cycle during the stage of propagation.

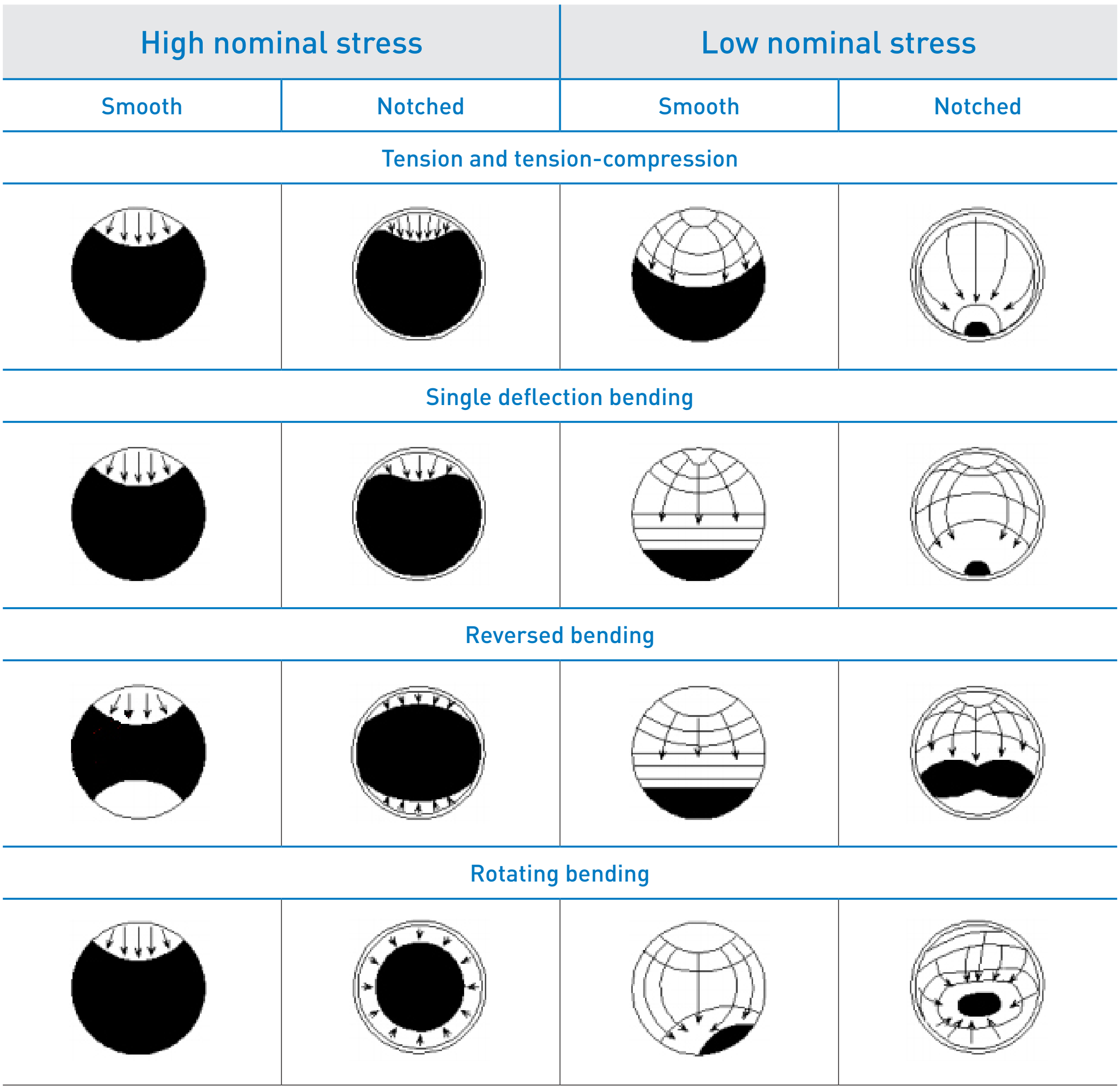

Figure 9: Schematic illustration of the surface of the fatigue fracture under different loading conditions

Generally speaking, that the bigger the area of final rupture, the higher were the dynamic loads causing the failure of a fastener due to the material fatigue. There are large residual ruptures present on the fastener fracture surfaces (left hand side of the Fig. 9) which indicate early stage fatigue cracks of a well tightened high-strength fastener. This situation occurs mostly due to the design error or high level of unexpected dynamic overload. The right hand side of the Fig. 9 shows small residual fracture surfaces linked to the late stage fatigue fracture with small dynamic overload. Such bolts were probably never tightened enough or they lost their preload due to the slackening or seating.

Figure 10 shows a photography of a real fastener broken due to material fatigue. Large portion of area with striations indicates relatively small dynamic overload. Striation dominates the fracture surface which tell us that the stage of propagation was quite long. Fracture crack was initiated at 7 o´clock and grew persistently into the shank of the fastener under the angle of approximately 30° which points at unilateral bending. The spot of initiation located off-center of the cross-section indicates the presence of notch, most likely an inclusion on the minor thread diameter of the bolt.

Summing it up, screw broke due to the material fatigue caused by small overload in dynamic unilateral bending combined with the notching effect of a material impurity close to the minor thread diameter of the bolt.

One should always remember that the situation could be much more complicated. A lot of types of loading and damage of a part could be combined, which could make the final analysis very difficult. Additional damage of fatigue fracture shall never happen. Scratching or contamination of fracture surface could make the final analysis very confusing or even impossible. That is the main reason why engineers at Bossard should act very precisely when investigating broken fasteners and a customer should be instructed not to touch damaged or broken parts and leave them at the place of failure without further manipulation. No additional damage of fracture nor corrosion development on the fastener surface should be secured. The knowledge of the cause of fasteners breakage is essential for prevention of future accidents and for keeping customer relationship vital.

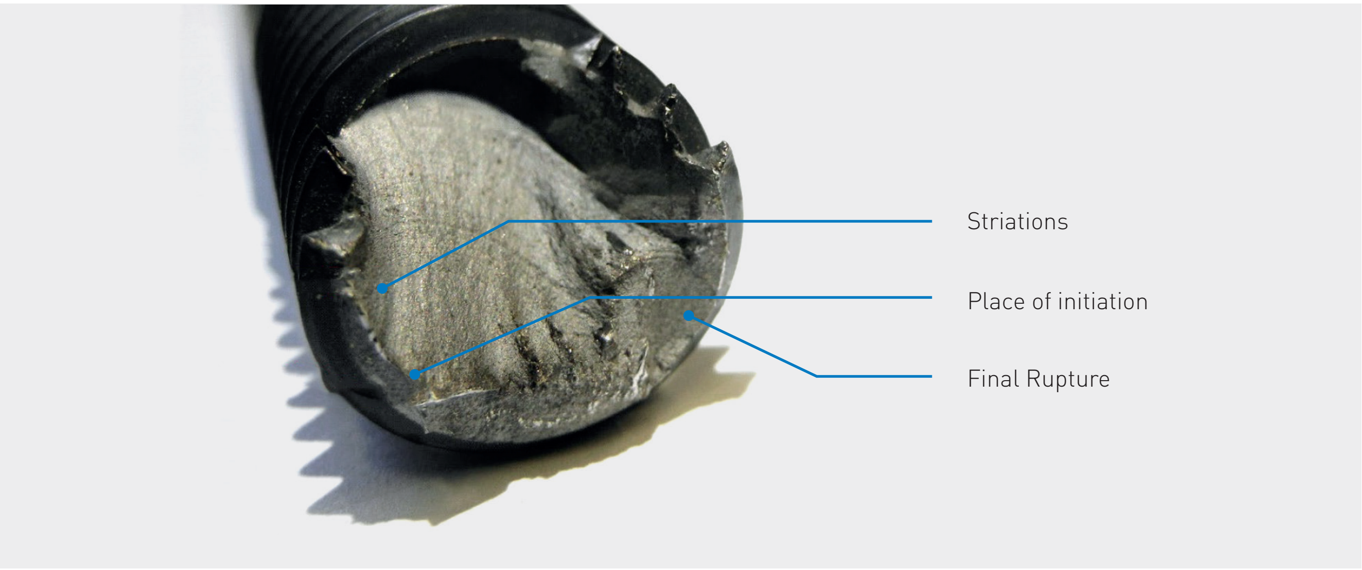

Figure 10: Example of a fastener broken due to material fatigue

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# Prevention

Previous sections described the nature of material fatigue. But how should a design engineer decide when dynamic loads are expected? Which criteria should the fastener or any other part meet?
The next section will provide basic knowledge about prevention of material fatigue.

There is a lot of factors influencing the fatigue behaviour. The most important aspect is geometry. Bossard recommended a solution for bolts resistant to extensive dynamic loads is to use bolts with waisted shank. Waisted shank has approximately 90% of the minor thread diameter which causes the movement of the critical area from thread to the smooth waisted shank. The presence of the thread in the critical area pictures the presence of the notch effect source directly on the surface. As it was mentioned before, fatigue crack always starts at the surface of the mechanical part (the only exception are composite materials). In addition waisted shank becomes more elastic which creates a possibility to compensate high dynamic loads by elastic prolongation or bending. The resistance to material fatigue rupture increases by 42% when using bolts with waisted shank instead of normal one. However, these kinds of bolts with waisted shank have decreased load bearing capacity in comparison with the normal ones.

Customer should be always advised that sharp edges and other types of notches could lead to development of a fatigue crack. Graphical illustration of this principle can be seen on the Fig. 11 above.

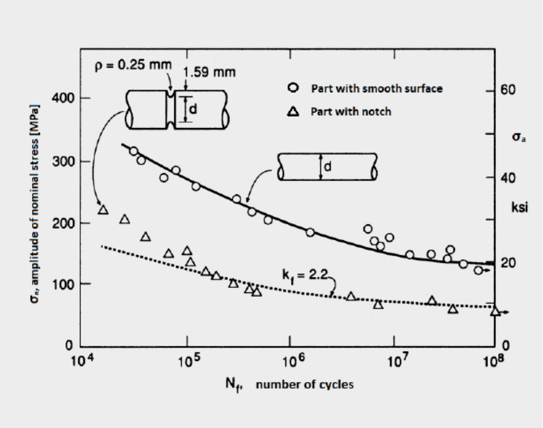

Figure 11: The influence of geometry on the position of Wöhler´s curve

The previous section described the influence of macrogeometry of the fastener (or any other mechanical part) on fatigue behaviour. But the influence of microgeometry takes its own portion of importance as well. The word microgeometry means the surface roughness. The profile curve is displayed on the Fig. 12. The most dangerous are the areas of local minima(one example is highlighted by red circle).

As it was mentioned many times before, fatigue cracks always start from the surface. These areas of local minimarepresent places with very high stress concentration with huge potential for initiation of a fatigue crack and they are located directly on the surface. When dynamic loads are expected, design engineer should use as smooth surface as possible. But carefully! Not all types of machining have a positive effect on the fatigue resistance. The only operation with positive effect on fatigue behaviour is polishing. Polishing effectively removes places of high concentrations without leaving residual stresses in the surface layer.
Any other machining operation leaves residual tension stresses in the surface layer, therefore has a negative effect on fatigue behaviour.

Compression stresses in the surface layer works in the exact opposite way, for example after coldforming. When coldforming a fastener, extensive plastic deformation caused by high level of stress occurs in the surface layer. But when we descent from the surface layer deeper into the material, the stress level will descent and the plastic deformation is replaced by elastic one. After finishing the forming operation, working loads disappears, leaving the surface level deformed plastically and elastic deformed area below. Elastic deformation tends to relax, which is pushing the surface layer above creating relatively high compression stress in the surface layer. This potential energy of compressive stress represents a barrier which is very difficult for fatigue crack to overcome. Mechanism of closing of fatigue crack is pictured on the Fig. 13. Arrows represent compression forces.

This needs to be taken into consideration when designing a joint. The VDI 2230:2015 standard warns, that bolts with thread rolled before applied heat treatment have considerably lower fatigue resistance than those ones which wouldn´t undergo heat treatment after rolling the thread. The reason is quite simple, HT operations cause recrystallization of the material structure and positive effect of deformed surface layer disappears.

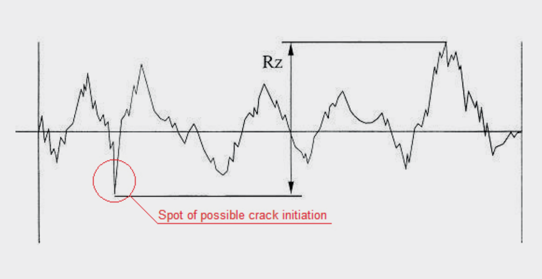

Figure 12: Surface roughness on micrometric scale

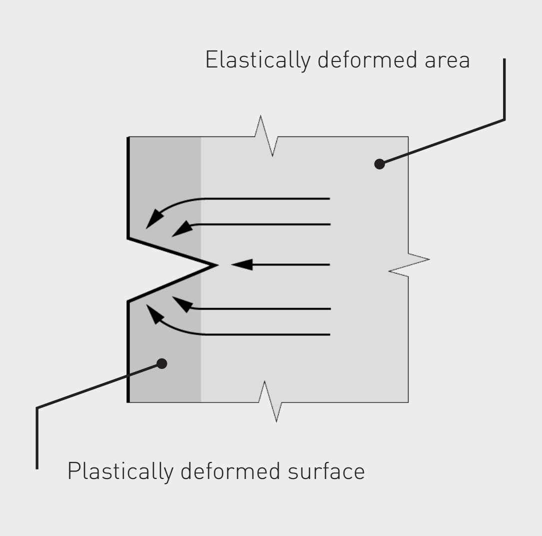

Figure 13: Mechanism of closing the fatigue crack due to the compressive relaxation forces

Previous figure leads us to a following conclusion. The more extensively coldformed surface is, the higher resistance to fatigue it provides.

Geometry of the fastener is not the only important aspect influencing the fatigue resistance. Depositing metallic layers on the surface of the fastener always creates tension stresses in the surface area which is making the fatigue resistance lower. Plain fasteners will have always better fatigue resistance then plated ones. Hot galvanised fasteners represent a special case. Tensile stresses present due to a deposition of zinc in combination with a very rough surface causes dramatic decrease of fatigue resistance. According to the standard VDI 2230:2015, this decrease can reach up to 20%!

The combination of dynamic loads and high temperatures has synergic effect. Defects created due to the influence of high temperatures make the fatigue crack propagation easier and faster. This effect has its greatest intensity when low frequency of dynamic load occurs. Illustration of this effect is pictured on the Fig. 14.

Previous sections discussed the influence of geometry of the part, loading conditions and structure of material. But influence of chemicals and chemical reactions shouldn´t be ignored. There are two ways how chemicals influence a fatigue behaviour. First negative influence is the corrosion, especially its local form. Dot corrosion can create cavities which can reach several diameters of the defect deep into the material. Such a defect creates high concentration of stress around it which creates perfect condition for initiation of a fatigue crack. The second way of influence is the chemical reaction itself. When it occurs near to the root of the crack, products of this reaction can be absorbed into the material weakening its the structure and making propagation of the crack easier and faster. Comparison of different environments is pictured on the Fig. 15.

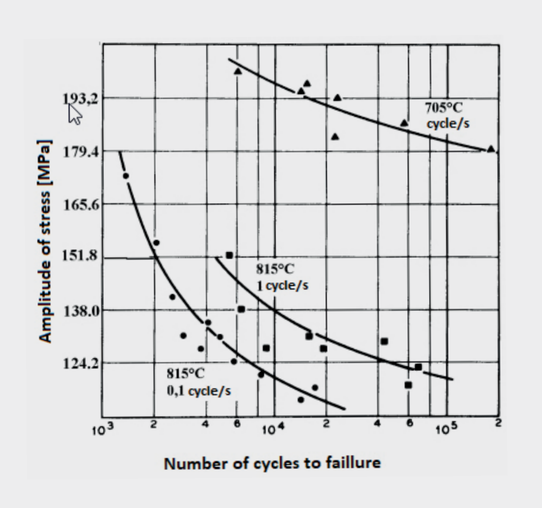

Figure 14: Influence of the temperature and frequency on fatigue life of the fastener

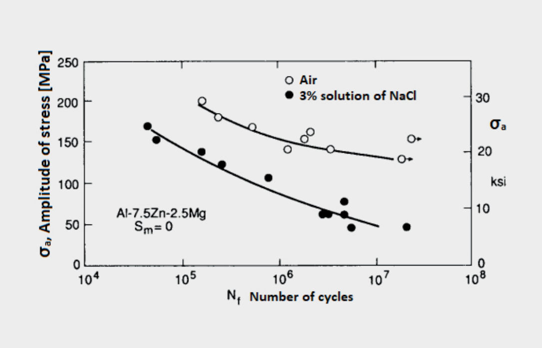

Figure 15: The influence of surrounding environment

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# Calculation

The last section is going to provide basic ways of calculation of fatigue limit of steels. All the data come from an extensive statistical research, so certain deviation from stated values should be expected. When using these relations, design engineer should be familiar with the risk and work with higher factor of safety.

Generally speaking, the higher the strength of the material, the lower the resistance to fatigue. Hard and brittle phases in the microstructure of steel have lower resistance to fatigue due to their poor ability to relax extensive dynamic amplitudes by realizing plastic deformation.

The Tab.1 provides average values of ratio Rm/σ0 for different phases of steel microstructure.

| | **Ferrite** | **Perlite** | **Martensite** |
|---|---|---|---|
| $R_m/\delta_0$ ratio | 0.6 | 0.4 | 0.25 |

Table 1: Average values of Rm/σo ratio for unalloyed steels

Information provided by the Tab. 1 leads us to a following conclusion: the higher the concentration of hard and brittle phases in the material microstructure, the lower the resistance to the material fatigue. Mischke and Shigley constructed statistical dependence described by Equations 1 and 2 below.

$$\sigma_0 = 0{,}504 * R_m \qquad \text{valid for} \qquad R_m \leqslant 1460\ \text{MPa} \qquad (1)$$

$$\sigma_0 = 740\ \text{MPa} \qquad \text{valid for} \qquad R_m > 1460\ \text{MPa} \qquad (2)$$

Graphical interpretation of Eq 1. and Eq. 2 is illustrated on the Fig. 16 below.

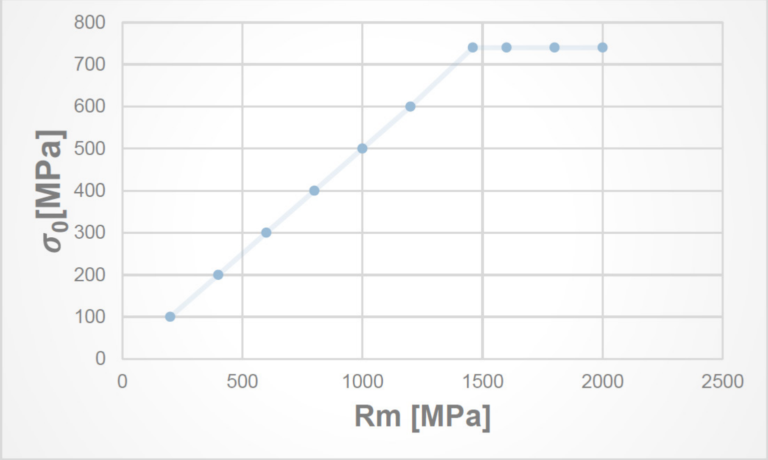

Figure 16: Dependency between tensile strength and fatigue limit (steels)

What implicates the change of behaviour at 1460 MPa is not clear yet. Most likely brittleness of phases present in the microstructure dominates over high value of its tensile strength. Further research of these statistical data should be undertaken in order to reach the full understanding.

The matter of the material fatigue is very complex. Some of the recommendations goes against each other which makes the work of a design engineer complicated. When considering the possible danger which material fatigue represents, design engineers should pay a lot of attention to every single aspect described above when dynamic loads are expected.

If you need further assistance or have special finish requirements, please check out our contact page at **www.bossard.com** and talk to your nearest Bossard customer service representative.